PROTECTION OF OVERHEAD TRANSMISSION LINES

by

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CHAPTER I

INTRODUCTION

The use of steam turbine units in sizes of 500 MW or larger has made it imperative to provide heavy transmission ties between bulk loads and generating points. This, for one, has increased the transmission system voltages, notably in U.S.A. and U.S.S.R. The high voltage lines not only have higher power capability but also higher fault capability. This high fault level demands fast clearance of faults to limit the damage because the capital investment involved in a power system for the generation, transmission and distribution is extensive. Besides ensuring protection to the equipment, the system has to operate as nearly as possible at peak efficiency.

The normal path of the electric current is from the power source through copper (or aluminum) conductors in the generators, transformers and transmission lines to the load and is confined to this path by insulation. This insulation, however, may be broken down, either by the effect of temperature and age or by a physical accident, so that the current then flows in an abnormal path generally known as the short circuit or fault. Whenever this occurs the destructive capabilities of the enormous energy of the power system may cause expensive damage to the equipment, severe drop in voltage and loss of revenue due to interruption of service. Such faults may be made infrequent by good design of the power apparatus and lines and by provision of protective devices such as surge diverters and relaying. However, a certain number of outages will occur inevitably due to lightning and unforeseen accidental conditions.

The purpose of protective relays and relaying systems is to operate the correct circuit breakers so as to disconnect only the faulty equipment from the system as quickly as possible. It would be ideal if protection could anticipate and prevent faults but this is obviously impossible except where the original cause of a fault creates some effect which can operate a protective relay like the Buchholz relay.

Insulation is either air or a high resistivity material which may also be used as a mechanical support. Air insulation can be accidently short circuited by birds, rodents, snakes, kite strings, tree limbs, etc., or can be reduced in insulation strength by ionisation due to lightning or a fire. Organic insulation can deteriorate due to heat or ageing, or can be broken down by overvoltage due to lightning, switching surges, etc. Porcelain insulators can be bridged by moisture, dirt, or salt and can become cracked.

There are a number of factors which influence the choice of protection for a particular system:

(a) The detailed characteristics of the line to be protected are a basic factor. As an example, a feeder may consist of a length of overhead line connected in series with an underground cable. Not all protective schemes suitable for protecting overhead lines are necessarily suitable for a combination of overhead line and cable; the relatively low impedance of the cable may be such that the effective length of the feeder is too short for the satisfactory employment of distance protection.

(b) The probability of various kinds of faults that occur on the transmission lines should be considered next. From the statistical data on lightning, tropical countries should have adequate protection against lightning.

(c) The magnitude of minimum and maximum fault currents at appropriate points on the system must be established in order to determine the sensitivity and stability requirements for protection. This is important because the fault current during off peak periods may be less than the full load current during the peak period and in case overcurrent protection is employed, due considerations must be made for it.

(d) Fast fault clearance times set especially for three phase faults may be essential to maintain system stability. System stability studies indicate that at many 275 kV and 400 kV stations system stability will be endangered if a close up three phase fault is allowed to persist for more than 0.2 seconds. Fast clearance times are also required on plants feeding large induction motor loads. The main reason for this is that a prolonged dip in voltage may result in the induction motors slowing down to such an extent that, when the fault is cleared and normal voltage is restored, the motors draw such a high current attempting to accelerate that the resultant current produces a large voltage drop between the source of supply and the motor terminals. This reduction in voltage may result in motors being unable to regain their normal speed.

Faster schemes are more expensive, more complex and, in some cases, more liable to maloperate.

(e) In transmission networks where substations are separated by only a few miles as in London, the most satisfactory and economic protection for feeders is to employ private pilot wire protection utilising cores in a network of private pilot cables. Where private piolt cables are not available, it is usually economic, at least in London, to hire pilots from the post office for the protection of two-ended feeders, but the protection of three-ended feeders by such schemes employing post office pilots is rarely satisfactory. Such a network of cables may not be available everywhere. This is true, in particular of underdeveloped countries, where communication systems are now being developed.

Transmission lines have to be protected from lightning and switching overvoltages, short circuits and in certain cases from the reverse flow of power.

Protection systems differ from country to country so a general method has been presented for protection. It does not relate to any one particular system.

CHAPTER II

PROTECTION AGAINST LIGHTNING

Lightning originates from thunder clouds which usually contain positive charge at the top and negative charge at the bottom. Lightning investigators generally agree that the accumulation of electricity in clouds takes place in the presence of ionised air, moisture in the atmosphere, and upward air currents. It is also agreed that the lower portion of the cloud is predominantly negative and the upper part predominantly positive, with a region of mixed charge at a level in which the temperature lies between 0° C and -20° C. In the tropics this region of separation occurs at a much higher altitude than in the temperate regions. Figure 1 shows meteorological and electrical conditions within a thunder cloud, according to Simpson's revised theory (14).

Potential gradient at the earth's surface due to storm clouds have been recorded up to approximately 300 kV per meter, as compared with the potential gradient due to the normal earth's field of the order of 100 volts per meter.

The Lightning Stroke

From photographs of lightning strokes taken by means of the Boys camera, the following generalised picture has been found

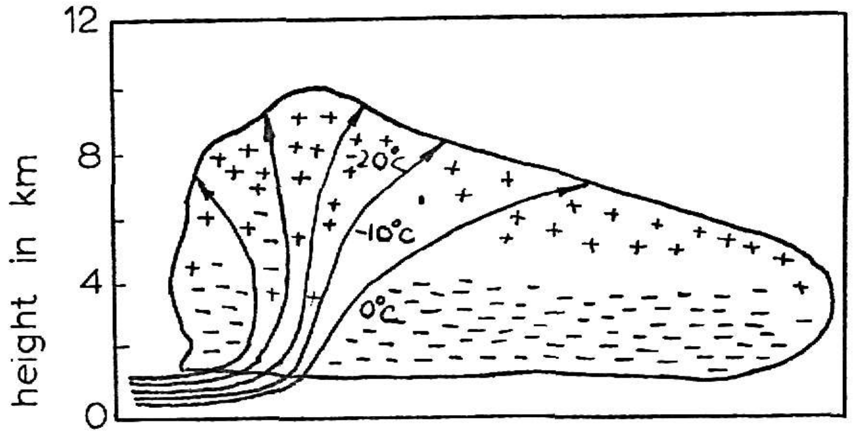


Fig. 1 - Meteorological and electrical conditions within a thundercloud according to Simpson's Revised Theory. (The unbroken lines with arrow-heads represent the stream-lines of air).

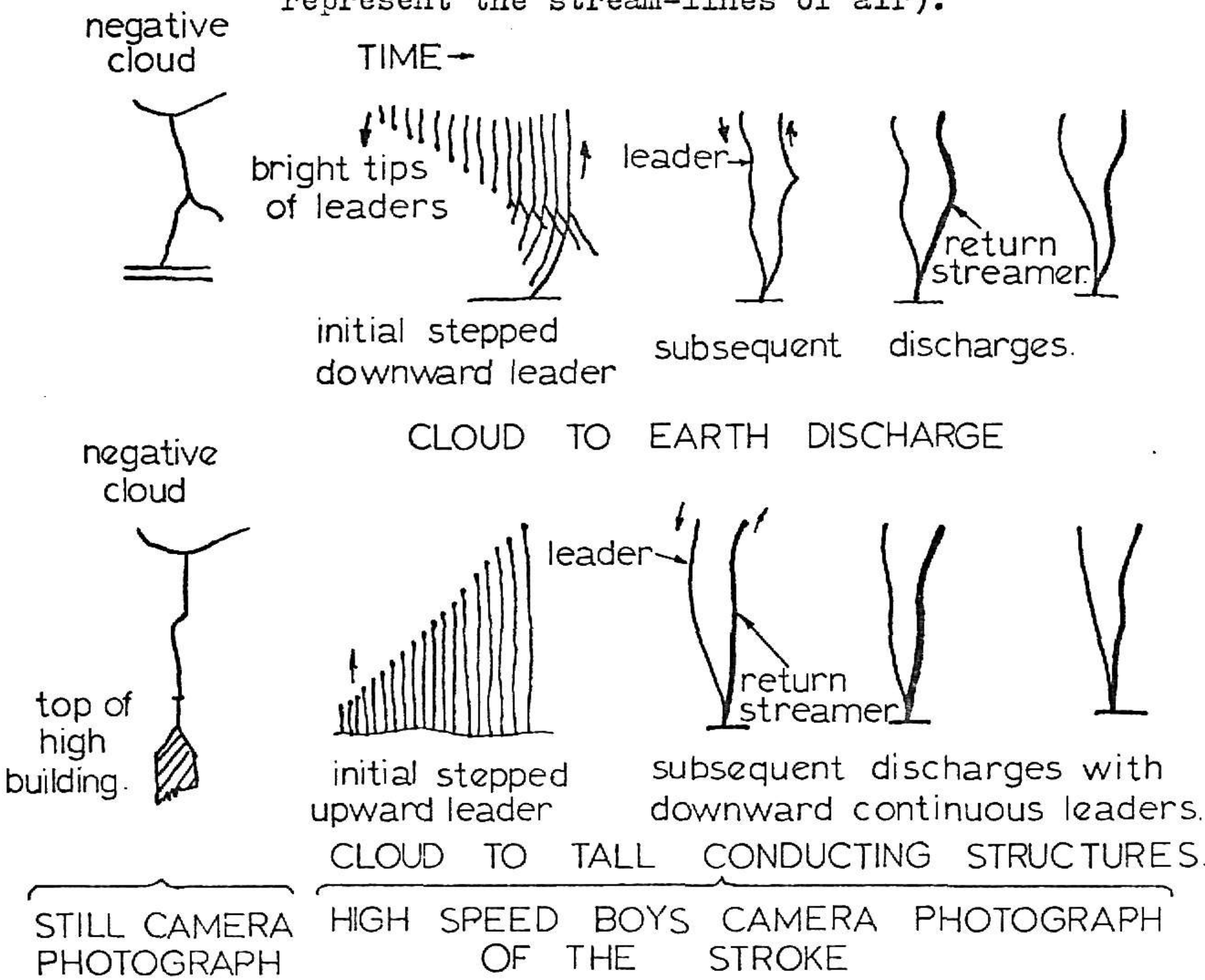


Fig. 2 - Mechanism of lightning flashover.

for the mechanism of the lightning stroke to a comparatively flat terrain or low structures from clouds.

The majority of the strokes recorded came from clouds of negative polarity. The first discharge starts with a stepped leader proceeding from the cloud to earth with an effective velocity varying from 10 to 2000 cm per microsecond. Effective velocity is the total path length from the cloud to ground divided by the total time taken over the path. It is surmised that a continuous pilot streamer travels downwards ahead of the step streamers. Subsequent strokes have a continuous or a dart leader proceeding downwards from the cloud at velocities ranging from 100 to 2600 cm per microsecond. Each leader which reaches the ground, both stepped and continuous, is followed by a return or main streamer proceeding from the ground to the cloud at a velocity ranging from 2000 to 14,000 cm per microsecond, that is approximately one fifteenth to one half the speed of light. The length of each step of the initial leader varies from 10 to 200 meters and the pause between steps varies from about 30 to 90 microsecond. The strokes consisted of 1 to 27 separate discharges.

In lightning discharges to tall objects a different stroke mechanism is observed. An investigation of the lightning strokes to the top of the Empire State Building in New York City, 1250 feet above the street level, confirmed in general the above conclusions, with however, an important difference in the stroke mechanism: the majority of the initial stepped leaders proceed upward from the top of the building to the cloud, instead of downwards from the cloud as to a flat terrain and low structures and were not followed by return streamers. In other respects the stroke followed the same procedure as in other observations. The continuous leaders of subsequent discharges were down from cloud to earth, and all the return discharges were upward from earth to cloud, as shown in Fig. 2. It was also found that the maximum duration of the stroke was 1.5 seconds, with more than half the strokes having a duration of 0.3 seconds.

Voltages and Currents Induced by Lightning

Very powerful lightning current flows along a highly luminous channel, in the form of a pulse which rises to its crest in the first few microseconds and then dies away. The steeply rising part of the pulse is called the "front" and the declining part the "tail". The maximum gradient measured for the front of a pulse is 50,000 amperes per microsecond.

The amplitude of the lightning current is of the order of 500 to 250,000 amperes. Figure 3 shows, in percentages, the probability curve for various lightning current strengths. As the strength increases, the percentage of lightning flashes falls. Thus, 20,000 ampere flashes constitute 45%, whereas flashes with a strength exceeding 100,000 amperes constitutes only 1% of all flashes. 200,000 to 250,000 amperes is the maximum strength known to occur. Another interesting feature found

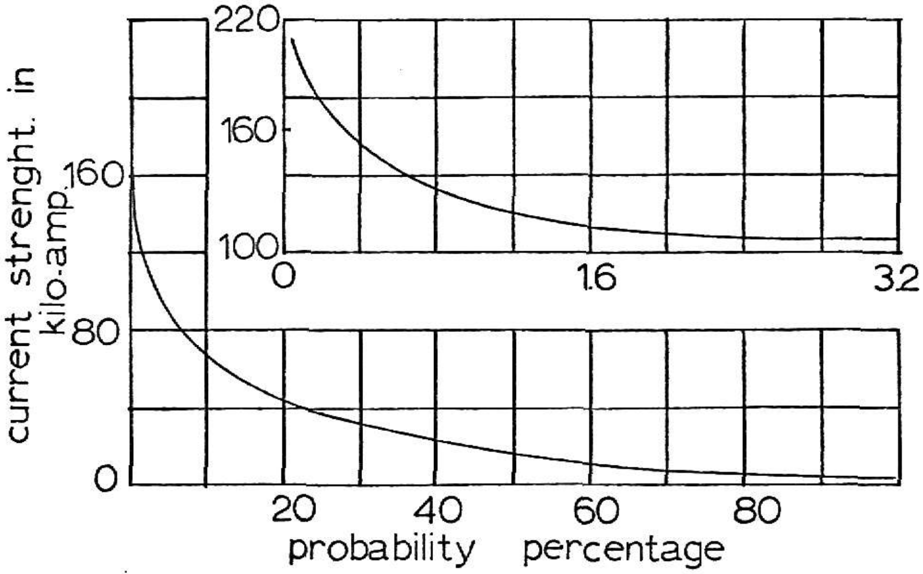


Fig. 3 - Current - Probability curve for lightning discharges.

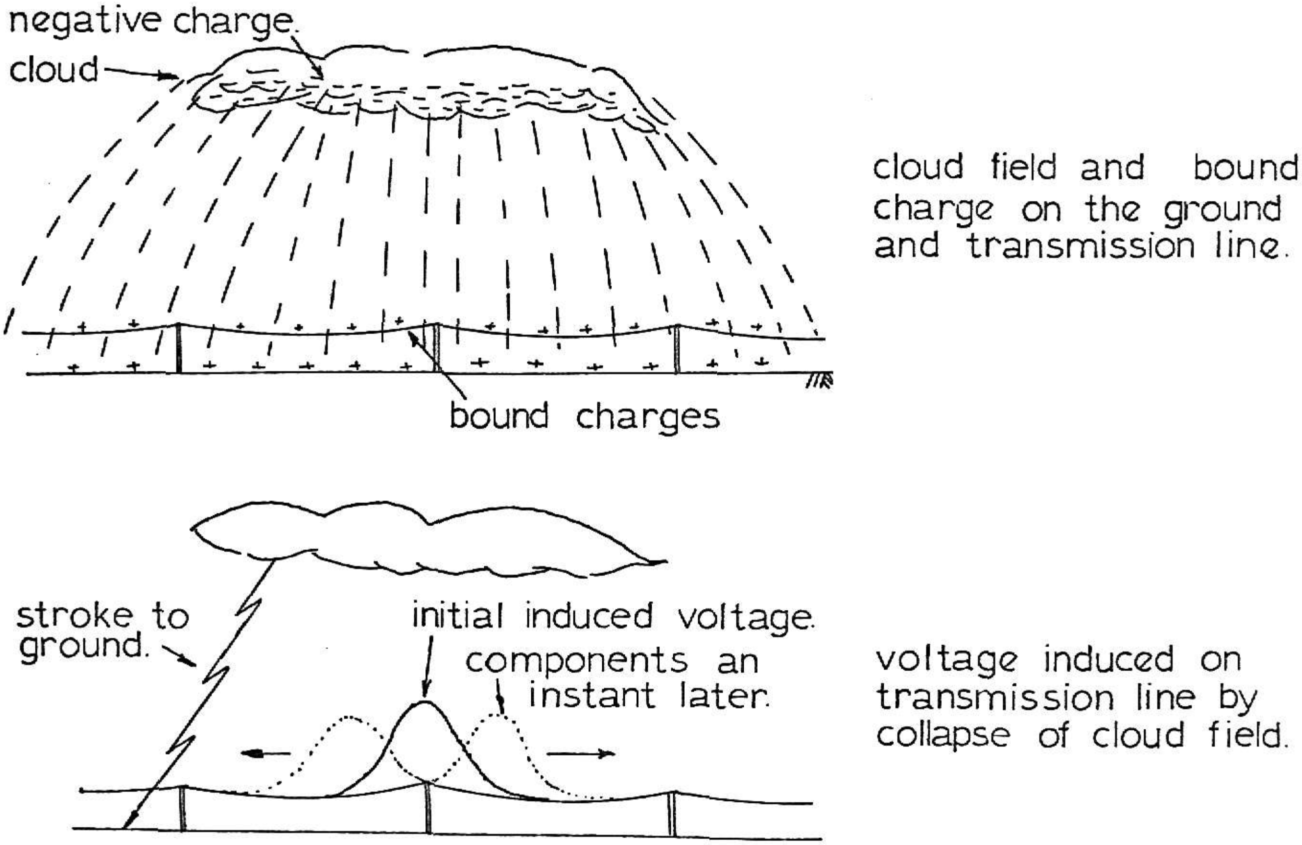


Fig. 4 - Mechanism of Induced stroke.

by Bulgarian experts (8) is that in mountainous regions, areas at more than 700 meters above sea level, there is no appreciable difference in the number of flashes, but the current strength is 50% lower than that of the flashes occuring at sea level.

From the point of view of insulation of electrical installations, the most important factor is the current and the gradient of its front. The largest excess voltages on power lines are caused by direct strikes. These must be reckoned with, even on lines operating at the highest working voltages.

Bewly (10) has given a very complex formula for determining the voltage across the insulation of a transmission line due to a number of factors such as the number of conductors and their configuration and corona to determine the coupling factor used in determining the voltage. He has taken care of the length of the span, tower footing resistance, ligthning wave front, and the conductor surge impedance by the term 'crest factor' in the equation.

Such high voltages on phase conductors produce flashovers on insulators and other dielectrics and will either cause interphase flashovers or flow to earth. This means that the excess voltage caused by a direct strike will produce flashovers on the insulators which may puncture the insulators and other equipment and thus cause severe damage to the installations.

Dangerous excess voltages may also result on indirect strike. Figure 4 shows how induced voltages arise by discharge from cloud to ground near a transmission line. When a charged cloud passes over the earth, charges are induced on the ground of a polarity opposite to that of the cloud. The field from the cloud to earth spreads out and covers an area on the ground considerably greater than the area of the cloud. Generally, the bottoms of the clouds are negative, so that induced charge on the earth is usually positive. If there is a transmission line in the field between the cloud and ground, charges of opposite polarity to that of the cloud will also appear on the line conductors and overhead ground wires. Charges accumulate more easily on the ground wire than conductors by direct migration up the towers from the ground. If a stroke takes place from the cloud to ground near the transmission line, the cloud field collapses in a definite time and the bound charges on the line conductors and ground wire are released. The former move off as travelling waves and the latter possibly as plain discharge currents. According to some authors, the surges reach voltages of from 200 to 300 kV; according to others (8, 14), voltages of from 400 to 500 kV, or even 500 to 600 kV, depending on the geographical location may occur.

Induced excess voltages produce flasovers only if the distance between the point of strike and the line is such that the induced excess voltage exceeds the breakdown voltage of the insulators used. The use of insulators with a high breakdown voltage is recommended in transmission lines as a means of protection against excess voltage.

The steps taken to protect electric power lines against lightning are based on the recorded frequency of the thunder storms. The frequency of thunder storms (the isokeraunic level) means the average number of days per year on which thunder is recorded at a given meteorological station. Given the number of days on which thunder is recorded, the number of hours of thunder per year can be calculated by assuming that thunder persists for an average of 1.5 hours per day. Although it is not possible by this method to calculate the strength and the number of lightning flashes which occur during a day on which thunder is recorded, the method does make it possible to classify regions into areas of intense, medium and low thunder storm activity. Thunder storms are distributed with extreme irregularity over the face of earth. In the equatorial regions, for example, intense activity is observed, whereas the opposite is true of the poles. No special protection against lightning is required where thunder is recorded on fewer than five days a year.

As direct strikes are known to produce higher voltages than indirect strikes, lines are now designed from the view point of the former. Protection against direct strikes is based upon shielding the conductor from lightning and providing adequate drainage facilities and insulation. In the shielding method there is no possibility of arc formation from line to ground, thereby giving inherent protection. The non-shielding method allows the formation of an arc between the ground structure and the conductor and provides a means to quench the arc without line interruptions. In the shielding method, the use of the ground wire above the conductor intercepts the stroke, provides a fairly good conducting path to ground, and distributes the currents into more paths, thereby reducing the voltage drop.

Protection by Shielding with Overhead ground Wires

The basic principles underlying the design of a line based on direct stroke theory are:

(1) Ground wires with sufficient mechanical strength must be located so as to shield the line conductors adequately from direct strokes.

(2) Adequate clearance from the line conductor to the tower or to ground must be maintained so that the full effectiveness of the insulating structure can be obtained.

(3) Adequate clearances from ground wires to conductors must be maintained, especially at the midspan to prevent flashovers to the conductors at any voltage upto the protective voltage level used for the line design.

(4) Last, but equally as important, tower-footing resistances as low as economically justified must be secured.

Experience has shown that when the protective angle (the angle formed by the vertical and a line through the ground wire and the outer phase wire) does not exceed 30 degrees good shielding of the line conductors is obtained and the probability of the side stroke is slight. Data taken from many lines show that as this angle increases, the probability of the side stroke the conductors increases.

The degree to which the fourth requirement - low footing resistance - can be met depends on local soil conditions. Experience of Westinghouse Engineers (14) indicates that some means of reducing the footing resistance to an equivalent of ten ohms as measured with the ground wires removed, is more economical than adding insulation. The resistivities of principal earth materials, listed in Table 1 below, vary over a considerable range so that the selection of the methods of securing low tower footing resistance will depend on local soil conditions.

Type	Meter Ohm	Foot Ohms	cm. Ohms
General Average	100	328	10,000
Sea Water	0.01-1.0	0.0328-3.28	1-100
Swampy Ground	10-100	32.8-328.	1000-10000
Dry earth	1000	3280	100,000
Pure slate	10^7	$3.28X10^7$	10^9
Sand stone	10^8	$3.28X10^8$	10^{10}

Table 1 - Earth Resistivity

Tower Footing Resistance

Tower footing resistance is usually expressed as the measured power frequency value; however, line performance depends on the impulse value of the footing resistance. The value of the impulse resistance depends on a number of factors such as soil resistivity, critical breakdown gradient of the soil, magnitude of the surge current and the length and type of driven ground rods or counterpoises. If long or continuous counterpoises are used because the soil resistivity is high, the initial impulse resistance is the surge impedance of the counterpoise. In soils of low or medium resistivity, adequate grounding can usually be obtained by driven ground rods. For these grounds the impulse resistance is usually less than the power frequency value.

If the tower footing resistance is not low enough, the grounds can be improved by driving rods in and around the tower either during or following the erection of the line. The curves of Fig. 5 show that the size of the ground rods does not influence the resistance materially whereas the length is most influential. Hence, it is better to use small-sectioned short rods. The curves of Fig. 5 also provide a method of estimating the number of rods necessary to reduce the tower footing resistance to a specific magnitude provided the resistivity of the soil is known. Resistance to ground can be calculated by the formula:

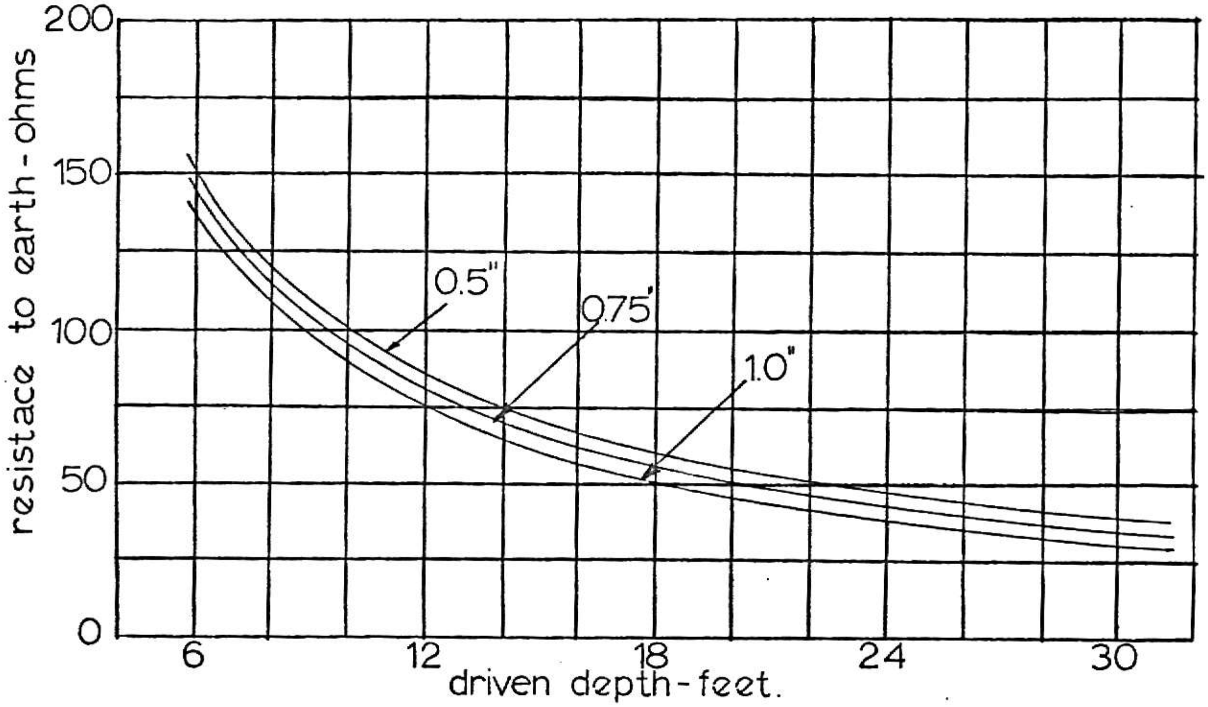


Fig. 5 - Resistance to earth of driven rods (for three different diameters and a specific resistance ρ = 1000 foot ohms).

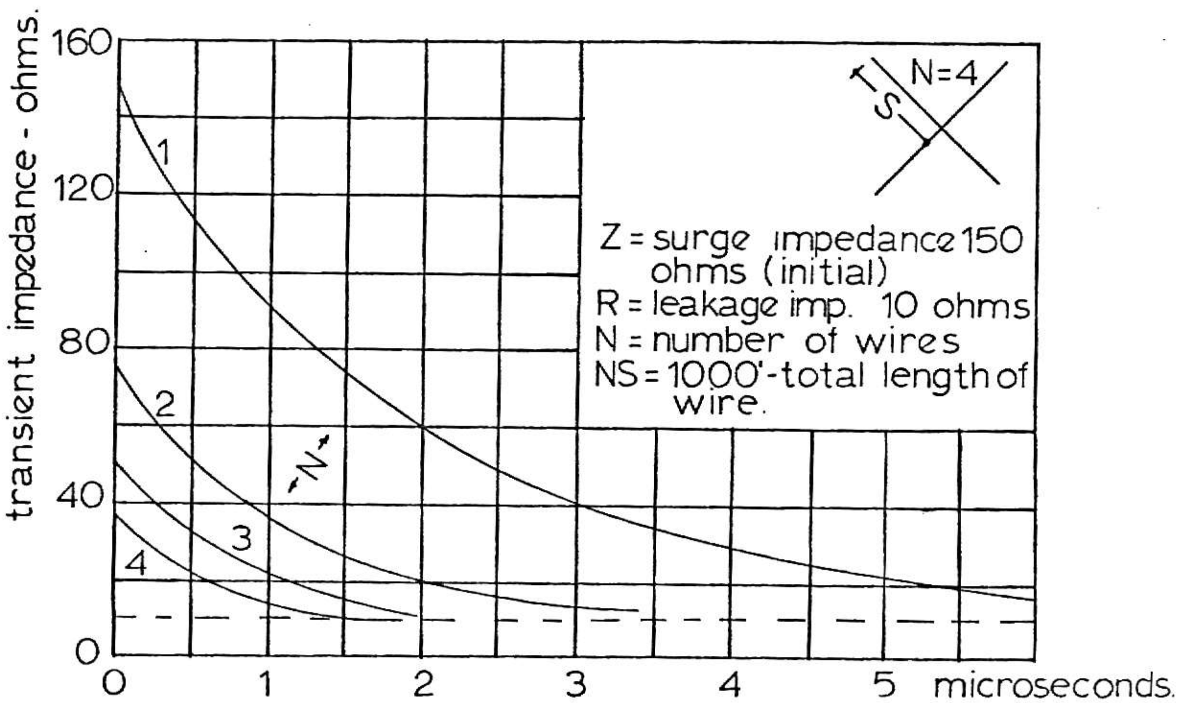


Fig. 6 - Effect of number of wires on the counterpoise impedance.

$$R = \frac{\rho}{2\pi L} \log_e \frac{4L}{a} - 1$$

where L = length in centimeter of rod,

a = radius of rod in centimeter,

ρ = resistivity in ohm-centimeter.

For further details refer to Reference 4. The resistances to ground are based on resistivity of 1000 foot ohms. For other resistivities the curves can be varied directly in proportion to the changed resistivity.

The counterpoise is another practical means of reducing the resistance by increasing the area of the earth in contact with the grounding system. This is nothing more than a wire buried in the ground, running parallel to or at some angle to line conductors themselves. The parallel counterpoise compared to one at right angles is found to be more satisfactory. This fact should not, however, be allowed to dictate as a choice as initial surge impedance is a more important factor in selecting a successful counterpoise.

A buried wire or counterpoise has an initial surge impedance of about 150 to 200 ohms depending somewhat on soil conditions. As the surge current travels along the counterpoise this initial surge impedance is reduced to the leakage impedance in a time depending upon the length of the counterpoise and the speed of propogation of the surge. In general, the surge travels at approximately one third the speed of light so that a 1000 foot counterpoise has an initial surge impedance of approximately 150 ohms and at the end of six microseconds an effective impedance equal to the leakage impedance. Likewise, a 250 foot counterpoise has an initial surge impedance of 150 ohms which falls to the leakage resistance in 1.5 microseconds. This indicates the desirability of using many short counterpoises instead of one long counterpoise as the leakage resistance is dependent largely upon the surface area which is the same whether one 1000 foot counterpoise or four 250 foot counterpoises are used. On the other hand, the counterpoise of four 250 foot sections has an initial surge impedance of 37.5 ohms and reaches the final leakage resistance in 1.5 microseconds as compared to 150 ohms and 6 microseconds for the 1000 foot counterpoise as shown in Fig. 6. Also resistance to ground does not vary too much for the various depths of burial of the counterpoise. This is shown in Fig. 7. The various arrangements for counterpoises are shown in Fig. 8.

Protection by Auxiliary Devices

The second method of protection, making use of auxiliary devices, has been extensively used in improving the performance of lines against lightning. Here the path of the discharge is controlled and some device is used to extinguish the power follow arc. Several devices have been used, such as lightning arresters, fuse arcing links, and protector tubes.

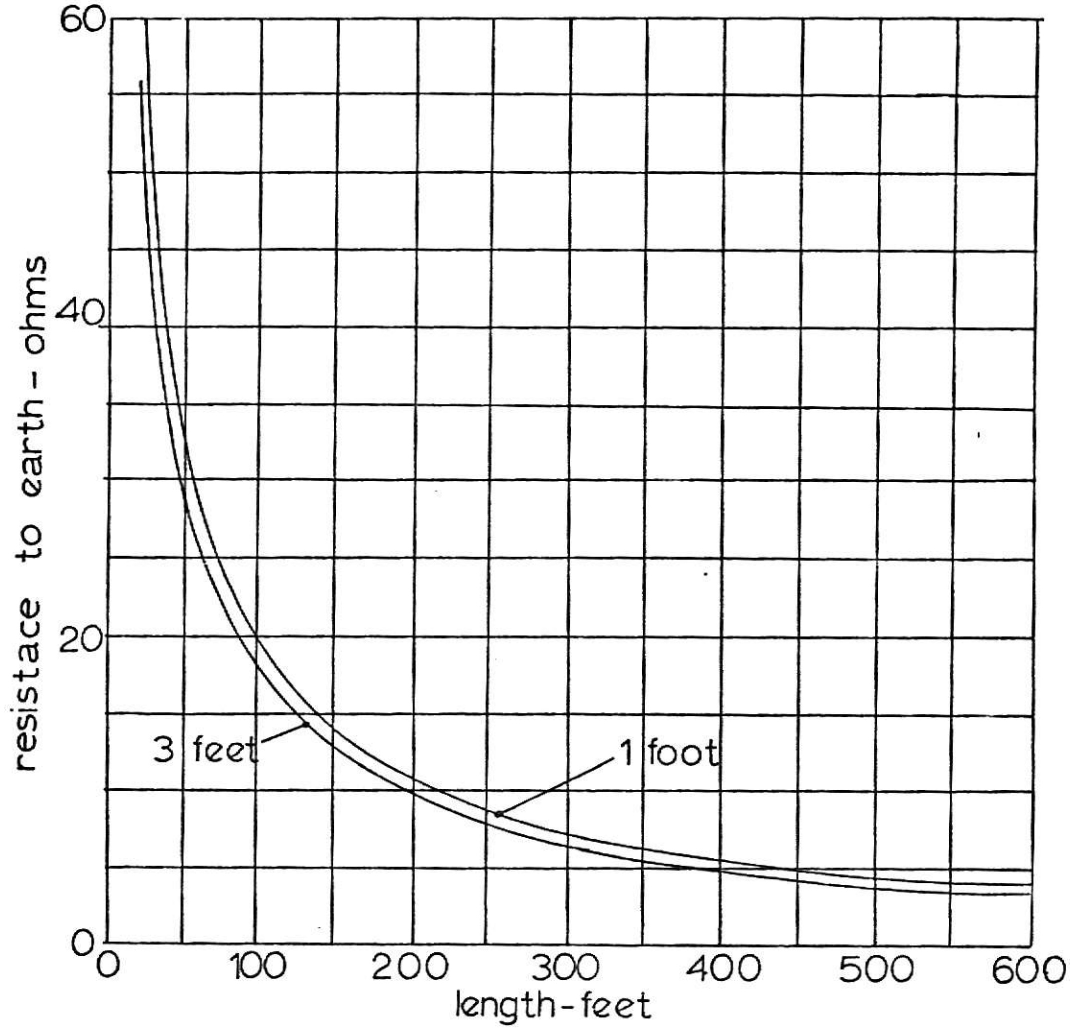


Fig. 7 - Resistance to earth of 3/8 inch single counterpoise for two depths (ρ = 1000 foot ohms).

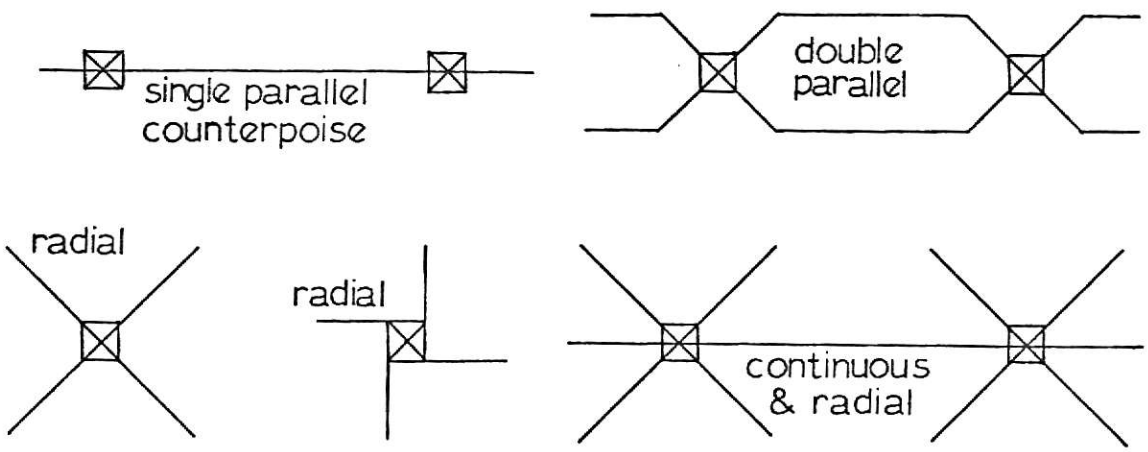
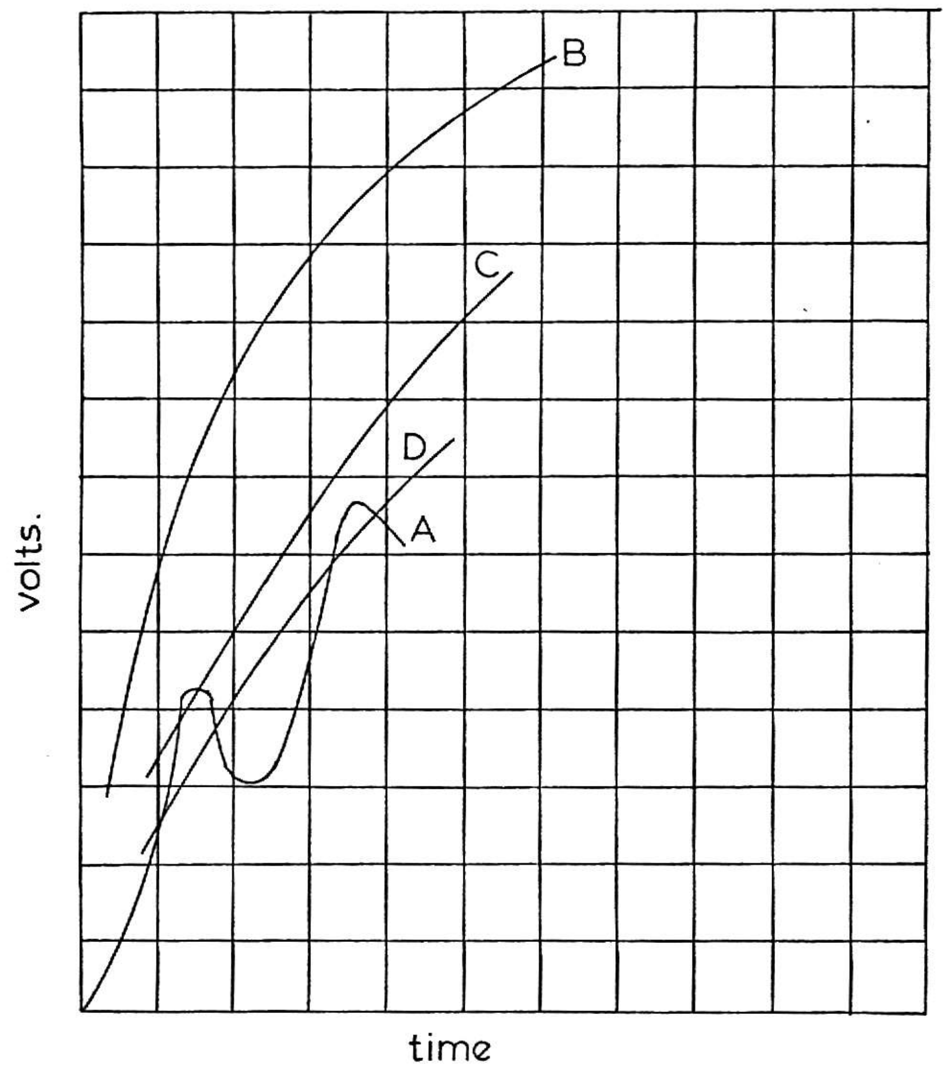


Fig. 8 - Arrangements of counterpoises.

The most popular device at the present is the protector tube. This device is simple both in construction and in operation. Basically it consists of a fibre tube with an electrode in each end. It is designed so that its impulse breakdown voltage is lower than that of the insulation to be protected. On a transmission tower one tube is mounted below each conductor so that the upper electrode is connected to an arc-shaped horn located the proper distance below the conductor, thus forming a series gap with the conductor and the tower. The lower electrode is solidly grounded. When a surge appears on the conductor, the series gap is spanned and an arc is formed in the tube between the electrodes. The heat of the arc vaporises some of the fiber of the tube walls, the resulting neutral gas being expelled violently into the arc stream, sufficiently deionising it to prevent the arc from restriking after the first zero point of the power frequency power current.

When a protector tube is discharged by lightning and power follow current flows through the tube, it must have for the satisfactory operation the properties of changing from a good conductor to a good insulator. In any interrupting device it takes time to establish the insulating characteristics which are commonly called the "insulation recovery characteristics" of the device. The interruption is therefore a race between the insulation recovery strength of the device and the recovery voltage of the system. Curve B in Fig. 9 is considered satisfactory, as the insulation recovery of the device is faster than the



A - Recovery voltage of complex system

B,C,D- Protector tube insulation recovery curves

Fig. 9 - Elements of protector tube operation.

recovery voltage of the system. Curves C and D in the same figure are not ideal since the recovery voltage overtakes the recovery insulation voltage at some time or other, and if this occurs at more than two consecutive current zeros, the operation is not considered satifactory.

The system recovery voltage curves and protector tube insulation recovery curves will vary for each current value, rising at a slower rate for lower current. The protector tube insulation recovery curves are also lower with increased bore or inside diameter of the tube.

The factors which normally will determine the magnitude of the current and associated recovery voltages are:

(1) Method of grounding the system neutral, that is, solid grounding, resistance or reactance grounding or any combination of these.

(2) Minimum and maximum connected system capacity (variations in operating conditions).

(3) Length of connected circuit and relative location of short circuit current sources.

(4) Tower footing resistance. With low resistance more current can be obtained for better operation of the tube.

(5) Protector tube location.

Generally speaking, protector tubes are used on grounded neutral systems. Experience has proved that solidly grounded systems are most favourable for tube operation, as in this case, the short circuit current is usually high and dependable. With systems grounded through reactance, protector tubes may be applied successfully, provided that the zero sequence reactance (Appendix B) viewed from the protector tube is not more than three times the positive sequence reactance. When the ratio of X_0 to X_1 is greater than 3, the currents may be reduced to such a low value that the system recovery voltage may increase faster than the tube insulation recovery, in which case operation will be unsatisfactory, and it may be necessary to use tubes with a high voltage rating.

Lightning Arresters

Lightning arresters are more sophisticated rod gap protectors. Such gaps have the virtue of being very cheap, but they have several disadvantages, the most important of which is that when they flashover they place a fault on the circuit. It is true that this can be removed by opening a circuit breaker, and that power can be restored by reclosing the circuit breaker after the rod gaps have deionised. Certainly this is perhaps preferable to a lengthy outage. But a device that can effect voltage limiting without creating a fault is obviously more attractive. The nonlinear resistor is such a device.

These resistors have the property that their resistance diminishes sharply as the voltage across them increases. This characteristic is usually expressed in the following way:

$$I = kV^n,$$

$$R = \frac{V}{I} = \frac{V}{kV^n} = \frac{1}{kV^{n-1}} \quad ,$$

where, I = the current through the resistance,

V = the voltage across the resistance, and

R = the value of the resistance.

Now n is not a strict constant and ranges typically from 2 to 6, while k for a given material is determined by the dimensions of the resistor. The material used for these resistors is marketed under a number of trade names, but is basically silicon carbide. It is formed into different shapes such as rods and discs to produce a range of resistance values.

These resistors are connected across the apparatus to be protected and so experience the system voltage under normal operating conditions. On the incidence of a surge voltage, the resistance falls rapidly as the voltage rises, thereby diverting much of the current and energy of the surge into the arrester. The energy dissipating capacity depends upon the mass of the resistor element, since the energy is usually put in so quickly that there is little opportunity for heat to be transferred elsewhere until the surge has passed.

If the ceiling voltage to which surges must be limited is even three or four times the normal system voltage, it may be found that the values of the resistance at nominal system voltage would be so low that the steady state losses would be prohibitive. The lower the permitted ceiling voltage the more acute will this problem become.

Hence, these resistors alone are not used as lightning arresters. They have a gap or gaps in series with them. In this way the resistor is isolated from the circuit under normal system conditions and is introduced when a surge appears by the flashover of the gap(s). However, an important problem in this case is quenching the arc that is formed in the gaps. Such an arc must be quenched quickly once the surge has disappeared. Various methods of arc control are available.

Forms of arresters vary depending on their voltage class and duty but they generally comprise gap units, coil units, and valve elements of the nonlinear resistance material. These are stacked in series and hermetically sealed in porcelain housing. A basic unit is shown in Fig. 10. Generally, the basic units are built for 6 kV. The required voltage is obtained by cascading a number of these in series. Operation is as follows: When a surge appears at the line terminal of the arrester, current flows through the two gaps, magnetic coil and thyrite valve elements. This causes the magnetic coil to develop a voltage across itself in the direction of the arrow in the figure. This voltage is sufficient to cause the bypass gap to flashover removing the coil from the circuit and leaving only the impedance of the valve element in the circuit. This is a low resistance path. When power frequency voltage is restored, the impedance of the coil is much lower which causes the arc in the bypass gap to become unstable and extinguish. The current

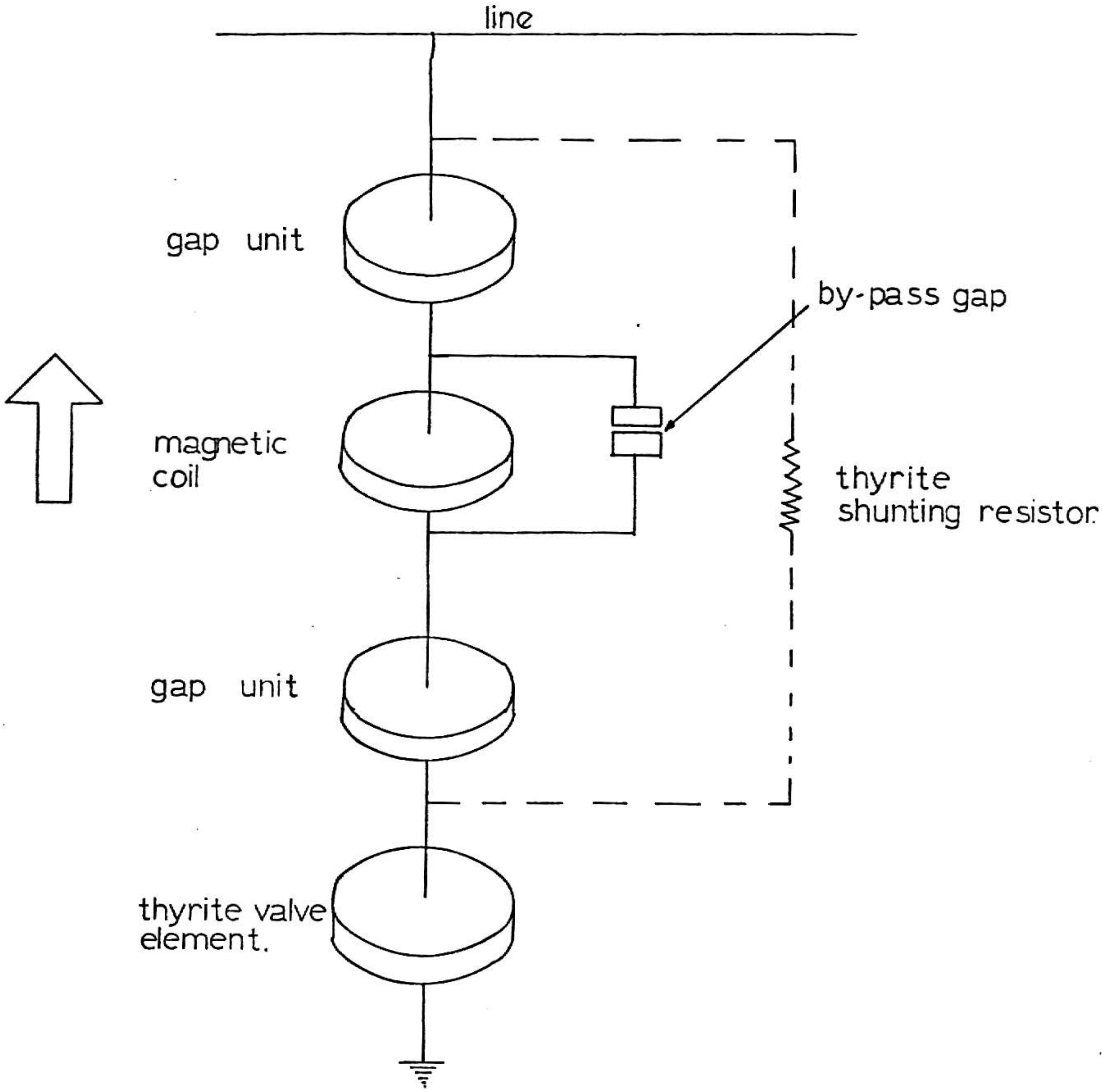


Fig. 10 - Basic lightning arrester.

is transferred to the coil so that the magnetic field created by the follow current in the coil reacts upon the current in the arcs of the gap assemblies, causing them to be driven into arc quenching chambers, which are an integral part of the gap units. Arc extinction is brought about at the first current zero.

As shown in the figure, the main gaps may be shunted by other nonlinear resistors to provide automatic self regulation of the power frequency voltage across each set of 6 kV gap elements.

Because the lightning arresters are so much more complex than the protector tubes, they are hardly used on line application but they may be called upon at stations to discharge transmission lines which store a considerable energy in the electric field associated with their capacitance. The arrester must be able to absorb this energy when it operates.

High-Speed Automatic Reclosing as a Lightning Protection Measure

It is found in the U.S.S.R. that in 90% of the cases on the average the disconnected line can be immediately reconnected. In the case of interruptions due to lightning, high speed automatic reclosing is particularly effective, the very brief interruption in service scarcely being felt by the consumers. At the present 93% of 35 kV and 110 kV lines and 99% of 150 to 220 kV lines are fitted with high-speed automatic reclosing devices.

Russian engineers have found this technique favourable for networks without earth wires (1).

Protection from Internal Overvoltages

The causes for the production of internal overvoltages are:

(a) Switching surges produced due to large charging currents on the transmission lines.

(b) Unsteady or momentary overvoltages which arise only during such processes as a sudden change of circuit like disconnection of inductive or capacitive network elements (reactors, capacitor banks and transformers).

(c) Overvoltages which are produced by restriking in circuit breakers when disconnecting loaded lines or faults.

Very high voltage lines need to be protected from internal overvoltages rather than overvoltages due to lightning. For long lines differential phase protection, using a carrier current system, is utilized as the basic protection. In some cases it would be possible to reduce internal overvoltages by means of such measures as adjusting transformer ratios and connecting a large number of reactors. Use of arcing horns as a protection against internal overvoltages was common. If the phase voltage increases some predetermined value, say 1.7 times phase voltage, the arcing horn gap will break down. Arcing horns are not discriminative and therefore use is avoided on very high voltage systems.

CHAPTER III

OVERCURRENT PROTECTION

Fault current can be used as a basis for fault detection only where there is an abrupt difference between its magnitude for a fault with in the protected section and a fault outside it. Also these magnitudes should be constant with time for satisfactory operation. Where this is so, a device sensing current magnitude can be used.

Overcurrent relays are employed on radial or loop circuits. Where there are several line sections in series, there is no difference in current between a fault at end of one section and beginning of the next one, as shown in Fig. 11A. Therefore, it is necessary to add time discrimination, with the time setting increased towards the source. This is a serious threat in case of definite time characteristics shown in Fig. 11B.

This problem can be overcome to a certain extent by using inverse time-current characteristics such as shown in Fig. 12. Where the impedance (Z) between the relay and the power source e.m.f. is small compared with that of the protected section, there will be an appreciable difference between the current for a fault at the far end of the section and the current for a fault at the near end. On systems solidly grounded at each station, Z is small so that excellent selectivity on ground faults can be obtained with inverse time current relays.

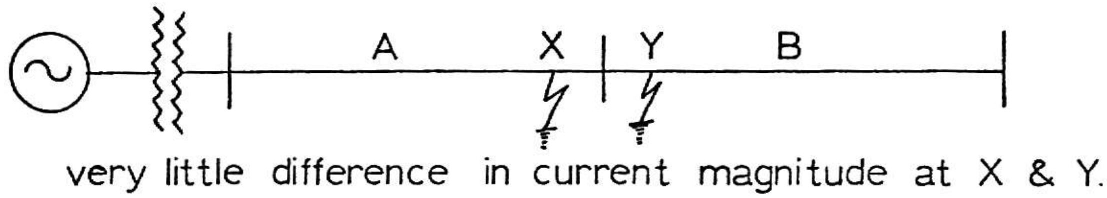


Fig. 11A - Lack of selectivity for overcurrent protection.

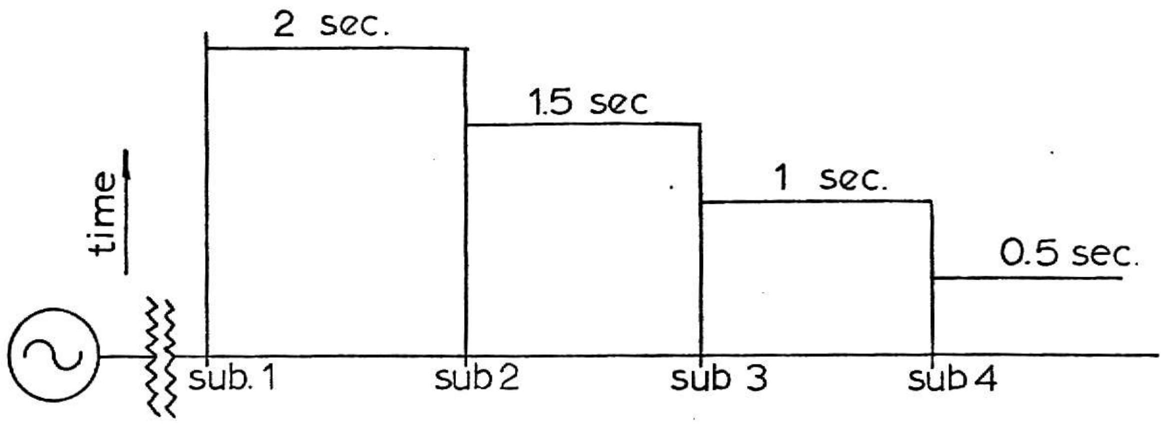


Fig. 11B - Definite time grading on radial circuit.

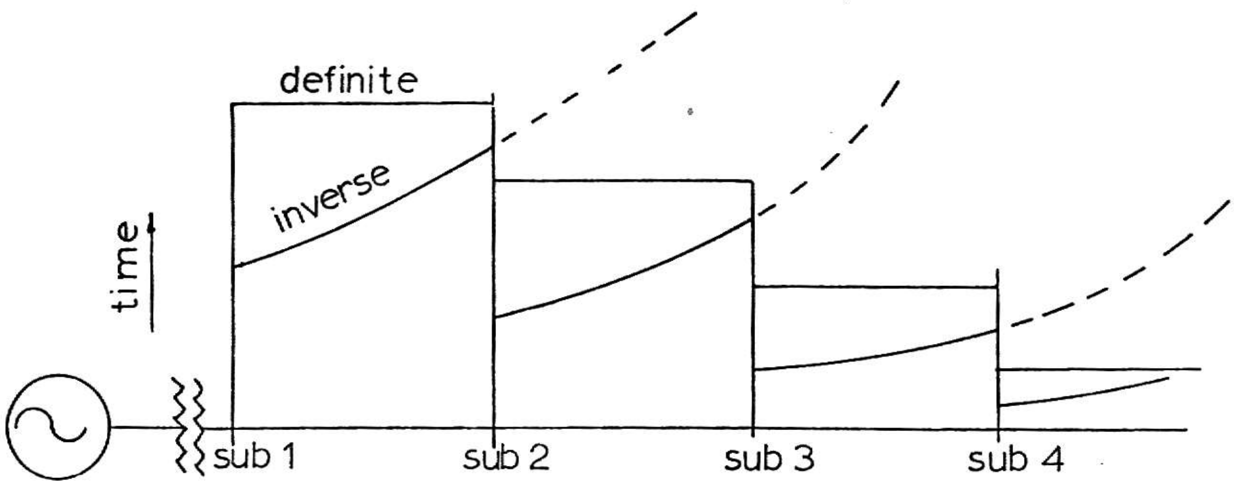


Fig. 12 - Definite time versus inverse time-current relaying.

However, Z can be so high on impedance grounded systems that the ratio of the currents for a fault at the far end to a fault at the generating end will be near unity. This loses sensitivity. Secondly, Z will vary if the generating capacity is varied, becoming larger during weekends and late at night when there is less load and hence less capacity connected. This increase in Z will not interfere with selectivity because the inverse curve increases the time discrimination at low currents, but it does not minimize the total operating time.

Inverse time relays generally find use on long radial or loop systems because lower tripping times can be achieved. Definite time relays are better on isolated systems and for use as back-up to differential and distance relays, but inverse time relays are advantageous on interconnected systems and solidly grounded systems.

The inverse time relays have a poor selectivity for low currents, the curves for adjoining sections becoming almost one at low current values. To overcome this, use of inverse definite minimum time characteristics is made; the characteristics being shown in Fig. 13. A static overcurrent relay is shown in Fig. 14.

Presently overcurrent protection is applied on very low voltage distribution systems.

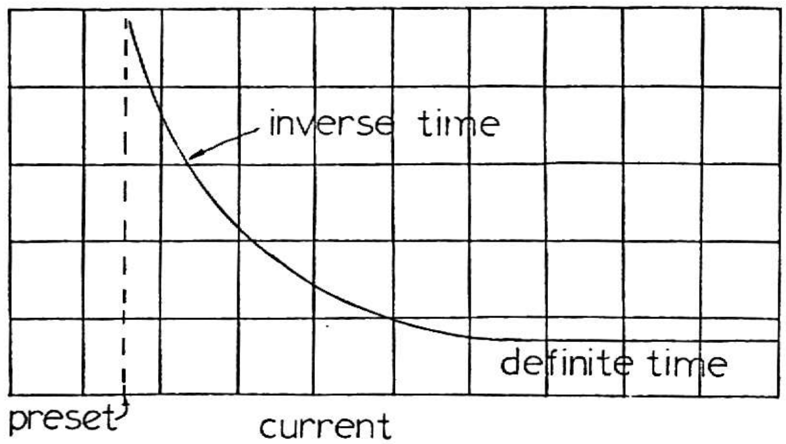


Fig. 13 - I.D.M.T. characteristics.

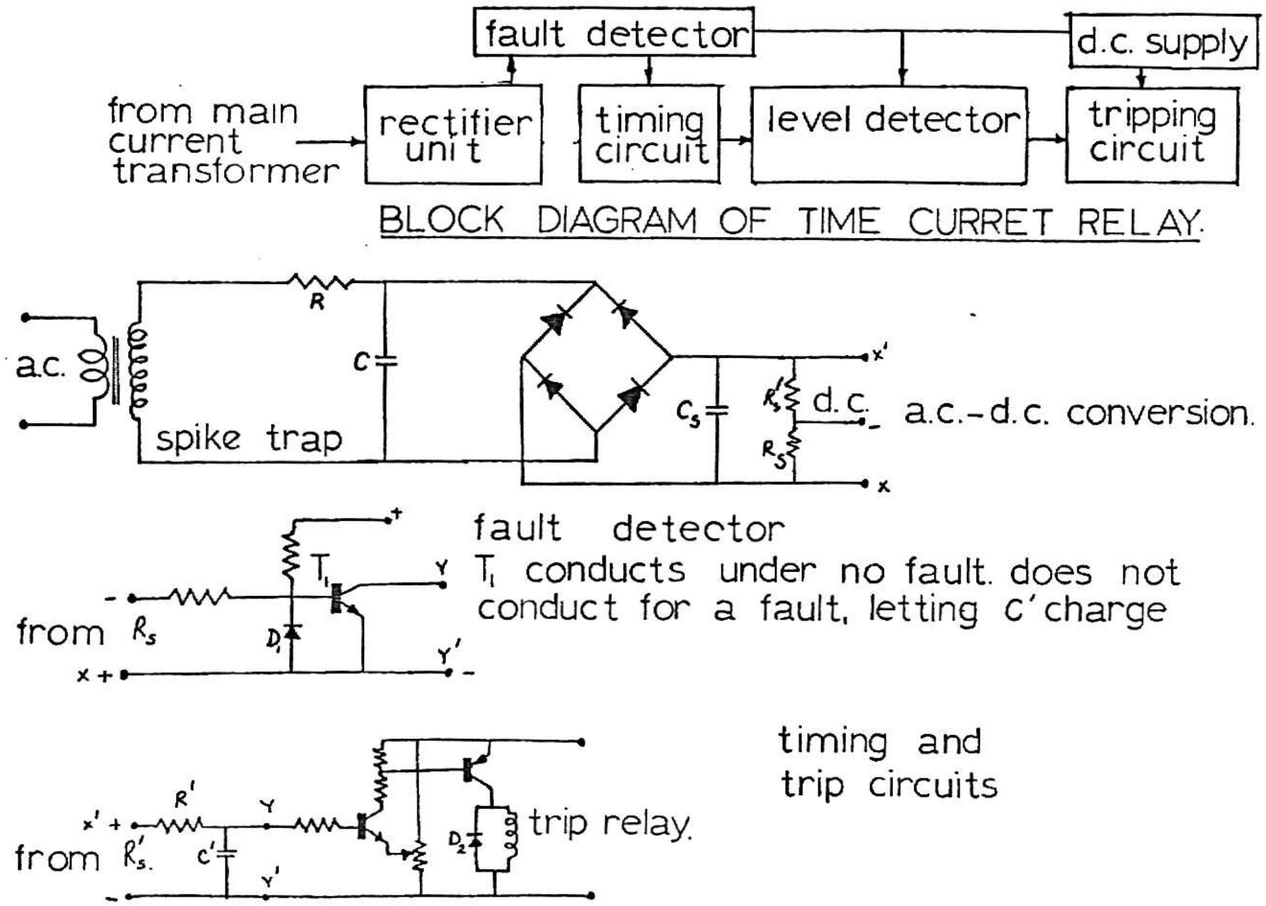


Fig. 14 - Static time-current relay.

CHAPTER IV

DISTANCE PROTECTION

The distance relay is most widely used for selective line protection because, in addition to its selectivity, it allows shorter times to be achieved, detects fault currents which are smaller than the service current, provided back-up for faults at the busbars or in neighbouring sections, and is completely independent of auxiliary links between stations. Current-voltage balances for measuring impedances were suggested as long ago as 1904, but Ackermann, in 1920, was the first to use a two-step high-speed impedance protection system in a 50 kV network.

Principles of Distance Measurement

The distance to the fault is measured in terms of line length and this is done by measuring the impedance of the line, which is almost linearly proportional to its length. Normally the relay measures a higher impedance than that of the line because it also measures the impedance of the load, as shown in Fig. 15. When a fault occurs, this short circuits the load and the relay measures only the impedance Z_1 of the line plus the arc resistance. If, however, the fault is not a dead short circuit, the fault appears to be more distant than it really is

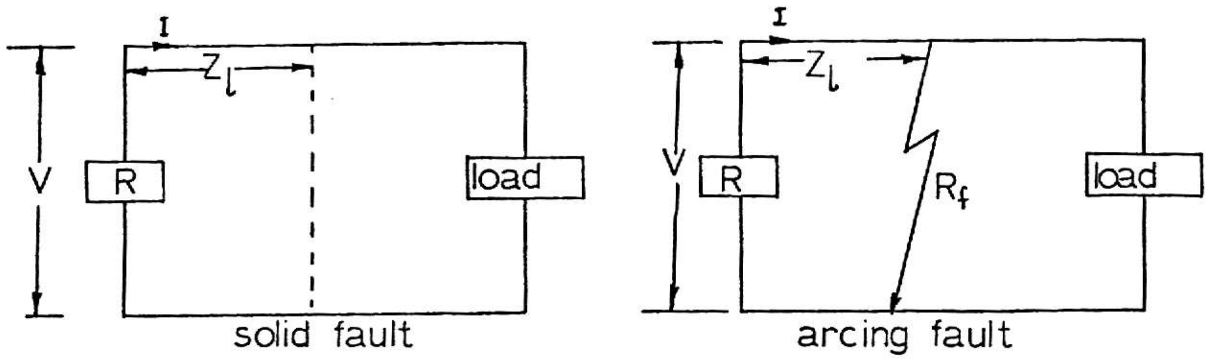


Fig. 15 - Impedance measured by the relay R reduced by fault.

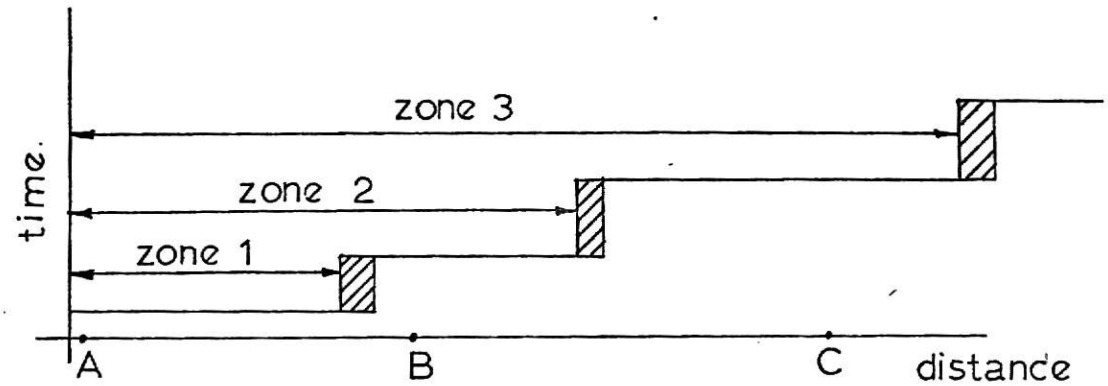


Fig. 16 - Zones of protection for relay at A.

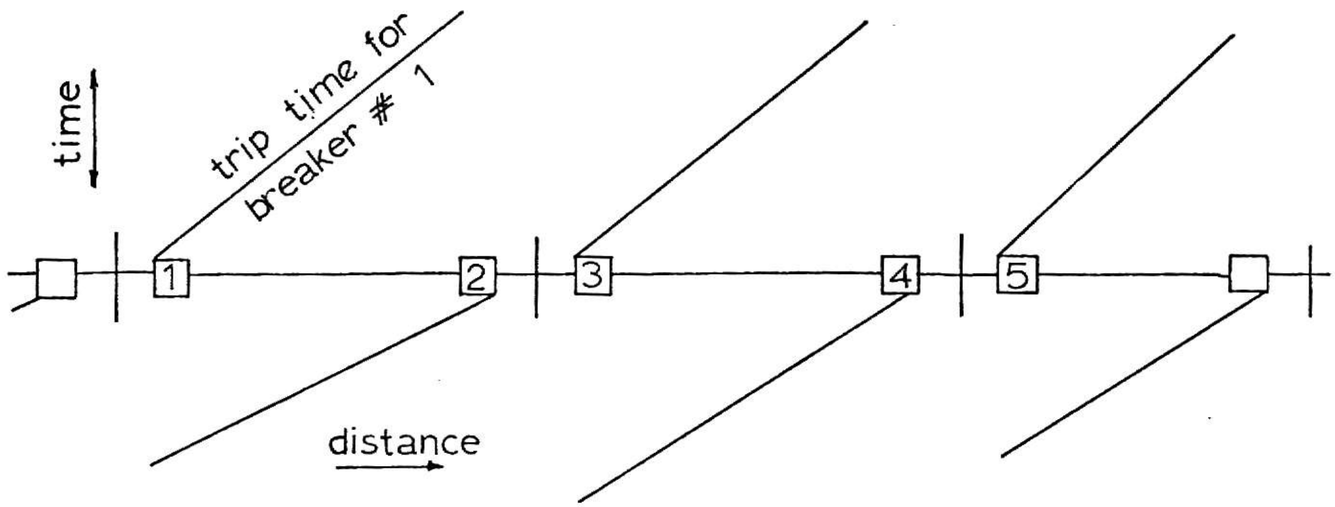


Fig. 17 - Normal speed impedance relay characteristic.

because the load also comes into picture. Thus, faults which are not dead short shrink the reach of the relay. For this reason, and because the relay cannot be made with 100% accuracy, there has to be a second distance measuring unit to take care of faults at the far end of the protected line near the fault bus. A third unit is generally provided to give back-up protection for the first two units of the distance relay in the next line section. Figure 16 shows this.

Normal-Speed Impedance Relay Characteristics

The time-distance tripping characteristics of the normal-speed directional distance relay are illustrated in Fig. 17 which shows a number of line sections in series. The line may equally well be a loop, the two ends of the section being at the same point. The tripping time of the relay increases in direct proportion to the distance from the relay to the fault, except that the mimimum time is about 0.25 seconds for a fault at the relay. Each relay is adjusted to trip in approximately 0.75 seconds for a fault at the next bus. This time can be adjusted by changing the slope of the curve by varying the resistance in series with the potential coil. It is essential that for a fault near bus 4, breaker number 3 be tripped in preference to breaker number 1. Thus the operating time of relay for circuit breaker number 1 must exceed that of the relay for circuit breaker number 3 for a fault at location 4 by one circuit breaker operating time plus a margin.

The particular time values mentioned are typical. The relay tripping time is independent of current magnitude once the overcurrent setting has been exceeded and timing thereby initiated. Thus variations in the amount and the location of connected generating capacity, or switching lines out, does not materially affect the coordination of the distance type relays over the remainder of the system.

High-Speed Impedance Relay Characteristics

The high-speed distance relay has the step type time-distance characteristics illustrated in Fig. 18, obtained by separate directional, impedance and timing elements with contacts connected as shown in Fig. 19. In a non-static relay, there are a total of three balanced-beam type impedance elements, each arranged with a current operating winding at one end of the beam and a voltage restraining winding at the other. When the ratio of the voltage to current falls below the impedance setting of the relay, high-speed action closes the contacts. The impedance elements Z_1, Z_2 and Z_3 are set successively for greater distances. The directional element closes only for the faults in the desired tripping direction from the relay. The third zone impedance element which operates when either of the other two elements operate, is used to start the timer that closes first a second zone timing contact T_2, and later a third zone timing contact T_3. Thus for a fault in the first 90% of the section,

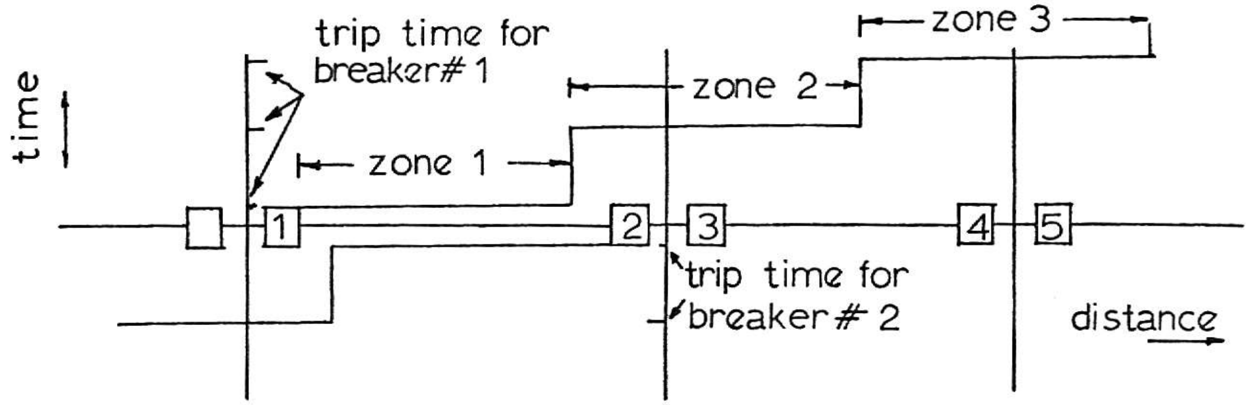


Fig. 18 - Time-distance curves for high speed distance relay.

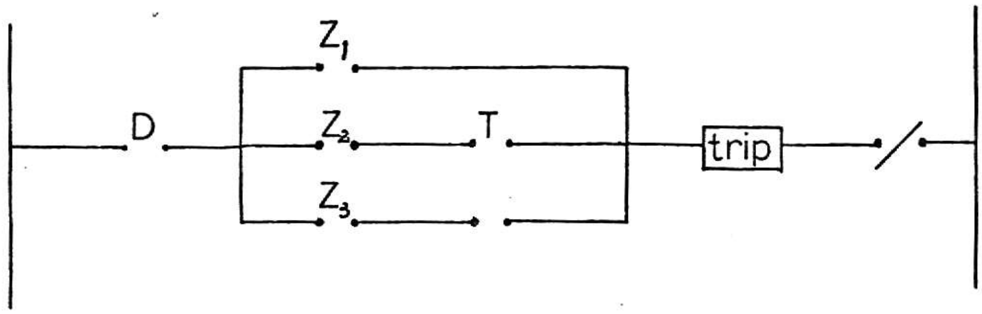


Fig. 19 - Contacts circuit for producing the stepped time-distance characteristics.

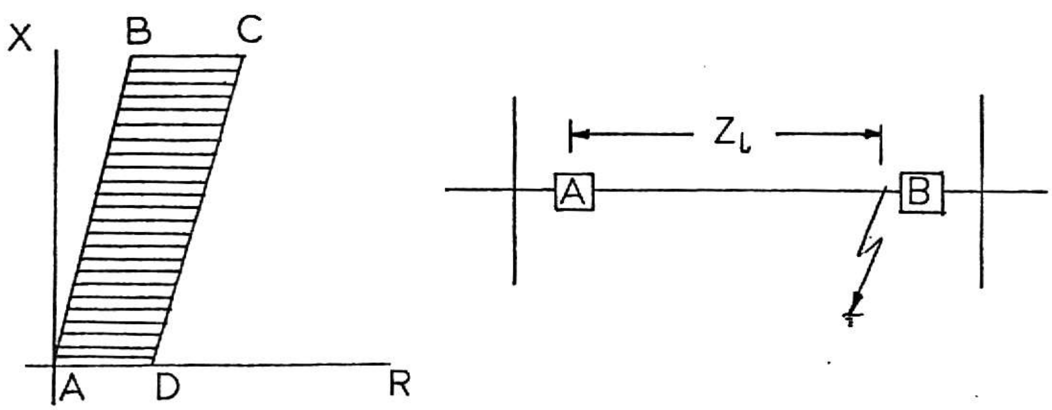


Fig. 20 - The fault area on an impedance diagram.

known as zone 1, the contacts D and Z_1 operate, give immediate high-speed tripping in one to three cycles, as indicated in Fig. 18. While the other elements also operate, their action in zone 1 is unimportant because the circuit breaker has already operated. Thus, in zone 1 the tripping time is that of the elements Z_1 and D.

For the second zone, which extends approximately to the middle of the next section, contacts D, Z_2 and T_2 in series do the tripping, provided the fault lasts for the time setting T_2. If the fault is in the next section it will be cleared by the proper breaker in advance of T_2 operation, although back-up protection is provided by the second zone setting extending into the next section. This also provides operation for bus faults if they are not previously cleared by protective relays.

The third zone, corresponding to tripping through the contacts of elements D, Z_3 and T_3, completely overlaps the next section, providing complete back-up protection. It must, of course be timed selectively with the T_2 timing of the next section.

For the proper operation of the relay, the line should be electrically such that there will be at least 5% voltage at the relay for a fault at the next bus.

Fault area on the Impedance Diagram

We can represent the fault on an impedance diagram by representing resistances on the X-axis and the reactances on the Y- axis as shown in Fig. 20. The figure also shows the effect of the fault resistance. A solid fault at B appears to the relay at A as the impedance phasor AB, but an arcing fault adds the resistance R_f so that the relay measures the impedance AC. The horizontal lines show the effect of the fault resistance at various position between A and B so that the fault area is the parallelogram ABCD. The fault resistance increases somewhat for faults towards the remote end of the section because less of the total fault current flows through the relay even though the actual resistance may be reduced by the extra current fed in from the remote end.

VARIOUS DISTANCE RELAY CHARACTERISTICS:

Impedance Characteristics

In this type of relay, the line current at the relay is compared to the line voltage at the relay, without any reference to the phase angle between them. The characteristic on the R-X diagram (impedance diagram), is a circle with center at origin. If the impedance seen by the relay lies within the circle, the circuit of the circuit breaker is energised with or without a series timer element. This is shown in Fig. 21. The disadvantage of this type of relay is that it is inherently non-directional, so an additional element has to be incorporated. Further, as the relay operation area on the R-X diagram does not fit snugly on the fault area of the line to be protected, also on the R-X diagram, it is more susceptible to maloperation due to load swing, as shown in Fig. 23.

Reactance Characteristics

In this type of relay, the line current at the relay is compared to the line voltage times Sin ϕ, where ϕ is the phase angle between the current and voltage. That is, the relay operates when the operating quantity I, the current, exceeds the restraining quantity V Sin ϕ. The relay operates when

$$kI > V \sin \phi$$

$$k > \frac{V \sin \phi}{I}$$

$$k > Z \sin \phi$$

$$k > X ,$$

where k is a constant of the relay

X is the reactance seen by the relay,

Z is the impedance to the fault point.

The advantage of this type of relay characteristic is that it is not responsive to arc resistance and so there is a lesser

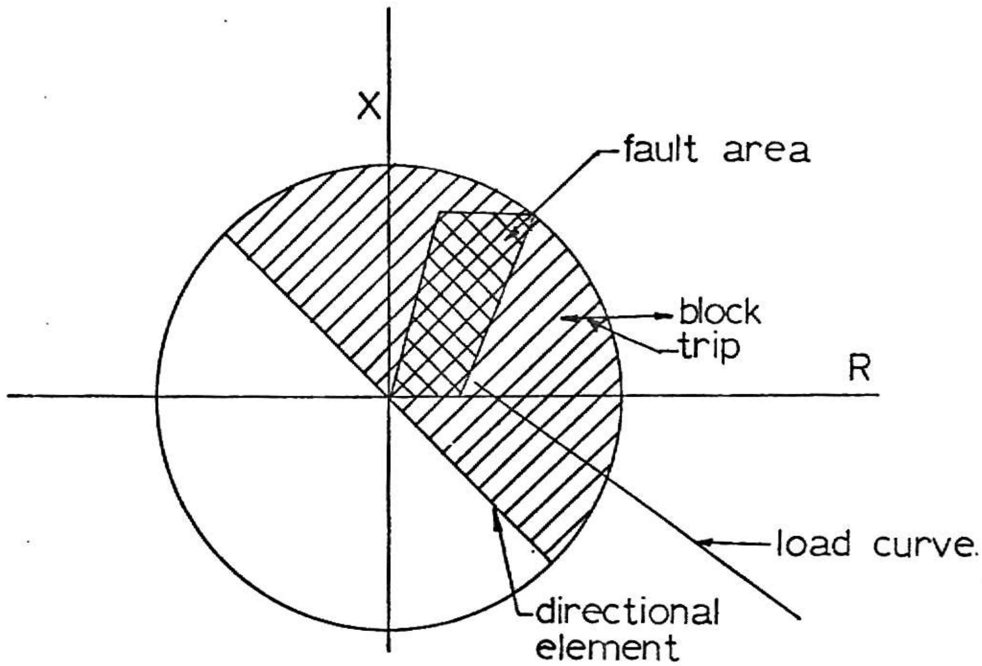


Fig. 21 - Impedance relay characteristic on impedance diagram.

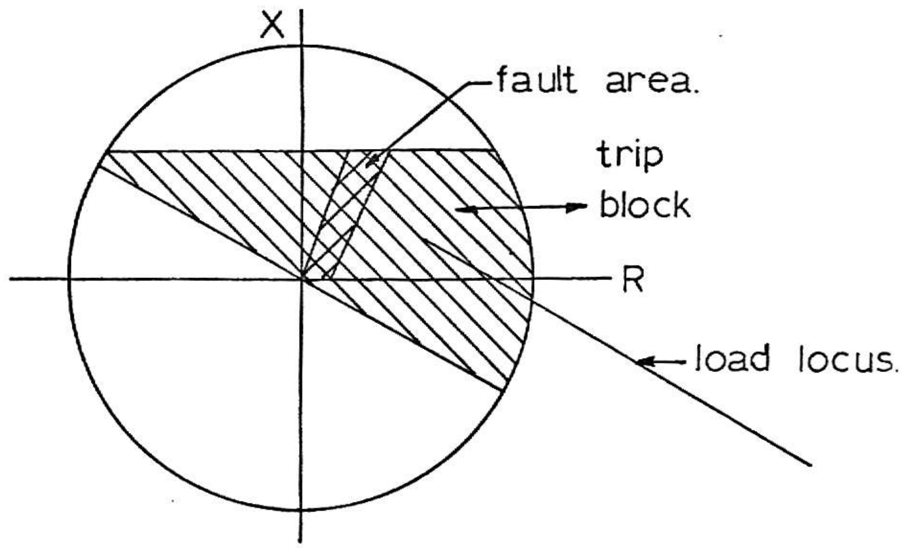


Fig. 22 - Reactance relay characteristic on impedance diagram.

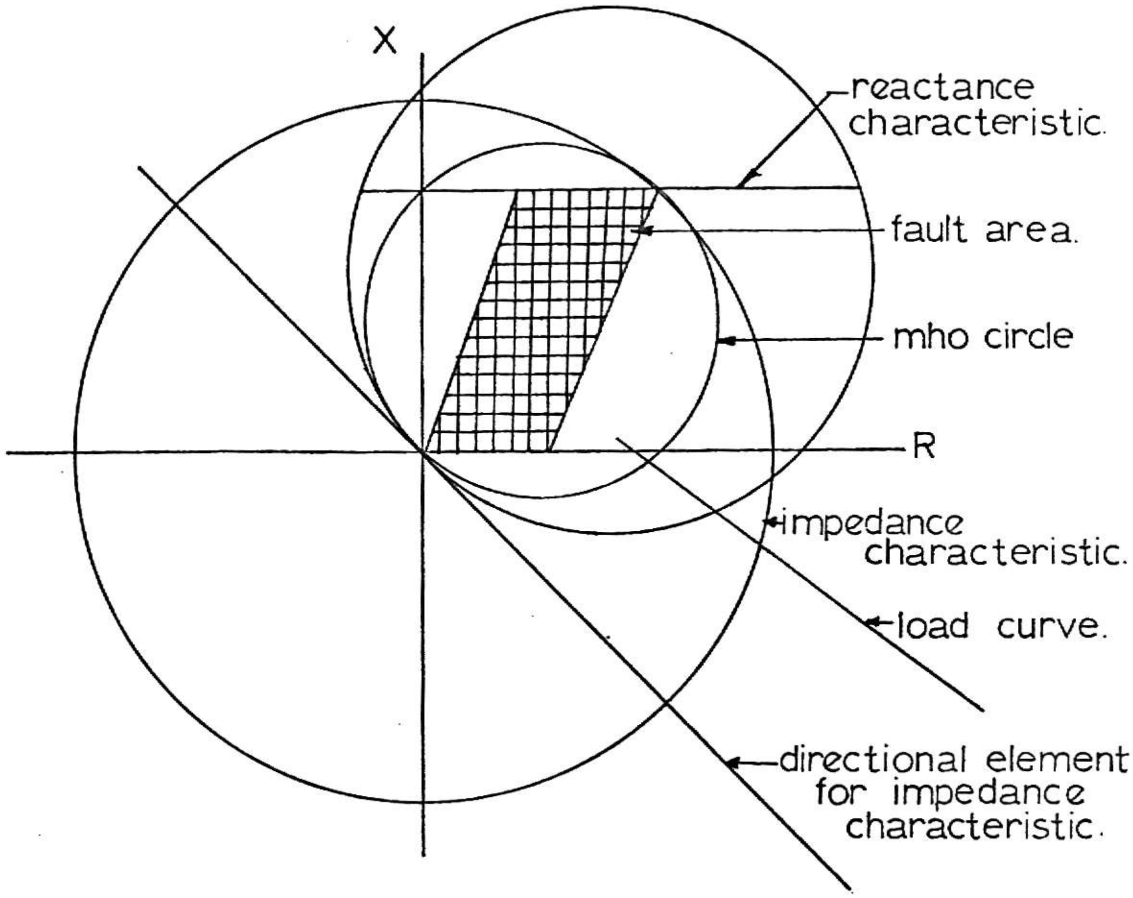


Fig. 23 - Consideration of power swing on various distance relays.

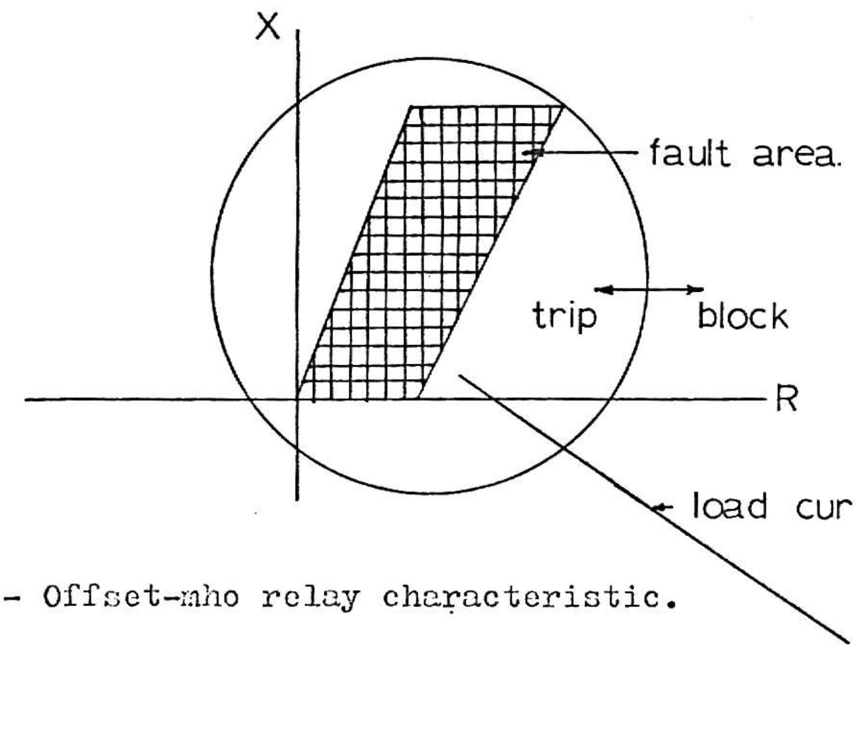


Fig. 24 - Offset-mho relay characteristic.

possibility of its maloperating in cases of large arc resistances. This is shown in Fig. 22. The disadvantage is that the relay is not a directional one and an additional directional element has to be incorporated.

Further, since the fault resistance is not related to the length of the line protected, it follows that it has more effect on the impedance measurement of a short line; hence, reactance relays are preferable for short lines. They are also preferable for ground faults since the resistance of the return path can be very high in some localities.

For a given fault area to be protected the reactance relay has the greatest likelihood for maloperation from power swings. This is illustrated in Fig. 23.

The Mho Relay

This relay has almost replaced the impedance and the reactance relay on the British Grid (15). It combines the characteristics of a directional and an impedance relay, and its application has therefore reduced the number of elements necessary for a complete distance relaying scheme. The main technical advantage of the mho relay as compared with the impedance or the reactance relay is its better stability on power swings, as shown in Fig. 23.

Mho relay is sometimes called the angle-admittance relay.

Offset-mho Relay

This characteristic is obtained by biasing either the impedance relay or the mho relay with an additional replica impedance. This is considered as an advantage over the mho relay because mho relay loses sensitivity in case of faults very near to it. Hence, the mho characteristic is offset as shown in Fig. 24, to include the protection of regions very near it, since the torque in the mho relay for a fault near the relay sensor is almost zero.

The impedance characteristics now in general use are circular, i.e. of the ohm or the mho type. In certain applications, however, a circular characteristic is unsuitable and has to be modified. For instance, on extremely long lines a mho relay tends to trip on heavy loads unless monitered by a blinder. On the other hand, on short lines the mho relay may not have enough tolerance along the R-axis to clear high resistance faults. Many of these difficulties can be overcome by the use of other conic characteristics such as ellipses, parabolas, etc. For example, an elliptical characteristic would avoid tripping on heavy loads, as shown in Fig. 25.

Theoretically the ideal characteristic for distance relays would be a parallelogram coincident with fault area of Fig. 20. Such a characteristic would naturally avoid tripping on power swings ! To obtain such a characteristic, it would require four electromagnetic relays with their contacts in series and each having a straight line characteristic corresponding to one side

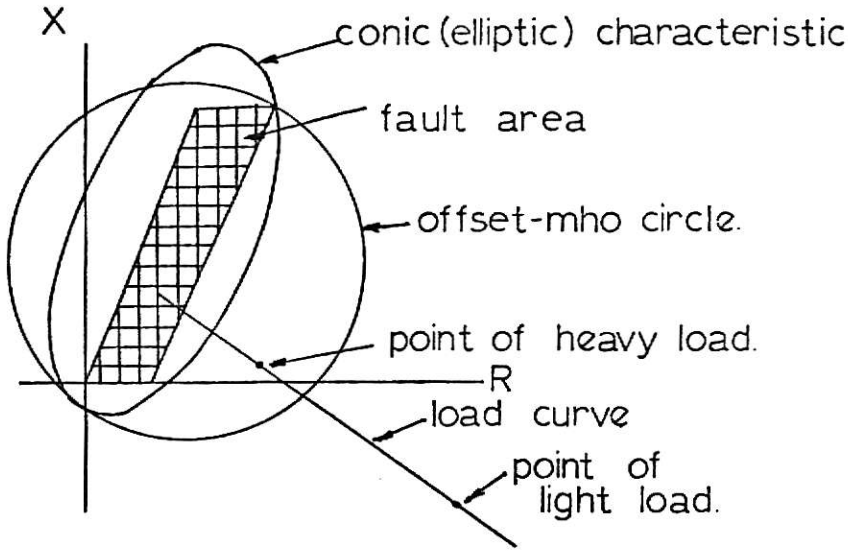


Fig. 25 - Conic characteristics (elliptic).

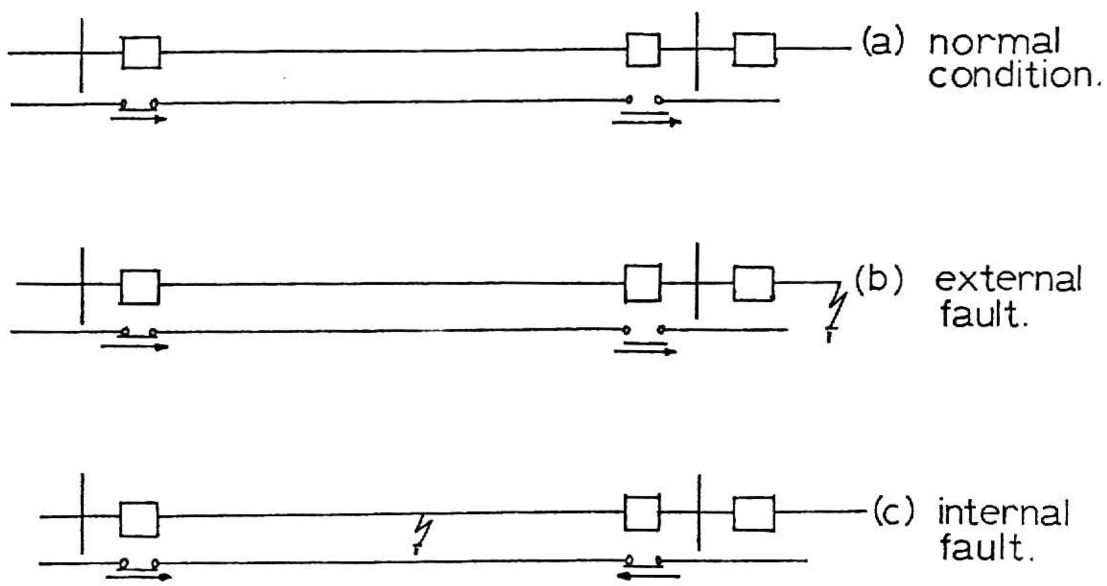


Fig. 26 - Basic Principles of directional pilot relaying.

of the fault parallelogram. In fact this characteristic has been achieved with an induction cup reactance relay and one blinder, the other unit being the mho relay. With semiconductor circuitry it is easy to obtain a quadrilateral characteristic by multiple inputs to such a relay.

Static distance relays are similar in basic principles to the electromagnetic type, but their lack of moving parts enables them to operate faster without fear of incorrect tripping. It is also possible with semiconductor circuits to obtain impedance characteristics other than the traditional sectors of circles. Since there are no contacts, the switching between the fault detectors, measuring units and timing units is done by biased transistors whose collector-emitter resistance is varied from near zero to near infinity, to act as a contact. Static distance relays are accurate over a wide range of fault current and line length. They also have a much lower burden than the electromagnetic predecessors of the induction cup type. The units of a modern three-step static distance relay are: the direct current power supply, auxiliary tapped transformers for control of characteristics, fast impedance measuring units, a two step timing unit and a tripping circuit.

CHAPTER V

DIRECTIONAL PILOT RELAYING

A unit form of protection may be used when it is important to clear all faults simultaneously at both ends of the protected section of line, such as when high-speed automatic reclosing is used. For unit protection it is necessary to exchange information about fault conditions at each end of the protected section and either a pilot wire or a carrier channel is used for this purpose. Two basic principles are employed: comparison of the direction of the power flow at the two ends and a continuous comparison of the instantaneous phase relation of the currents at the two ends.

In directional comparison pilot schemes, the direction of power flow is compared by means of the relative position of the contacts of directional relays at the two ends of the protected section. This type of protection utilises the fact that during an external fault the power must flow into the protected section at one end and out at the other, whereas, during an internal fault, the power flows inwards at both the ends. This is shown in Fig. 26. Directional relays at each end are connected so as to block tripping when fault power flows from the protected line to the bus-bar. By suitably interconnecting these directional relays through a pilot wire or a carrier channel, the position of their contacts can be compared and thus the location of the fault determined. An external fault will cause the directional relay nearest the fault to block tripping at both ends of the protected section. On the other hand, tripping will not be blocked on an internal fault because power will be from the bus into the line at both ends, or at one end if there is a single end feed. Load current will have the same effect as an external fault; the relay at the load end prevents tripping.

The communicating circuit between the two ends can either be a pair of pilot wires or a carrier channel using power lines themselves, or a v.h.f. radio signal transmitted directly between the line terminals. Economic basis and importance of the line generally decide the choice of the communicating circuit. However, a pair of pilot wires are generally used for short lines, upto 15 miles in length; a carrier channel is more economical for long lines; and where 'line of sight' exists between stations, microwaves can be employed.

Schemes Using a Pilot Wire Channel

Systems of d.c. pilot relaying are seldom used because practice has found a.c. pilot relaying more superior.

Although phase comparison or amplitude comparison can be employed on a current or on a voltage basis, most present day systems use amplitude comparisons in a circulating current system since they are easier to apply to multi-ended lines and are less affected by pilot capacitance, especially when pilot wires are used. The quantities available for comparison at each terminal are the local current and the pilot current. Depending on the relative polarity of the currents at the two ends of the line, the pilot wire current under normal conditions may either be zero (balanced voltage scheme) or equal to the through current (circulating current scheme), assuming negligible capacitance and leakage.

The phase comparison voltage balance scheme shown in Fig. 27 has been used in U.K. for at least 25 years. It compares the phase angle of the local current with that of the pilot wire current. The actual comparison in the relay is between voltages derived from the currents, using the upper pole of wattmetric type induction disc relay as a transactor. It will be seen that this pole is also used as a three phase summation transformer. The same pole carries a secondary winding across which appears a voltage corresponding to the combination of the local currents. The voltage is opposed by the voltage produced by a similar arrangement at the other end of the protected line section, and the difference voltage is impressed on a lower coil of the relay electromagnet. Normally, because the two voltages are equal and opposed, no current flows in the pilot wire or the lower coil and the relay has no torque. On the other hand, when an internal fault occurs, the voltages assist each other and current flows in the pilot wire and relay coils, thereby causing tripping.

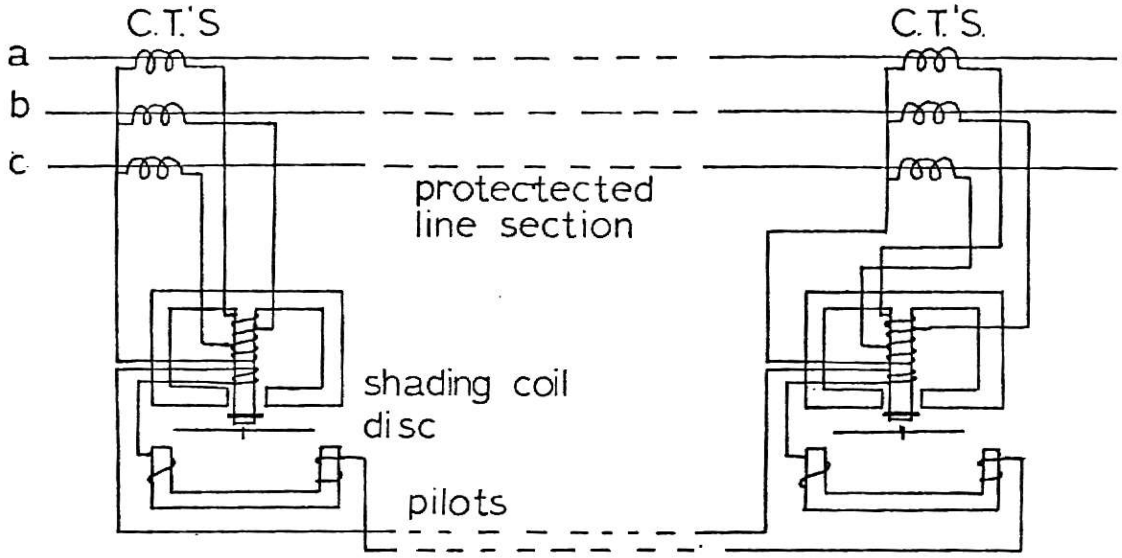


Fig. 27 - Phase comparison pilot relay.

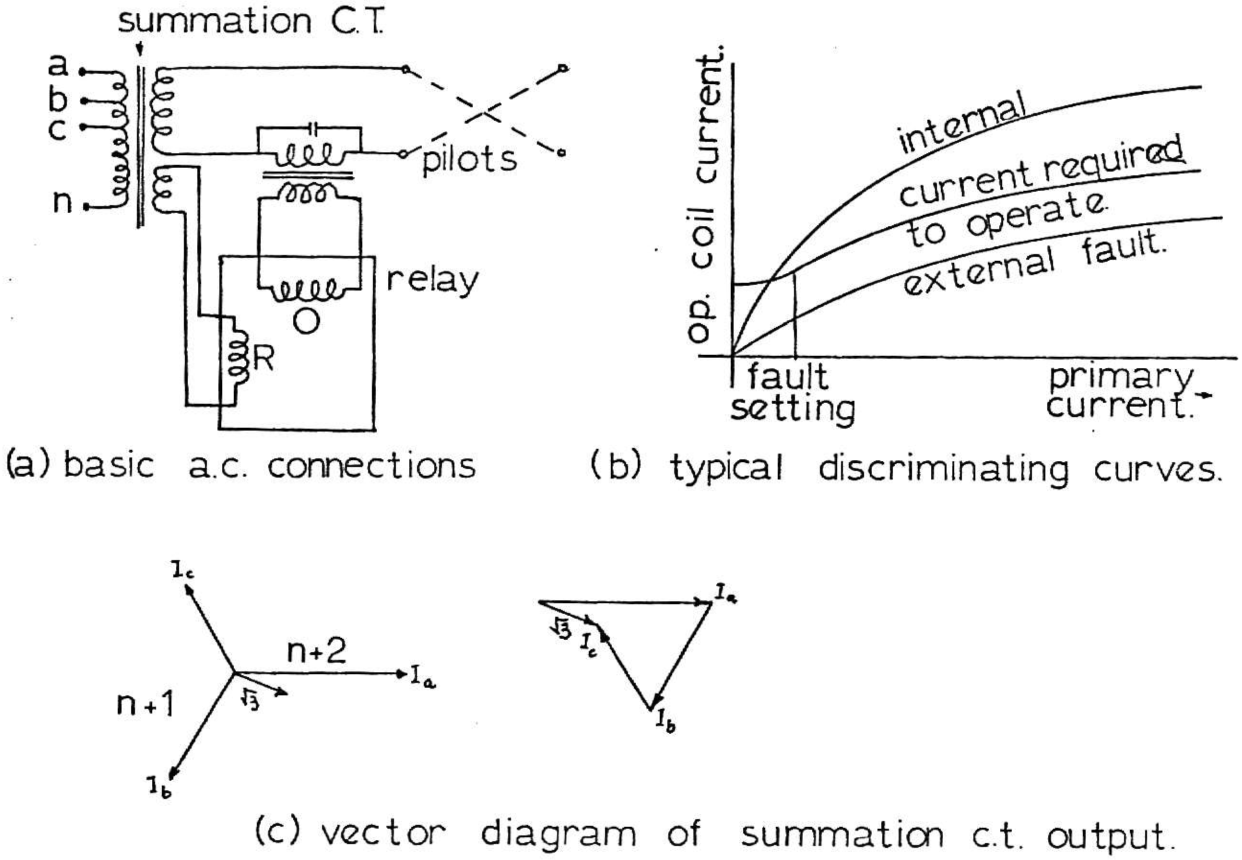


Fig. 28 - Voltage balance scheme.

As in the phase comparison scheme, the basic aim in the amplitude comparison scheme is to sum the three phase currents into a single quantity so that this information can be transmitted over the pilot cables.

Balanced Voltage Scheme

Here a transactor at each end provides a voltage proportional to the local current that is opposed by a corresponding voltage from the relay at the other end of the pilot wire. Theoretically, the current flows in the pilot wire only during an internal fault. The relay coils are connected as shown in Fig. 28 so that the pilot wire current tends to operate the relay and the potential across the pilot wires tends to restrain it. In this way the relay measures the impedance seen from one end of the pilot wires. The impedance will be higher normally and during an external fault. This arrangement does not have any compensation for pilot wire capacitance so that often a more sophisticated arrangement of Fig. 29 is used. In voltage balance schemes, compensation can be effected by the use of a replica impedance equivalent to the series resistance and distributed shunt susceptance of the pilot wires. This is a more practical scheme than the circulating current scheme and is generally used in practice.

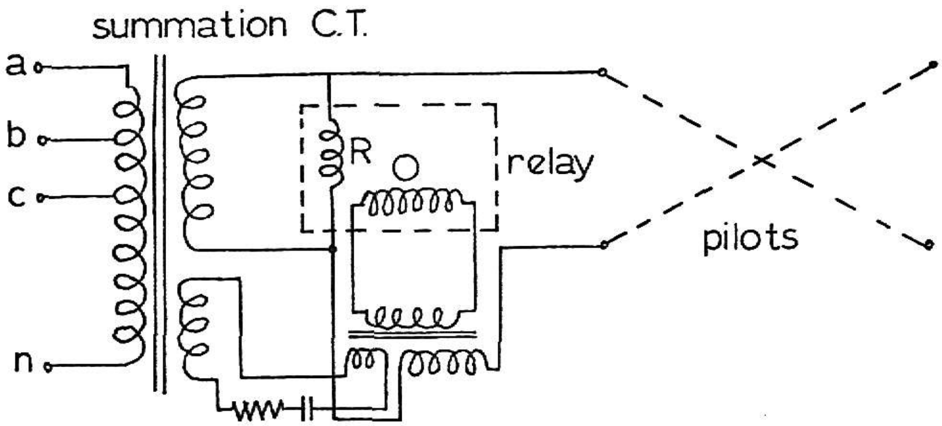


Fig. 29 - A voltage balance scheme.

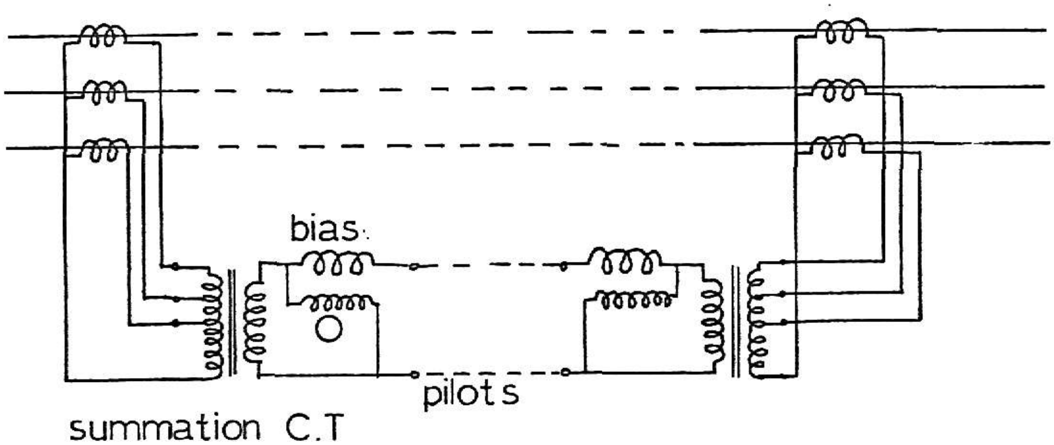


Fig. 30 - The circulating current scheme.

The Circulating Current Scheme

In this scheme, the present practice is to connect relays at each end. Under normal and through fault conditions, the operating force exceeds the biasing force and the relays trip the circuit breakers. This is shown in Fig. 30.

Transverse Differential Protection

The previous types of differential protection have been longitudinal. Balanced current protection is a type of transverse differential protection of parallel lines. It is based on a comparision of the magnitudes of the current passing through the lines. It is established at that end of the line which is constantly connected to the source. The principle of balanced protection of parallel lines is based on the fact that when the impedances of the parallel lines are equal, the currents in them are distributed equally under normal and external fault conitions. Balanced relays which compare the absolute magnitudes of currents of both lines, do not operate in these circumstances.

In the presence of a short circuit on one of the parallel lines, the larger part of the current from the source passes along the faulty line, while the smaller part passes along the undamaged line. In these circumstances, the balanced relay will trip the faulty line. At the receiving end of the parallel lines, without an additional feed source, the currents in the presence of a short circuit on one of these lines are equal in magnitude but opposite in direction. A balanced relay which reacts to the ratio of the current magnitudes and not to their direction would in this case not operate. Also the healthy line may carry additional current to supply load. Thus, the receiving end of the parallel lines, where the feed source may be absent, is the place for differential directional protection.

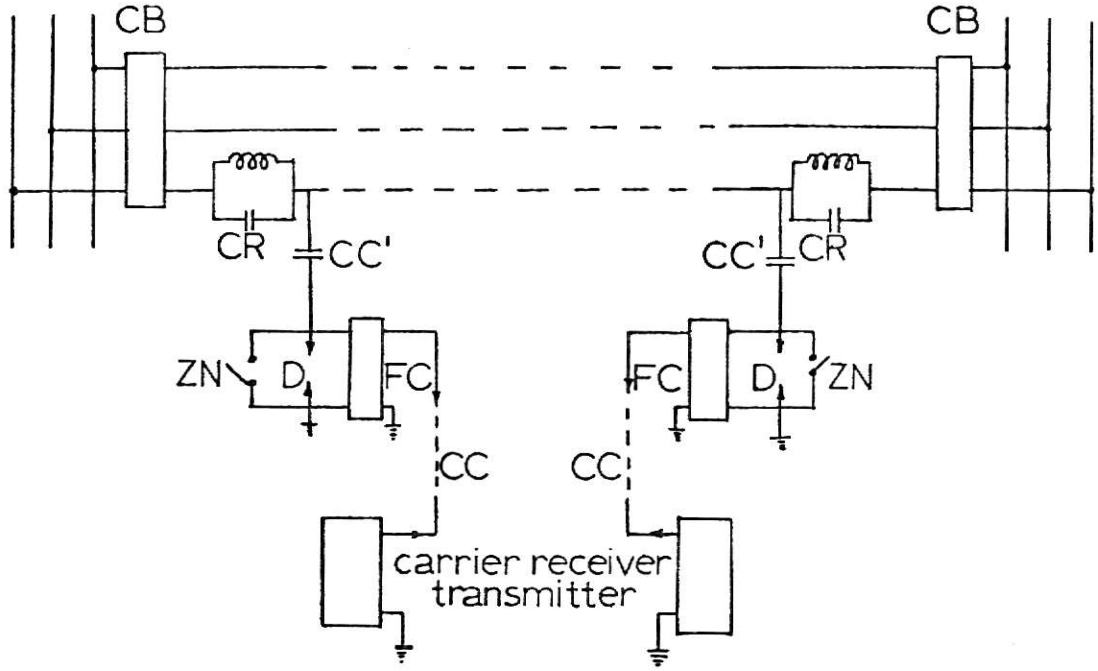
Carrier Protection

As mentioned before, the development of modern power systems is proceeding with the unification of regional power stations by branch high voltage networks of great length and by complex connection networks. Distance protection in conjunction with current cut-offs does not always ensure clearance of short circuits without time lag.

For high voltage and complex networks, as well as for transmission lines connecting power systems, carrier protection is used as the basic protection from short circuits of all kinds, whenever the simpler types of protection do not ensure the clearance without a time lag for all interphase short circuits, reduce the voltage below 6 percent of the normal at the point where the protective gear is installed. Unlike longitudinal differential protection with pilots, which has a field of application restricted to short sections, carrier protection is not limited by the distance of transmission, the lines usually being used as the carrier conductors. Recently there has been a marked tendency towards the use of radio links operating on decimeter wavelength.

The working principle of the carrier blocking protection is that the directions of power or currents at the terminals of the transmission line are compared with the aid of high frequency currents. When a fault occurs within the limits of the protected line, there is either no current in the carrier channel or it is of such a nature that the protective gear clears the fault. Protection is blocked when external short circuits occur. The transmission of carrier signals along the transmission line conductors is effected simultaneously with the transmission power frequency currents. The main carrier scheme, using phase-earth system is shown in Fig. 31.

A high frequency current is generated by the carrier transmitter, which is usually installed in the control panel of the station or sub-station and is transmitted by carrier cable CC through a filter FC and coupling condenser CC' to the carrier line. The filter, acting as a connecting link between the carrier cable and the coupling condenser, forms together with the latter a filter with a band pass. In addition, the filter matches the input impedance of the carrier cable to the output impedance of the transmission line. The discharger D, connected in parallel with the line winding of the filter, protects the carrier cable and the receiver transmitter from high voltage shocks.



CC - carrier cable

FC - filter connection

CC' - coupling condenser

D - discharger

Fig. 31 - Principle scheme of a phase-earth carrier link.

Carrier rejectors or traps, CR, are installed at the ends of the protected line. The carrier rejectors are resonant circuits with a high impedance to high frequency currents and low impedance to line frequency currents. High frequency currents transmitted along the line enter the receiver, which operates on the relay part of the circuit, blocks it or permits the clearing of faults.

Usually the carrier signal is generated by a transmitter consisting of an electronic oscillator and amplifier with an output usually of about 15 to 20 watts at a frequency between 50 and 500 kc/s. Below 50 kc/s the size and cost of the coupling components would be too high; above 500 kc/s the line losses, and hence the signal attenuation would be too great on long lines. Fifteen watts output has been found sufficient to cope with the losses of the line upto 100 miles. The coupling capacitor consists of a stack of capacitors, series connected, inside a porcelain insulator for injection into and receipt of the carrier signal from the line. The carrier signal may be of a fixed frequency and can operate in an on-off fashion or it may be on continuously (at a lower power) and a frequency shift employed to operate the relays at the other end of the protected section. The carrier signal can be introduced between one phase and ground or between two phases. The latter is found to be technically better but much more expensive, since it requires two sets of line traps. The single conductor scheme requires an earth wire for consistent results and demands more careful engineering since it has higher attenuation and a higher interference level with strong coupling with other phases.

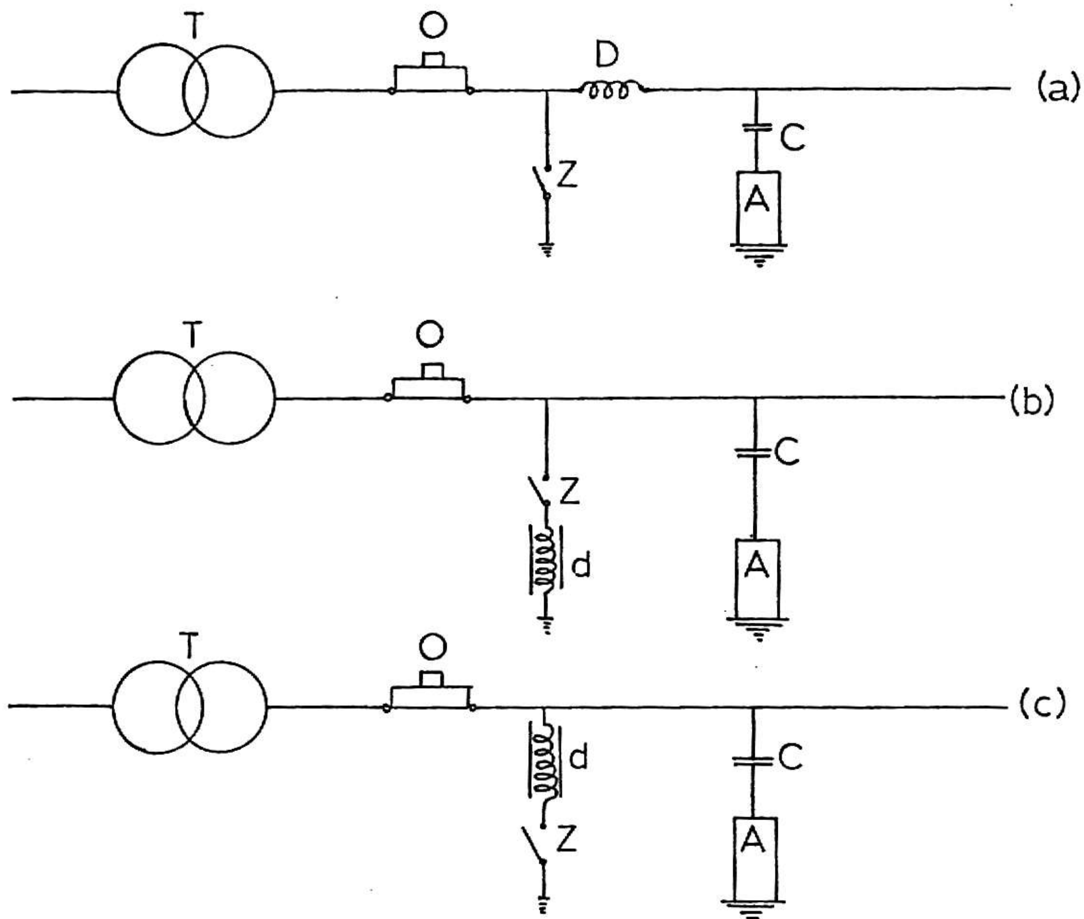
Besides the use of high frequency currents in power systems for relay protection, remote operation and telemetering devices, as well as high frequency methods of communications, have been extensively employed in practice in power systems.

Another Kind of Line Trap for Carrier Systems

This particular method is called the "shunting traps" method. The principle is based on the results of power transformer measurements carried out previously in Poland (9). As a result, it is known that power transformers for high tension lines have comparatively high impedance for very high frequency currents. This property has led to a different system of traps for the carrier protection system.

The usual way of connecting line traps D to a conductor of a transmission line is shown in Fig. 32a. Figures 32b and 32c represent a method of application of a new line trap in the shunting condition, called "shunting trap" d, working only with a switched off and earthed transmission line.

Shunting traps are not subject to full operating currents, therefore the sectional area of the wire used for them is smaller and thermal strength is lower than that of usual line traps. Shunting traps are subjected only to short circuit currents caused by faulty switching, the probability of which is



A - h.f. carrier equipment

C - coupling condenser

D - usual line trap

O - isolator and circuit breaker.

T - power transformer

Z - earthing switch

Fig. 32 - Alternate arrangement of carrier equipment.

much smaller than that of short circuit currents in usual line traps. The new choking equipment is much smaller and cheaper than the usual traps and is of universal application on various types of transmission lines having different rated and surge currents. The Polish engineers claim that while manufacturing shunting traps it is possible to assure better communication properties than with usual line traps, and furthermore, they are easier to manufacture in the form of all-wave shunting traps. This is a definite advantage.

However, there is also a minor disadvantage. These carrier currents applied to the transformer introduce generally a very small insertion loss (end attenuation).

Carrier Protection Schemes

There are 3 schemes for the carrier scheme: the blocking scheme, the interdependent tripping scheme and carrier acceleration scheme. In the blocking scheme, similar to the shunt pilot scheme, the carrier is started by fault detector relays which are countermanded by directional relays only if the fault current is flowing away from the bus; under external fault conditions this will be the case at one terminal and the carrier will still be transmitted from the other end, so the carrier signal thus appears on the line and blocks tripping at both ends. The interdependent tripping scheme is also known as intertripping or transferred tripping; a carrier signal received from the other end of the line causes local tripping, whereas, in the blocking scheme, it would prevent it. The zone 1 units of the directional distance relays at the end nearest to an internal fault not only trips locally but sends a carrier signal to the other terminal. This signal causes immediate tripping at that end also, although the fault may be beyond zone 1 reach of the relays at that end; this is shown in Fig. 33. Failure of carrier prevents simultaneous instantaneous tripping at the end furthest from the fault, and this results merely in delayed tripping at that end. In the carrier acceleration scheme the receipt of a tripping carrier signal from the other terminal increases the zone 1 reach to the zone 2 reach, resulting in instantaneous tripping at both ends. This is shown in Fig. 34.

The presence of a fault on a line protected by blocking carrier causes no trouble, because the carrier is in any case cut off for an internal fault. On the other hand, the carrier channel must be operative for the inter-tripping and carrier acceleration schemes and some allowance must be made for the effects of faults, although the attenuation of the carrier signal is generally less than expected. The amount of attenuation varies from about 20 to 50 dB with single phase to ground faults. It is of course worse with multi-phase faults.

Frequency shift carrier is considered better because it permits a more sensitive setting of the receiver since the blocking frequency prevents tripping on spurious H.F. signals from disconnecting switches and arcing external faults. Back-up

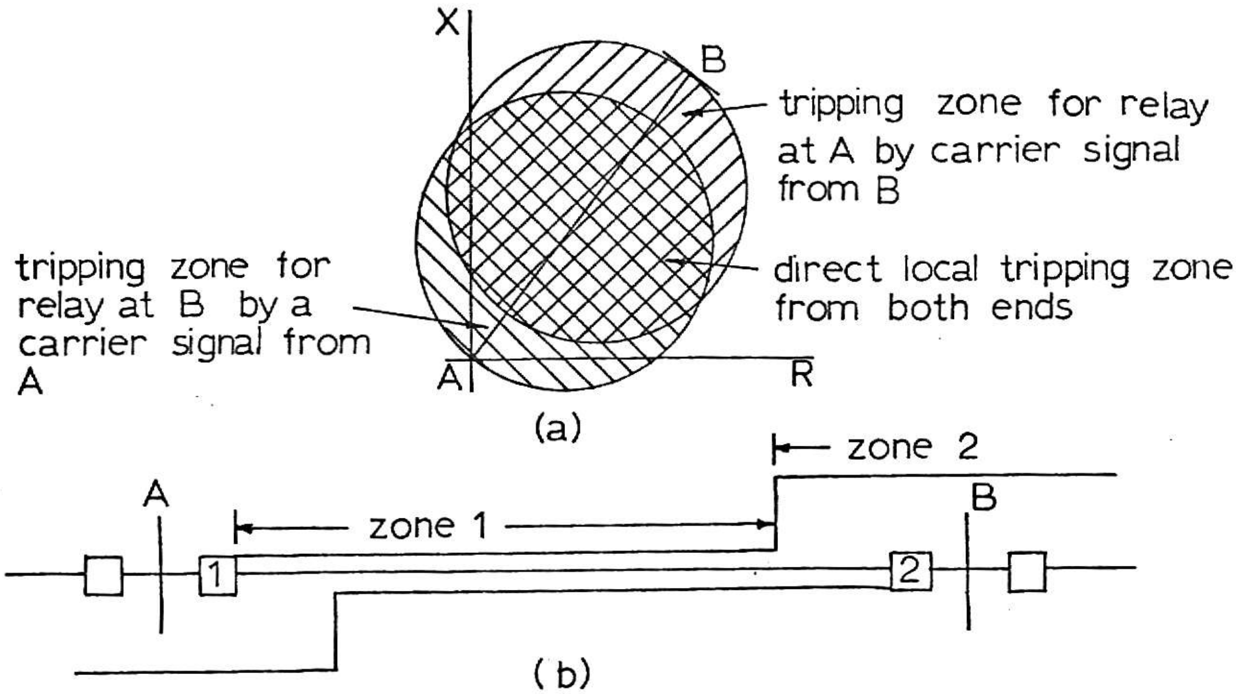


Fig. 33 - Carrier Intertripping
(a) Mho characteristics for carrier intertripping scheme and (b) distance setting for carrier intertripping scheme.

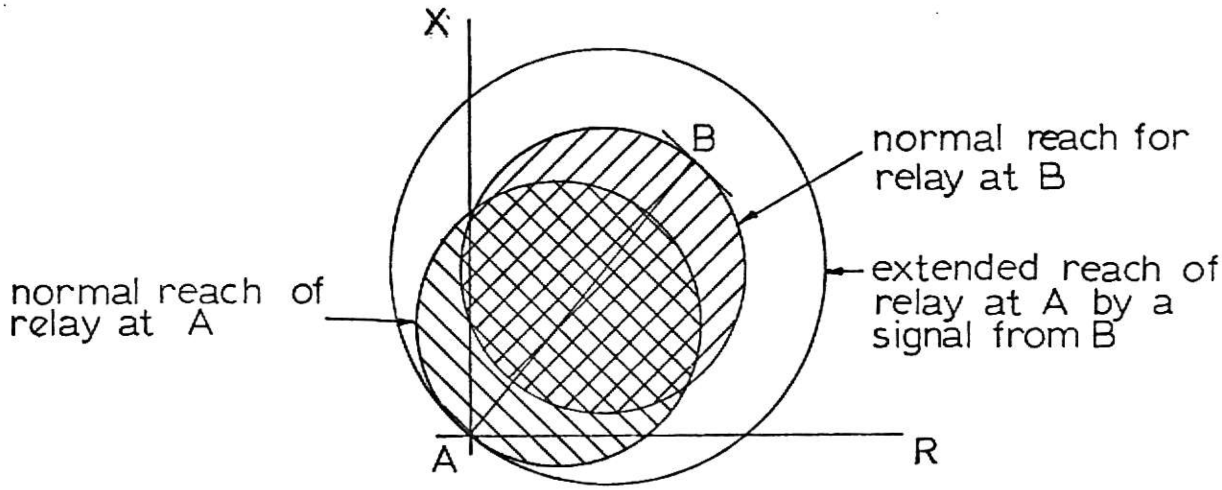


Fig. 34 - Carrier acceleration scheme.

protection is necessary in either case if three phase to ground are considered a practical risk.

In the U.S.S.R. still another method is used to some extent, protection with circulating high frequency currents. This scheme requires carrier treatment of all the three phases. This scheme is illustrated in Fig. 35. High frequency currents are generated by a carrier generator and applied to one end. Under normal conditions the balance of these high frequency currents is maintained, but in the presence of a short circuit within the limits of the protected section, the balance of the high frequency currents is disturbed and carrier relays, installed at the ends of the section, operate the tripping.

Use of Microwaves in Protection

This forms the third type of pilot channel in use. Signals of frequency from 900 to 6,000 Mc/s are used. The signals are beamed by parabolic antennae from one station to the next; upto 90 miles range is possible in flat country but obviously the range is limited by hills and buildings. This system is applicable only where there is a clear line of sight between stations. Because of high frequency as many as 30 signals can be transmitted spaced about 10 kc/s apart. Each frequency channel can be modulated by multiplexing transmitter with sub-carrier frequencies of about 500 kc/s. Experiments have been conducted and limited success claimed for v.h.f. transmission,

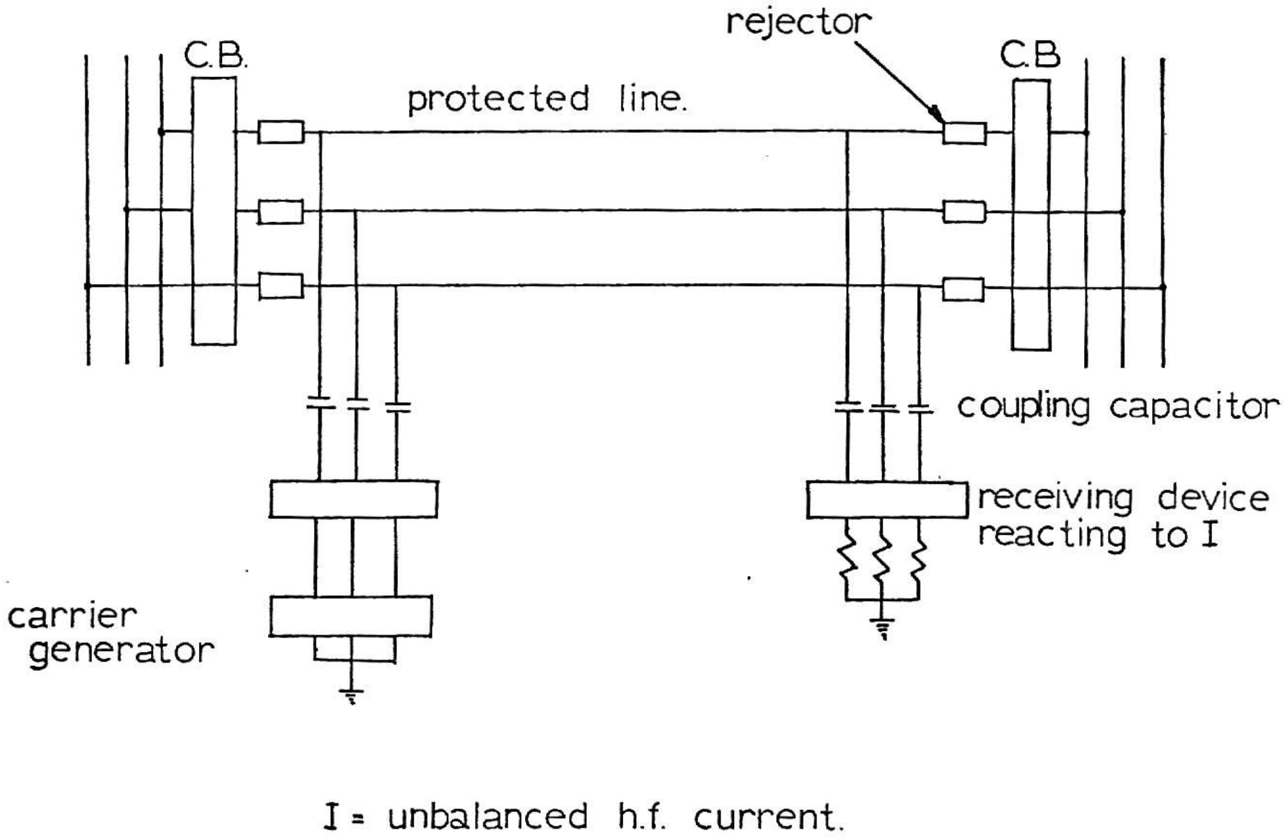


Fig. 35 - Protection in the presence of h.f. circulating currents.

other than line-of-sight, using flat reflecting surfaces mounted at convenient geographical points without auxiliary electric amplification. However, the use of microwaves has the following advantages:

(a) It is not necessary to have carrier treatment of transmission lines; i.e. there is no need to install rejectors and coupling condensers on transmission lines.

(b) These channels are not liable to interference (e.g. switching); investigations carried out on decimeter wavelengths have shown that the transmission of these waves does not depend on weather.

(c) It is not necessary to disconnect the transmission line when checking and erecting the pilot channel.

CHAPTER VI

CONCLUSION

"Mass production" is the word for many industries. This is also true of the electric power generating industry, the power plants. This mass produced power has to be transmitted by some means to various places of consumption. So far the overhead transmission line has been a means of transport. A. C. cable transmission has also been tried and proved successful at many places, viz, in Scandinavia where numerous fjords and channels in the sea present a problem to overhead lines. New Zealand has also found cables quite suitable on some of its transmission networks. Cables have lower impedance than transmission lines and provide better regulation. The third scheme of transmission is making reappearance after briefly serving the electrical industry in its pioneer days: the D. C. transmission. The essential difference is that the present D. C. transmission uses much higher voltages. Still another method of power transmission is being talked about: transmission by using superconductors. It is not known how soon this will be possible.

The main advantage of cables over transmission lines is that cables are safe from lightning strokes. Oil is used as a cooling media in cables, so the cables must be "oil tight" at its joints, which is the main problem. The voltage rating is limited to 345 kV.

The future of the distance relays, it is believed, with the present pace of progress, is at stake. Cables have lower impedance than transmission lines and to protect cables using distance relays requires very sensitive relays. Also when superconductors are commissioned there will be no impedance in the cable to provide distance protection!

The unit method of protection using carrier relaying will outlast the other forms of protection. This system has one disadvantage - a very good level of insulation has to be provided between high voltage lines and the transmitting and receiving equipment. But the use of the laser as a means of insulation protection for current transformer has been studied. Such a method could be provided on carrier equipment. Further, the use of insulated ground wires as a means of carrier relaying is being studied in U.S.A. Insulated ground wires are being used at the present for transmitting communication signals.

Circuit breakers though huge and massive, have attained operating times of 2½ to 3 cycles. Relays have operating times of about a cycle. Though small, someone would wonder why relays cannot obtain lesser times ? The answer to that question is that circuit breakers are a slave to a power system whereas the relays are its masters. The advantage of solid state relays, which are now fast replacing electromechanical relays, are discussed in Appendix A. Micro-miniaturisation is another big step forward. Saving in panel space is obvious advantage of miniaturised relays but more important advantages of the micro circuits are consistency, reliability, cheapness and speed of operation.

The use of computers in power system protection is also anticipated. They could also be used for determining the setting of the relays and fuses.

APPENDIX A

SEMICONDUCTOR RELAYS

The main advantages offered by semiconductor relays are low burden and superior performance, viz:

(a) Fast response, long life and high resistance to shock and vibration.

(b) Quick reset, a high resetting value and the absence of over-shoot are easy to obtain in static relays because of the absence of mechanical inertia and thermal storage.

(c) With the absence of bearing friction and contact troubles (corrosion, bouncing and wear), better characteristics can be obtained and there is less necessity for maintenance.

(d) Very frequent operation causes no deterioration.

(e) The ease of providing amplification enables greater sensitivity to be obtained.

(f) The low energy levels in the measurement circuits permit miniaturization of equipment and minimize current transformer inaccuracy.

On the other hand, static relays have a number of limitations which must be compensated for:

(a) Variation of characteristics with temperature and age and also from unit to unit.

(b) Vulnerability to voltage spikes and high ambient temperatures.

(c) Dependence upon the reliability of a large number of small components and their electrical connections.

(d) The lack of life test data due to rapid replacement by new designs.

(e) Low short time overload capacity compared with electromagetic relays.

The means for dealing with the above limitations will be mentioned briefly. Ageing can be minimised by presoaking for a number of hours at a relatively high temperature. Variation from unit to unit, where a difference amplifier has to be employed, can be eliminated by using integrated form of solid state devices. Protection against voltage spikes can be provided by filters and shielding. Silicon technology can be used where high temperatures are involved. Also modern methods of soldering, wire-wrapping and the selection of superior components can ensure a high degree of reliability. About the comment (d) above, the manufacturers of transistors say that the experience gained with one transistor is embodied in its successor. Overload can be avoided by circuit design.

APPENDIX B

FAULTS AND THEIR CALCULATIONS

In a system which is continually expanding, the fault level, i.e. the power available to flow into a fault, will rise as the generating capacity and the degree of interconnection rises. To protect the lines better, it would be necessary to determine the fault levels at various points on the system; not only for the satisfactory operation of the relays but also for the proper installation of circuit breakers, i.e. of due capacity. Two types of faults can occur on the system: symmetrical and unsymmetrical. The probability of the first kind of fault is very low, i.e. nearly all the faults are unsymmetrical.

To make complete and accurate calculations is virtually impossible, and certainly too tedious for operational work. The following simplifying assumptions are therefore made:

(1) All voltages remain constant and balanced at the source, and all voltage sources are in phase.

(2) The reactance used for the synchronous machine representation is constant.

(3) All transformers are at the normal taps.

(4) Load currents are considered negligible in comparison to fault currents.

(5) Transformer magnetizing currents are negligible in comparison to fault currents.

(6) Line capacitance currents are negligible and so ignored.

(7) Resistances can sometimes be considered negligible in comparison with reactance. This assumption cannot be applied if overhead lines of considerable length are included in the network. The assumption is also untrue when system neutrals are earthed through resistance, although neutral resistance does not enter into symmetrical fault calculations.

Symmetrical Fault Calculations

Because of the balanced nature of the fault and the system, any conditions which apply to one phase apply equally to the other two. In this way the problem reduces itself to a single phase problem involving a single source of supply acting through the equivalent network impedance upto the fault. Although the potentials at the point of the fault will be zero, it is normal to quote the fault capacity in kVA instead of amperes. Machine reactances are usually quoted in percent (or per unit value) together with the kVA rating on which the reactance value is based. Line and cable impedances are given in ohms per phase, and the grid feeds are given in terms of the short circuit kVA available at the point. All information must initially be converted to percent at the same arbitrarily chosen kVA base.

By definition,

$$\%X = \text{percentage reactance} = \frac{I.X}{V} \; 100\;\% ,$$

where I is the full load current,

V is the normal phase voltage,

X is the reactance in ohms per phase.

It follows that 3VI = rating in voltamperes.

Short circuit current is calculated on the assumption that full system voltage is used to drive the fault current through the system impedance.

$$I_{sc} = \frac{V}{X} = \frac{100 \times I}{\%X} ,$$

$$kVA_{sc} = \frac{kVA_b \times 100}{\%X} ,$$

where kVA_b is the arbitrarily chosen kVA base.

The advantage of working on percentage value is that they remain unchanged as they are refered through transformers, unlike ohmic reactances which become multiplied by the square of the transformation ratio. In converting percentage reactances from their individual bases to the standard base, the reactance changes in the same ratio as the kVA rating.

A symmetrical 3 phase fault is the severest type of fault which can occur and generally a single line to ground fault in the same system would be less dangerous.

Unsymmetrical Faults and Calculations

There are three ways in which unsymmetrical faults may occur in a power system:

(a) Single line to ground fault (L.G.)

(b) Line to line fault (L.L.)

(c) Double line to ground fault (L.L.G)

The above faults are listed in increasing order of severity and the symmetrical fault follows these as the most severe. In the calculation of unsymmetrical faults the seven assumptions made above will be carried forward. It is necessary to state more clearly what 'unsymmetrical' means here. In an unsymmetrical fault, the network impedances and source voltages are always (to a certain extent) symmetrical, that is to say, no piece of equipment ever has a red phase impedance which differs from the yellow phase or the blue phase impedance. The unsymmetry applies only to the fault itself, and to the resulting line currents. To calculate these currents and voltages it is necessary to introduce the concept of symmetrical components.

Symmetrical Components

The method of symmetrical components was first introduced by Dr. C. L. Fortescue in 1918. His work proves that an unbalanced system of N related phasors can be resolved into N systems of balanced phasors called the symmetrical components of the original phasors. For a three phase system, the system now under consideration, the three balanced sets of phasors are:

(1) Positive sequence components consisting of three phasors equal in magnitude, displaced from each other by 120^{o} in phase. They have the same phase sequence as the original phasors, viz, RYB or ABC.

(2) Negative sequence components consisting of three phasors equal in magnitude, displaced by 120^{o} in phase, and having the phase sequence opposite to that of the original phasors.

(3) Zero sequence components consisting of three phasors equal in magnitude and with zero phase displacement from each other.

The above three sets of components are shown in Fig. B-1. 1, 2 and 0 in the subscript to V represent positive sequence, negative sequence or zero sequence. The lower case letters - a, b and c will represent the three phases.

Operator 'a'

The operator 'j' causes a rotation of 90^{o} in the counter-clockwise direction. Also $j \times j = -1$ and $j \times j \times j = -j$ and $j \times j \times j \times j = 1$.

In a similar manner to the above familiar operator j, the letter 'a' is commonly used to designate the operator that causes a rotation of 120^{o} in the counterclockwise direction. Such an operator is a complex number of unit magnitude with an angle of 120^{o} and is defined by the following expressions:

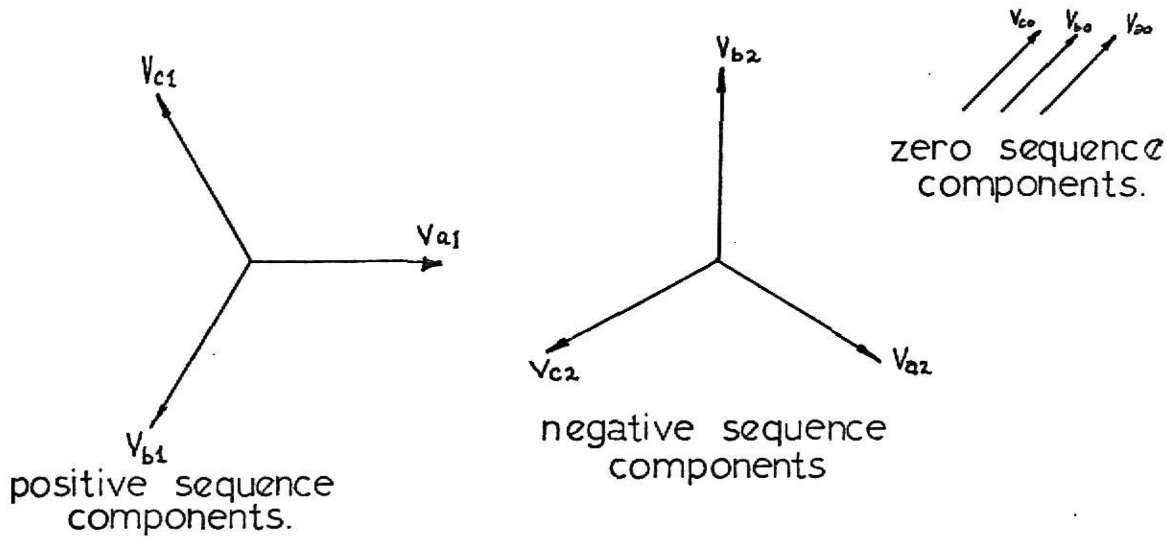


Fig. B-1 - Three sets of balanced phasors which are the symmetrical components of three unbalanced phasors.

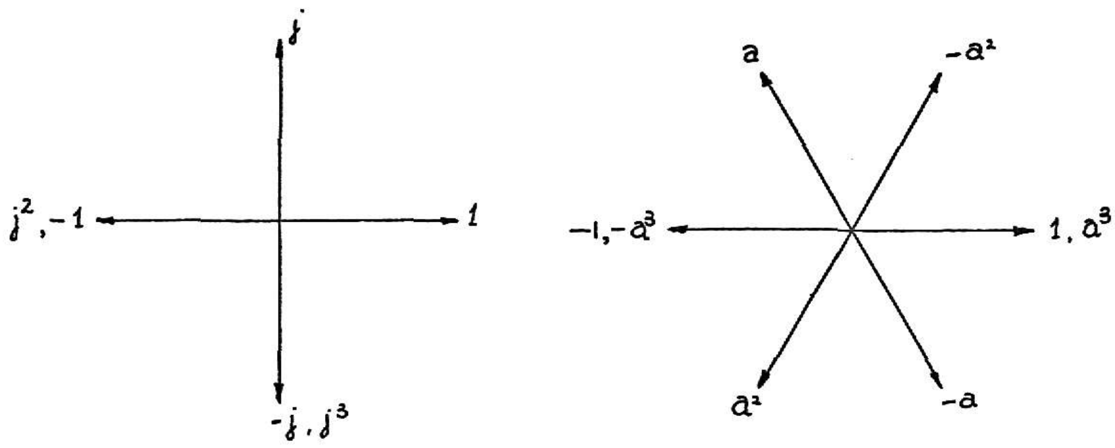


Fig. B-2 - Phasor diagram of the various powers of the operators 'j' and 'a'.

$$a = 1\angle 120^\circ = e^{j2/3} = -0.5 + j0.866,$$

$$a^2 = 1\angle 240^\circ = -0.5 - j0.866, \quad \text{and,}$$

$$a^3 = 1\angle 360^\circ = 1\angle 0^\circ = 1.0 \quad .$$

It should be noted that:

$$a + a^2 + a^3 = 0 \quad \text{or} \quad 1 + a + a^2 = 0.$$

a, a^2, a^3 are shown in a phasor diagram representation of Fig. B-2.

Solution of unsymmetrical fault essentially requires the writing of all the voltages in terms of the components of any one phase, namely:

$$V_{b1} = a^2 V_{a1} \qquad V_{c1} = a\, V_{a1}$$

$$V_{b2} = a\, V_{a2} \qquad V_{c2} = a^2 V_{a2}$$

$$V_{b0} = V_{a0} \qquad V_{c0} = V_{a0}$$

The phase voltages, V_a, V_b and V_c can be written in a matrix form as follows:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

Representing:

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}, \qquad A^{-1} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$$

Various Impedances

In any part of a circuit, the voltage drop caused by current of a certain sequence depends on the impedance of that part of the circuit to the current of that sequence. The impedance of any section of a balanced network to current of one sequence may be different from the impedance to a current of another sequence.

The positive sequence impedance, Z_1, is the impedance of a circuit when positive sequence currents alone are flowing. Similarly, the negative sequence impedance, Z_2, is the impedance of the circuit when negative sequence currents alone are flowing. A similar definition follows for zero sequence impedance, Z_0.

Since the system of generation is a balanced one, it follows that the generated e.m.f. E consists only of positive sequence voltage.

The paths for currents of each sequence in a generator, and the corresponding sequence networks are shown in Fig. B-3. It should be noted that any impedance in the neutral appears three times its value as a zero sequence impedance. This impedance in the neutral presents no impedance to either positive sequence or negative sequence currents as they are balanced.

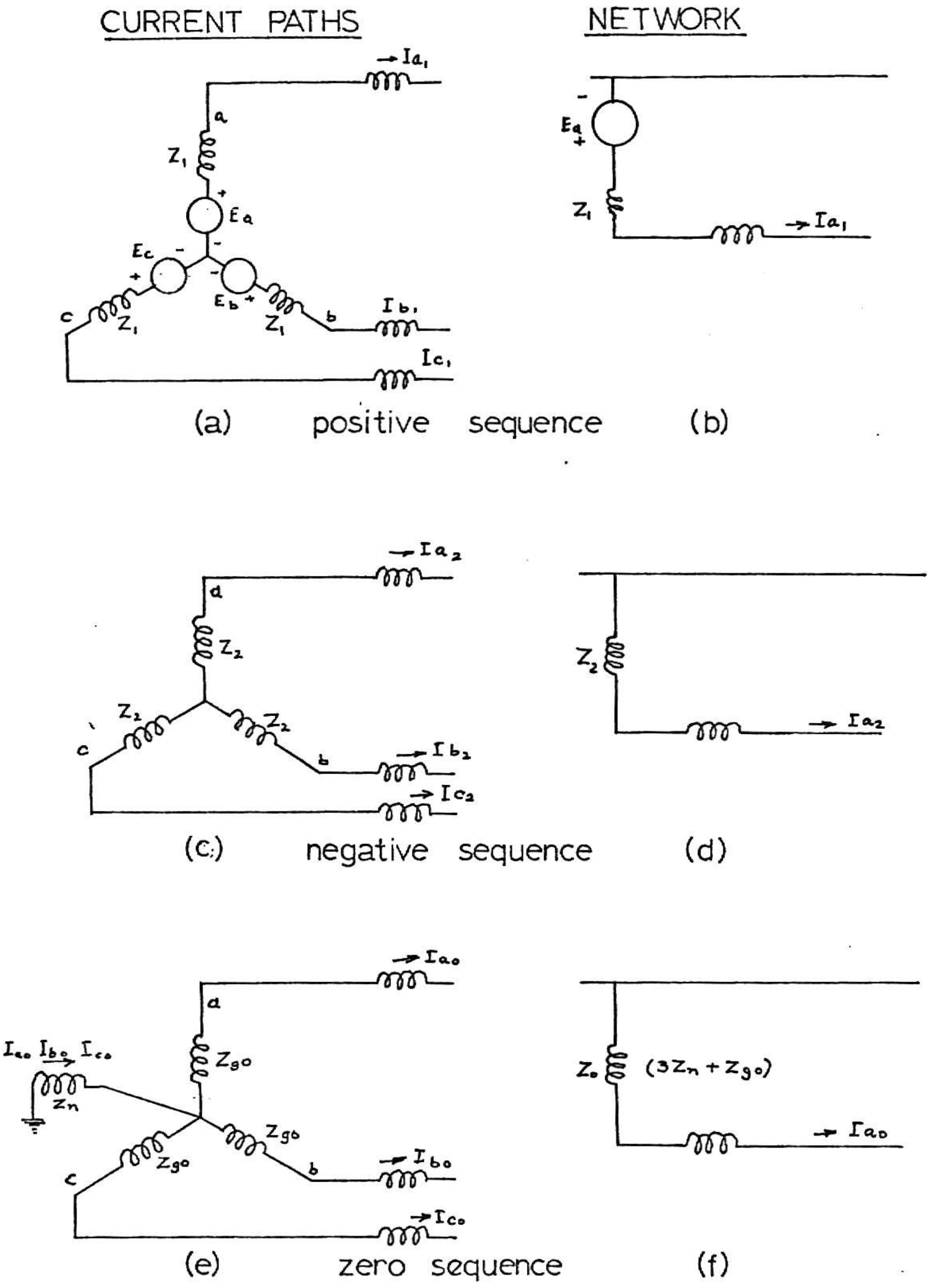


Fig. B-3 - Paths for current sequence in a generator, and line, and the corresponding sequence networks.

The general set of voltage equations, regardless of the type of the fault, is expressed in the matrix form:

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

Z_1 represents the total positive sequence impedance in short circuited circuit. Z_0 and Z_2 are similarly defined.

Single Line to Ground Fault
on an Unloaded Generator

The relavent diagram is shown in Fig. B-4. The various equations worked out are:

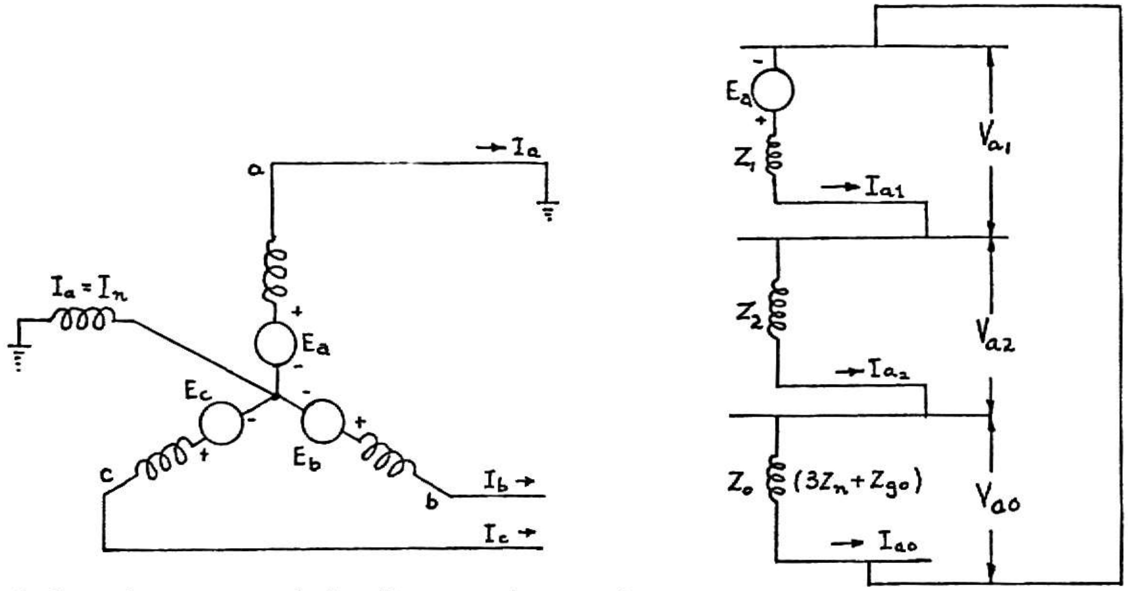
$$I_{a1} = I_{a2} = I_{a0} = \frac{E_a}{Z_1 + Z_2 + Z_0} \quad ,$$

$$I_b = I_c = 0 \quad ,$$

$$V_a = 0.$$

Line to Line Fault on an Unloaded Generator

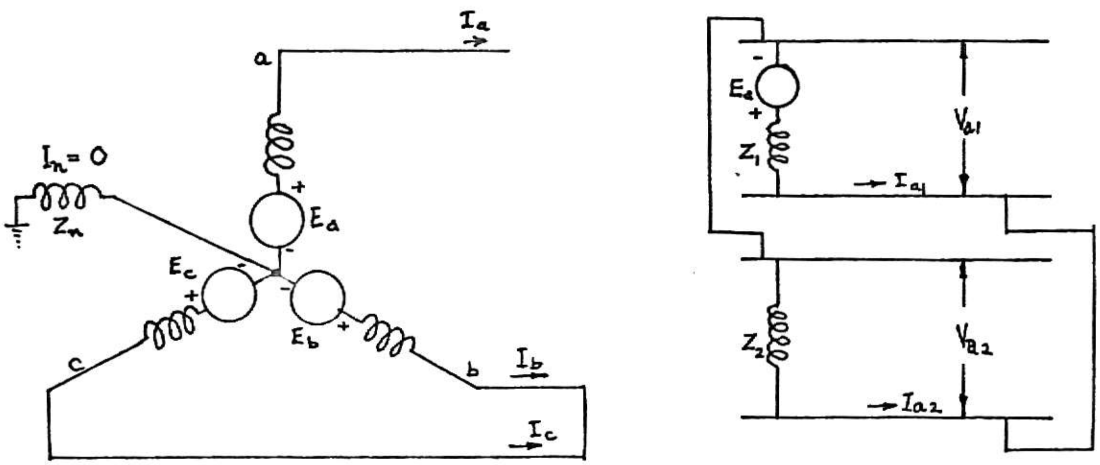
The conditions at the fault, for a fault on phases B and C, are expressed by the following equations:



(a) line to ground fault on phase A

b connection of sequence networks.

Fig. B-4 - Single line-to-ground fault.



(a) line to line fault on phase B & C.

(b) connection of sequence networks.

Fig. B-5 - Line-to-line fault.

$$V_b = V_c \qquad I_a = 0 \qquad I_b = - I_c \quad ,$$

which leads to

$$V_{a1} = V_{a2}$$

$$V_{a0} = 0$$

$$I_{a0} = 0$$

$$\text{and} \quad - I_{a2} = I_{a1} = \frac{E_a}{Z_1 + Z_2} \quad .$$

For a relavent diagram see Fig. B-5.

Double Line to Ground Fault

Fig. B-6 shows the necessary circuit diagrams. The conditions at the fault are:

$$V_b = V_c = 0 \qquad \text{and} \qquad I_a = 0.$$

These lead to:

$$V_{a1} = V_{a2} = V_{a0} \quad ,$$

$$I_{a1} = \frac{E_a}{Z_1 + \dfrac{Z_2 Z_0}{Z_2 + Z_0}} \quad ,$$

$$\text{and} \quad -I_{a1} = I_{a2} + I_{a0} \quad .$$

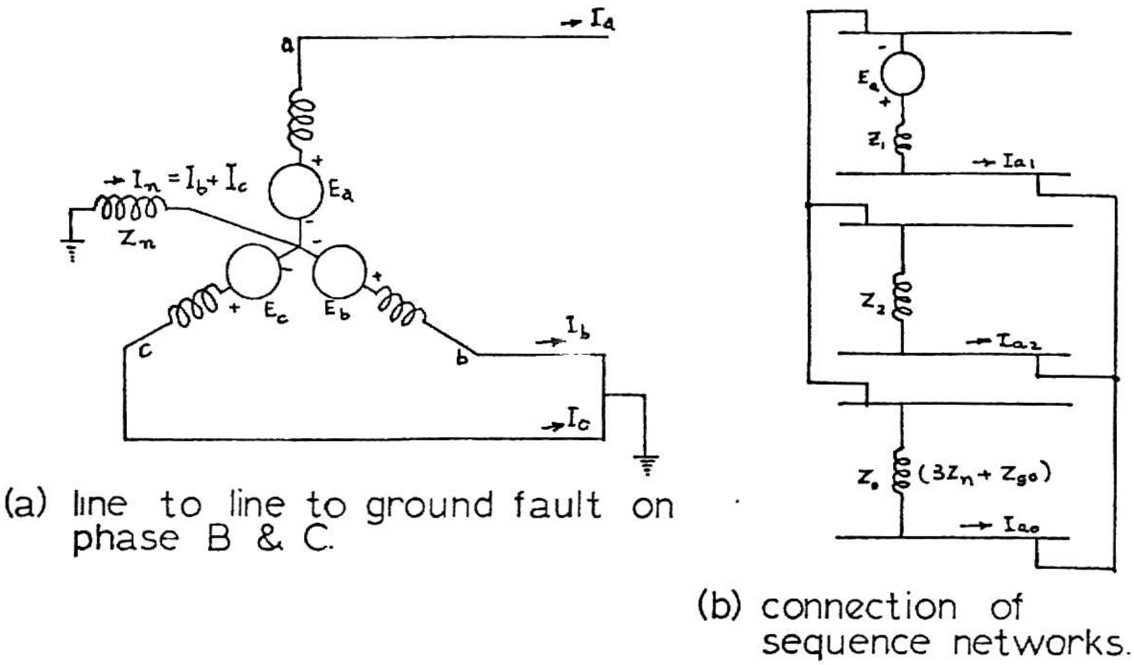


Fig. B-6 - Line to line to ground fault.

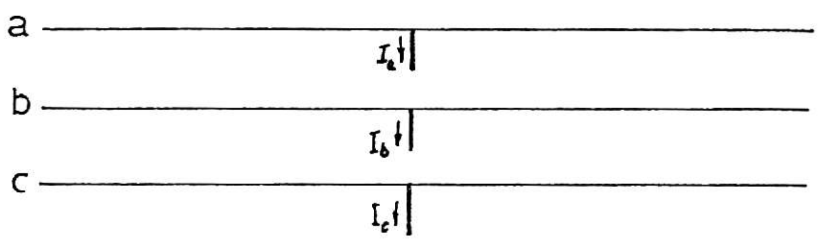


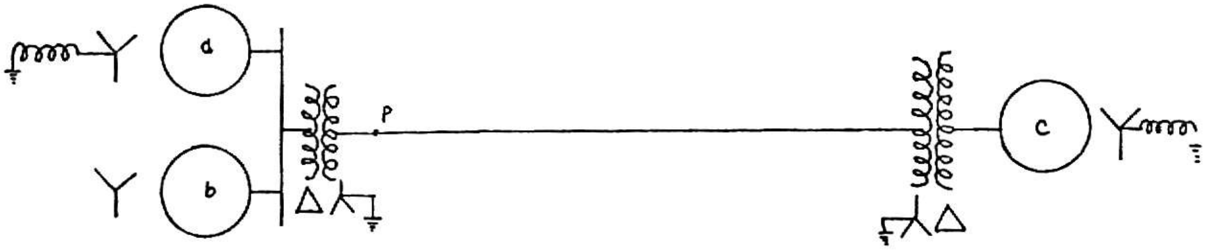
Fig. B-7 - Three conductors of a three-phase system.

Unsymmetrical Faults on Power Systems

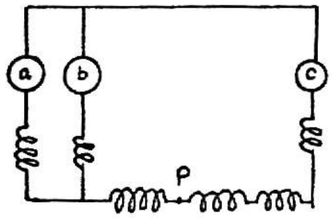
In the derivation of equations for the symmetrical components of currents and voltages, hypothetical stubs connected to each line at the fault condition need to be introduced. Currents I_a, I_b and I_c can be visulised as fault currents as shown in Fig. B-7. The stubs may be interconnected to represent different types of faults.

Let V_a, V_b and V_c denote line to ground voltages at the fault. Before the fault let the line to neutral voltage of a phase at the fault be V_f. For a method of solution consider a typical system shown in Fig. B-8(a). P is the point of fault. The Thevenin equivalent circuit of each sequence network is shown adjacent to the corresponding network in Fig. B-8. The impedance Z_1 of the equivalent circuit is the impedance measured between point P and the reference bus of the positive sequence network, with all the internal e.m.f.s short circuited. The value of Z_1 is dependent on whether subtransient, transient or synchronous reactance is used in the sequence network, which is, in turn, dependent on whether subtransient, transient or steady state currents are being computed. Since no negative or zero sequence currents are flowing before the fault occurs (i.e. on assumption that the load is of a balanced nature), the pre-fault voltage between point P and reference bus is zero in the negative and zero sequence networks.

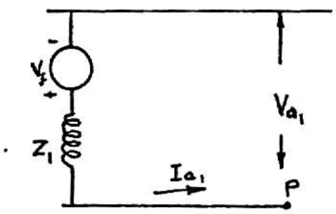
The same equations as derived for faults on unloaded generator apply.



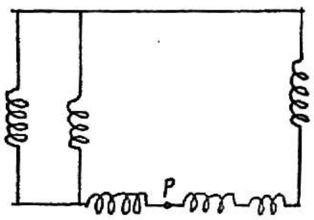
(a) one line diagram of balanced 3 phase system.



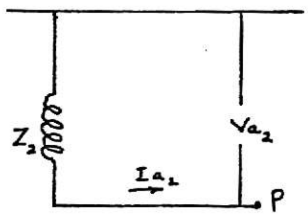
(b) positive sequence network



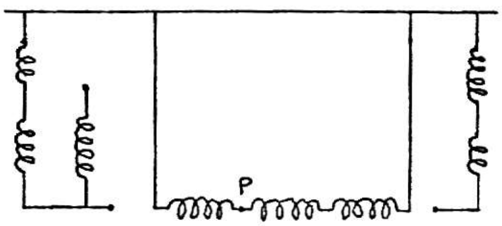
(e) Thevenins equivalent of (b)



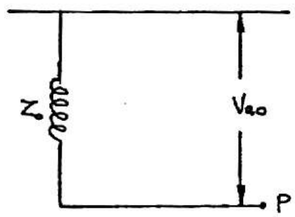
(c) negative sequence network



(f) Thevenins equivalent of (c)



(d) zero sequence network



(g) Thevenins eqivalent of (d)

Fig. B-8 - Sequence network calculation, example for fault on power system.

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PROTECTION OF OVERHEAD
TRANSMISSION LINES

by

PRADYUMNA NATUBHAI PATEL

B.E., Sardar Patel University, 1970

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1972

The ever increasing demands of electric energy have necessitated the building of large generating stations, particularly nuclear and hydroelectric stations; both being situated near water sources. If the load center falls away from the generating source, the problem of transmission arises and with it arises the problem of protecting the power system from various calamities: lightning strokes and discharges to the line or unaforeseen insulation breakdowns.

Sixty-five percent of the faults on overhead transmission lines are due to lightning and thus particular attention has been given to lightning protection. To understand this protection better, a study of clouds and lightning strokes has been included and protection by ground wires and auxiliary devices, particularly protector tubes, has been discussed. Tower footing resistance, a measure of how fast the induced or direct lightning is cleared from line and normal conditions restored, has been considered.

Overcurrent protection has only been included from the standpoint of historical interest. Overcurrent protection is losing its place in the field of high voltage protection to other more effective systems. Directional overcurrent protection has still some scope of protection and is used for parallel lines. Directional elements are also incorporated in the 'distance scheme' of protection. There are three most basic forms of distance relays: impedance, reactance and mho type. The use and significanse of each is shown.

Pilot relaying, using pilot wires, is an important form of protection for short lines. Various pilot wire schemes are discussed. For carrier current schemes the basic principles are discussed and the various schemes: inter-tripping, blocking and accelerated, are mentioned in detail.

Appendix A outlines the advantages and disadvantages of static relays. Appendix B considers some methods to estimate fault currents using symmetrical components.

This report deals with the various methods available for protection, but it does not go very deep into the study and construction of various relays. However, an effort has been made to include at least the most basic fundamentals involved.