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DISTRIBUTION SYSTEM PROTECTION AND SAFETY

By

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The increasing number of accidents on distribution systems has been a cause of concern. A number of remedial measures are possible; however, there is no consensus regarding the set of measures to be adopted for correction of the faults leading to the accidents. In the past few years changes have also been made in distribution system design such as the elimination of the cradle guards under the 11 kV lines and the cageguards from the low voltage lines, the removal of all LT fuses and the introduction in some areas of the multiple earthed neutral. The significance of all these measures has not yet been appreciated fully. This paper attempts to list some of the factors which influence distribution system safety and the significance of measures taken towards this end. The discussion is with reference to the overhead distribution systems of the West Pakistan WAPDA.

While overhead distribution systems are always subject to numerous faults, the impression is that at present the number of faults is excessive and this is reflected in frequent interruptions of supply to consumers. Some of these interruptions, however, are attributable to other factors (*a*) the gross overloading of lines as a result of an exceptional growth of load on the one hand and very limited funds for system augmentation on the other (*b*) the existence of long distribution lines; under pressure of demand from the consumers the distribution lines are kept on edging farther and farther, ultimately ending up in excessively long lines giving rise to interruptions over wide areas even in case of minor or temporary faults. These factors also contribute to the wide voltage fluctuations which are so large a part of the poor quality of supply (*c*) faults in consumers' installations due to work having been carried out by incompetent contractors or due to use of substandard equipment. These faults affect the distribution system, often giving an impression of a defect in the system.

But the types of failure which have been rather frequent are breakages of conductor and energisation of metal parts which are normally at earth

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potential. Most accidents have resulted from contacts with broken conductors remaining live for long periods and from energised metal parts. This has led to the conclusion that something is wrong with the design of the distribution system as normally such situations should arise very rarely and the protection should enable us to clear these faults rather quickly.

It is necessary to review the causes of these faults, the principles of the protection schemes and the earthing requirements for safety and proper operation of the system.

Protection

The functions of the protective system are :—

1. To prevent danger and accidents to persons arising out of normal or abnormal conditions.
2. In the case of a fault to confine system damage and to de-energise the faulty part of the system.

The protective equipment that may be used for the protection of 11 kV and LT systems comprises of circuit breakers and fuses. For 11 kV lines generally circuit breakers are used and these are operated from relays responding to overcurrents and earth fault currents. In the LT system the circuit breakers generally incorporate series overcurrent trips where they are used. Fuses are extensively used for overcurrent protection. For protection against earth faults two distinct systems are available. Firstly, overcurrent devices, generally fuses are used; in this case it must be ensured that the fault current is large enough to operate the fuse. Alternatively earth leakage circuit breakers may be used. These overcome the problem of insufficient fault current as they respond to very low fault currents. However, in most countries they have not come into very widespread use as they are very sensitive and difficult to maintain. In Pakistan they have not been used.

In LT systems the need of having sufficient fault current to operate the overcurrent devices requires that the impedance of the earth fault path must be severely limited. In a single phase 240 V system, for instance, if the fault current is to be greater than say 240 amp the total impedance of the fault path must be less than 1 ohm. A major function of the earthing system is to provide the very low earth resistance that is necessary. Since such low resistances may be difficult to obtain, this requirement is a major determinant of system earthing design.

Earthing

The function of the earthing system is :—

1. To stabilise the neutral to prevent dangerous overvoltages.

2. To permit system protection to operate in case of system fault.
3. To prevent dangerous voltages from arising in nominally earthed metal parts.

In HT systems at 11 kV and above, the system voltage is quite high in relation to commonly obtainable earth resistances and the essential protective requirements can be fairly easily met. Moreover the most elaborate protective schemes can be used. Earthing design follows common principles.

In the case of LT systems the only protection that is economically available is overcurrent protection by fuses. The fault voltage is low and hence the impedance of the earthing system assumes major importance. Most consumers are more in proximity to the LT system and the dangers of accidents are correspondingly greater. Conditions in the supply authority's system may also affect the safety of the consumers' installations. In designing the LT earthing system, therefore, attention must be paid to methods of obtaining the lowest possible resistance and the possible kinds of fault that may arise.

In general it is only possible to obtain the necessary low resistances by connection to a large interconnected earth system. In many countries, particularly the USA, it is mandatory to connect all earths to the waterpipe system. It would be appreciated that connection to such a system particularly in cities makes possible a good earth resistance at lowest possible cost. In any case interconnection of as many earths as is practicable is always beneficial. The benefits of schemes of multiple earthing are based on this. Isolated earths have to be much larger and costlier than individual earths of the multiple connected systems and except in soils of the very lowest resistivity it is prohibitively expensive to obtain a satisfactory earth. Fortunately in Pakistan the ground resistivity is generally low and it is relatively easy to achieve satisfactory earthing. But for this fact we might see very many more accidents.

The earthing system is designed to minimise the risk of shock. It must be noted that a certain time which may be many minutes, may elapse before the fuses blow on the occurrence of a fault. During this time, while fault current is flowing the affected metal parts will be at voltages above the general mass of earth. Secondly, it is impossible to make sure that the fuses will blow if the impedance of the earth fault is sufficiently high, and as already noted it need be only a few ohms for this to happen. It must be accepted that normally earthed parts may experience a voltage rise in some conditions and it is necessary to consider what may be regarded as a safe voltage. In U.K. the IEE Regulations permit a voltage rise up to 40 volts. In Germany a rise up to 65 volts is permissible. The voltage rise in the neutral and in earthed parts is a function not only of the total earth resistance but also of the distribution of the earth resistances throughout the system. If some portions have an earth resistance

earthing of the neutral also has the advantage that it stabilises the neutral and makes neutral inversion impossible.

Earlier regulations including the 1937 Electricity Rules provided for earthing of the neutral at one point only. This is a historical hangover from the days when three wire D.C. systems were used. In this case the middle conductor was earthed only at one point as multiple earthing of the middle conductor resulted in stray ground currents causing electrolytic corrosion and damage to other buried metal structures. This is not applicable to the A.C. systems. Considering the present system we find that where a separate earth-wire exists it is multiply earthed and the neutral wire is earthed only at one point. Multiple earthing of the separate earth wire may give a low enough impedance provided it is earthed in a sufficient number of places. If reliance has to be placed on this earthwire then it must be of the same conductivity as the phase conductors. The Electricity Rules recognise and require this. Steel earthwire may not be adequate because of the high resistance of the wire itself. To prevent neutral inversion resulting from neutral breaks or load unbalance the neutral also should be multiply earthed. When this is done, the use of the separate earthwire as a protective conductor becomes redundant. The multiple earthed neutral system shows distinct economic advantages here.

Fusing practices

The essential protective requirement of any fusing system is that when a fault between line to line or line to neutral occurs the protective fuse should blow. This means that the minimum fault current must be at least equal to 1.25 to 1.5 times the melting current of the protective fuse. Approximately this means that the minimum fault current must be at least $2\frac{1}{2}$ to 3 times the rating of the protecting fuse.

It should be noted that faults from line to the general mass of earth must develop into a line to neutral fault. The contact resistance of any conductor falling to the ground is at least 5 to 10 ohms, such resistances are too high and the fuses do not blow. A typical situation in urban areas is that a conductor may break and fall on a hard-top road or on dry soil. The area of contact is not likely to be great and the contact resistance could be quite high.

With the primary requirement met, the location of fuses and the number of fuses to be used would depend upon an assessment of the number of consumers that may be permitted to be disconnected during an outage. It would also depend on how far the protection can be coordinated in case there are a number of fuses in series.

Past practice has been to have fuses on the HT and LT side of the supply transformer, on each circuit, at all branch points, and on each service.

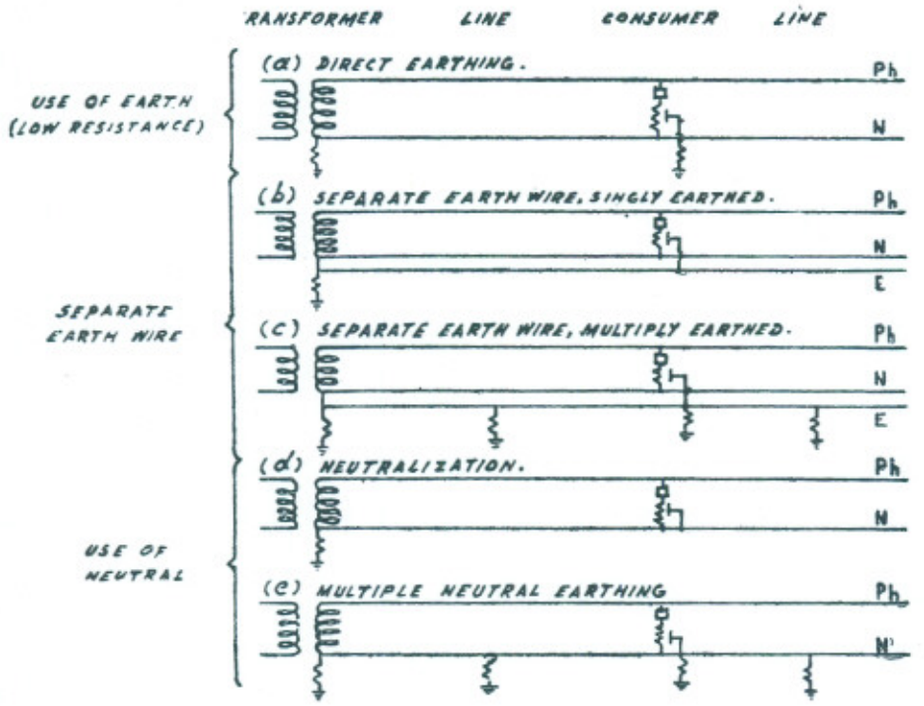
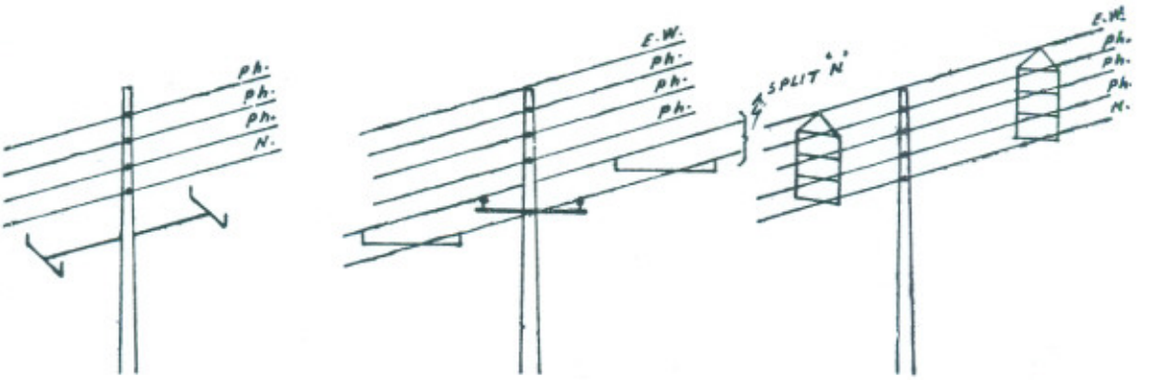


FIG: 1 VARIOUS SYSTEMS OF EARTHING.



(a) PUNJAB EARLY DESIGN. (b) UHL RIVER SCHEME:-1933. (c) CAGE GUARDS:- 1935.

FIG: 2 DESIGNS OF L.T. GUARD WIRES.

Experience with this system was not good as it was found that it was impossible to maintain coordination between the various fuses.

It is obvious that in the presence of 11 kV transformer fuses, the large fuses on the LT side have no function and are not justified. If the conductor sizes taper off too much or the line length is very great, the 11 kV fuse would no longer be able to meet the criterion stipulated above and the remote parts of the lines would remain unprotected. In this case branch fusing would be justified.

In present practice all LT circuit fusing has been eliminated and reliance is placed on the 11 kV fuse to clear all faults on the LT side. Only the fuses at consumers' installations have been retained. In this case it is essential that the conductor sizes should be sufficiently great and line length should be sufficiently small so that the entire length of all LT lines and all branches is within the protective zone of the fuse. Investigation has shown that this is frequently not the case. Whenever an accident has been investigated it was found that the line lengths were too great for the protection to be operative. This is a major cause of the accidents which have been occurring. Table I shows the maximum line lengths which are permissible for the various sizes of conductors fed from different ratings of distribution transformer.

TABLE I :—*Maximum line length with fuses on LT side.*

Transformer and Fuse rating	Conductor sizes		
	Gnat, 26 sq mm	Ant, 52 sq mm	Wasp, 106 sq mm.
25 & 50 kVA / 3 K fuse	400 yds	800 yds	..
100 kVA / 10 K fuse	72 yds	240 yds	440 yds
200 kVA / 20 K fuse	..	140 yds	320 yds

When consideration is given to the installation of fuses it must be ensured that they are reliable enough to retain their characteristics over long periods of time. In the past semienclosed porcelain cutouts have been used, the fuse element being a tinned copper wire. Such fuses are subject to long term deterioration due to oxidation of the element. This oxidation is due to the heating of the element when carrying load current. Because of this oxidation

and reduction of cross-section the fuses blow after a certain time on normal load. If there are a number of fuses in series the problem is compounded. If co-ordination is to be maintained in the face of the long term deterioration of the fuses then whenever a fuse blows all fuses in the coordination chain must be changed. These are practical difficulties which have resulted in practice in the fuse wire being invariably replaced by solid links. The protection then no longer exists and the system is saddled with a number of weak points at all the connections of the fuses. In such a case it is certain that accidents would occur.

It is clear that LT fusing on an extensive scale is not a practicable proposition unless HRC fuses are used as these fuses are highly reliable and deterioration of fuses and maloperation are no longer troublesome. The cost of the HRC fuse however is very much higher. The present practice of no LT fusing is satisfactory provided that the line lengths are not excessive. In the case of very long lines a minimum of branch fusing would be justified.

Broken Conductors

It may be fruitful to review the causes of conductor breakages. Normally such breakages are due to storms or mechanical obstructions of the lines such as tree branches falling upon them. Such faults however are well within the normal limits. The majority of conductor breakages occur in calm weather. Investigations show that in most cases breakages are due to burning of the conductor at the joints or at the tapping points. The incidence of broken conductor faults has risen sharply since the introduction of aluminium conductors some years back. Faults on copper conductor are rare and generally occur when they are jointed to aluminium. As yet the use of proper accessories and fittings has not been introduced everywhere. What has happened is that the same techniques were used for jointing aluminium and ACSR conductors as were used for copper conductor. These are not satisfactory as aluminium is a soft metal and therefore does not make joints of high mechanical strength. Aluminium wires are covered with an oxide which is an insulator. Unless the oxide film is removed the joint has a high resistance and runs very hot and soon fails. This is the main reason for the present abnormal conductor breakages.

When electric supply was first introduced solid copper conductors were used. They were of rather small size and were not very reliable mechanically, conductor breakages were fairly frequent. Precautions therefore were usually taken by providing cradle guards under the conductors. Regulations were also introduced regarding the minimum breaking strength of the conductors. For instance, the Electricity Rules 1937 require the minimum breaking strength to be 700 lbs for main line conductor and conductors of 300 lbs strength are

allowed for small spans and service lines. Today we are using stranded wires of big cross-section. The smallest conductor in use, the all--aluminium Gnat 26 sq mm has a breaking strength of 980 lbs. Modern manufacturing processes are much advanced and today conductors are altogether more uniform in their mechanical characteristics. Secondly, conductors are usually erected at very low tensions in urban areas. The every-day stress in aluminium conductors is less than 9% of the ultimate tensile strength, while the maximum tension under the worst wind load does not exceed 30% of the strength. For ACSR conductors these figures are 6% and 16% respectively. For rural areas and long span lines only ACSR conductors are used and the maximum stresses do not exceed 35% of the conductor strength. These very low tensions are used because the condutor stress has to be limited to prevent damage from aeolian vibration. In urban areas where there are many angles and deadend poles the use of higher tensions results in many guying problems. Mechanical weakness is therefore no longer a cause of conductor breakage.

The cause of the present abnormal conductor breakages are not the same as in earlier years, the remedies must correspondingly be different. It is well known that most countries of the world today do not require the use of special measures such as cradle guards for protection against broken conductors. This is in recognition of the great reliability of present conductor manufacturing techniques. With proper workmanship and the use of the correct accessories and joints the incidence of conductor breakages can be kept at an acceptable level.

It should also be noted that if an LT conductor breaks and falls to the ground it may still remain live and contact with the cradle guard may not make it dead. If only one conductor breaks and its associated fuse blows the other fuses may well remain intact. In this case the conductor on the side remote from the transformer will remain energised through the consumer loads beyond the break. No fuse will operate as the fault current will be limited by the high impedance of the loads. This hazard can only be guarded against by using ganged three phase tripping devices. This means that circuitbreakers may have to be used on the LT side or reclosers or some similar device on the HT side. However in this case the cost of the installation goes up so much that it would be well to consider other system designs such as the use of aerial cable. Unquestionably the best practice is to ensure the integrity of the conductor which is perfectly possible with present techniques.

Guard wires

In the past guard wires have been used for protection against breakage of conductor both for 11 kV and for LT lines.

In 11 kV lines the guards were installed under the conductor. Their function was to prevent broken 11 kV conductors from falling to the ground or touching the LT conductors in composite lines. In most countries conductor breakages are no longer a problem and the guards have been given up. In the WAPDA system, only ACSR conductors are used for 11 kV lines and the factor of safety is very high. If there is a fault it is rapidly and readily cleared by the protective system. The 11 kV circuit breakers protecting the 11 kV lines operate from overcurrent and earth fault relays which are sensitive enough to cater for all fault conditions. Accidents on account of broken 11 kV conductors remaining live are exceptional.

In the case of LT lines cradle guards have been used under the lines. The function of these guards has been two-fold. Firstly as in the case of 11 kV lines to guard against broken conductors falling to the ground. Secondly to facilitate contact between the broken conductor and the neutral or the protective earthwire. Figure-2 shows the various designs that have been used. The first design used was merely a bracket sticking out a few feet from the pole and connected to the earth wire. It was hoped that broken conductors would invariably touch this bracket. This did not work very well. Later on the neutral was split and placed under the line conductors which were in vertical formation. This construction led to difficulties with street light conductors and the cage guards were introduced which have been in use up till now.

Numerous difficulties have always been experienced with the guard wires. The wires of the guard may break and be a source of fault. With present design this is very frequently the case. Secondly, with present design the clearances to the conductors are such that even in mild storm conditions the phase conductors or the streetlight wires clash with the guards and cause outages. Frequently faults are caused by the cageguards becoming loose and coming in contact with the conductors, as the installation of the cageguards reduces the clearances. The aluminium conductors have a much higher coefficient of expansion and variation in sag as compared to the steel guard wires. This results in a further reduction in clearances and greater danger of faults. The effect of the guard wires is to bring earthed metal in close proximity to line conductors. This is in itself highly undesirable. It would of course be possible to design the lines with ample clearances between the conductors and the guards and to make them of substantial size so that these troubles are minimised. The Electricity Rules require that the guard wires meet such requirements. However, this was never done in a thorough manner as it involves very considerable expense. It was generally attempted to more or less fit on the guards to the lines and clearances were allowed to be impaired. For instance if safe clearances between LT phase wire and cage guards are to

be maintained, the distance between phases would have to be increased to something like 18 in. from the present 12 in. When this is done the pole heights are substantially increased, the quantity and loading of conductors is increased, the amount of hardware is also greatly increased and stronger poles have to be used. It has been estimated that the increase in cost of the line might be from 30 to 50% of the cost of a line without such guarding. With little to be gained and with possible hazards of their own there appears to be full justification for eliminating the guard wires and this has been done.

Consumers' premises

The supply system affects the protection and the safety of the consumer's installation. The source of the fault current which must blow the consumer's fuse in the case of a fault is the supply authority transformer and the fault current available at the consumer's terminals must be such that the consumer's fuse blows on the occurrence of a fault in his installation. Secondly, the authority must ensure that over-voltages are not experienced by the consumer. This means that conditions such as load unbalance or neutral inversion should not arise the phase to neutral voltage received by the consumer sufficiently to endanger his equipment.

The lack of a solidly earthed neutral has in the past resulted in frequent incidents of high voltage faults and burning out of equipment. This can only be rectified by a multiple earthing of the neutral.

To ensure that the fault current at the consumer terminals is sufficiently high the total impedance of the fault path must be low. Since the consumer can only instal a single earth which can easily have a resistance up to 10 ohms, it is obviously the responsibility of the supply authority to undertake to provide an earth connection of the necessary low resistance. This also calls for the introduction of multiple neutral earthing.

APPENDIX I

British Requirements for Multiple Neutral Earthing

(*a*) (*i*) The neutral point of the transformer from which the specified system is supplied with energy (hereinafter referred to as "the supply transformer") shall be connected to an earth electrode and the said point shall be bonded to the metal sheathing and metallic armouring (if any) of the electric lines concerned.

(*ii*) Provided that a connection from the said neutral point to an earth electrode may be omitted where the specified system includes two or more distributing mains whose respective neutral conductors are connected with earth in accordance with the provisions of para (*b*).

(*b*) The neutral conductor of the specified system shall be connected to earth electrodes located :

(*i*) At the end remote from the supply transformer of each distributing main and each branch of a distributing main forming part of the specified system;

(*ii*) At such additional points, as equally spaced as possible, as are necessary to ensure compliance with the provisions of para (*e*).

(*c*) A specified system shall be connected only with earth electrodes as aforesaid if the overhead neutral conductor thereof is of the same material as that of the phase conductor or conductors, and has a cross-sectional area not less than that of any phase conductor.

(*d*) Every earth electrode to which connection is made in compliance with these recommendations shall, if specially installed, consist of one or more rods or tubes driven into the general mass of earth so as to be as nearly vertical as possible, or of a metal strip or wire laid horizontally in the general mass of earth. All earth electrodes shall be so installed as to prevent danger from voltage gradient at earth level, and connection with them shall be made above the surface of the ground in a position where the said connection can be inspected when necessary.

(*e*) The connection of the neutral conductor to earth shall be as follows :—

(*i*) To an earth electrode connected to the neutral at or near the transformer, of such a resistance that the fuses protecting the high-voltage side of the transformer will operate should break-down occur between the windings. (Subject to (*a*) (*ii*) above).

(*ii*) To such additional earth electrodes as will give an overall resistance to the general body of earth of not more than 10 ohms.

(*f*) It is recommended that where, at any supply transformer, the neutral point and any metal-work associated with the windings at the higher voltage are both connected to earth electrodes, separate earth electrodes shall be used and the following requirements shall be complied with :—

(*i*) One of the earth electrodes shall be connected to the neutral point of the supply transformer and any metal-work associated therewith which is electrically separate from any metalwork associated with the windings at the higher voltage. (Subject to (*a*) (*ii*) above).

(*ii*) The other earth electrode shall be connected to the metal-work (including the metal case and connected metal-work of the supply transformer) associated with the windings at the higher voltage.

(*iii*) The earth electrode connected to the neutral point of the supply transformer shall be situated outside the resistance area of the other earth electrode.

(*g*) There shall not be included in any part of the neutral conductor of the specified system a fuse, automatic circuit-breaker, removable line or singlepole switch.

(*h*) As from the date when protective multiple earthing has been effected in relation to the specified system a supply of energy shall not be given to any new consumer from the specified system, or shall not be continued to be given to any existing consumer from the specified system, unless the following requirements in relation to the consumer's installation are complied with :

(*i*) Metal-work enclosing, supporting or near to any part of the consumer's installation and not designed to serve as a conductor

shall, where necessary to prevent danger, be connected by means of an earth continuity conductor with the neutral conductor of the specified system at the supply terminals.

(*ii*) The electrical resistance of the earth continuity conductor, between the point where it is connected to any metalwork as aforesaid and its connection with the said neutral conductor at the supply terminals, shall preferably not exceed 0.5 ohm, but under no circumstances must it exceed 1 ohm.

(*iii*) Any conductor on the consumer's side of the supply terminals which is connected to the neutral conductor of the specified system shall not include any fuse, automatic circuit-breaker, removable link or single-pole switch in any part thereof.

(*iv*) It is recommended that, before the earth continuity conductor is connected with the neutral conductor of the specified system at the supply terminals, the electrical resistance of the earth continuity conductor shall be verified by the application of a testing current of not less than 15 amp flowing for a period of not less than 1 min.