A LIMITED SURVEY OF ELECTRICAL DISTRIBUTION PRACTICES IN THE U.S.A. WITH POSSIBILITIES OF ADAPTABILITY IN PAKISTAN

A THESIS

BY

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CONTENTS

LIST OF FIGURES

I INTRODUCTION

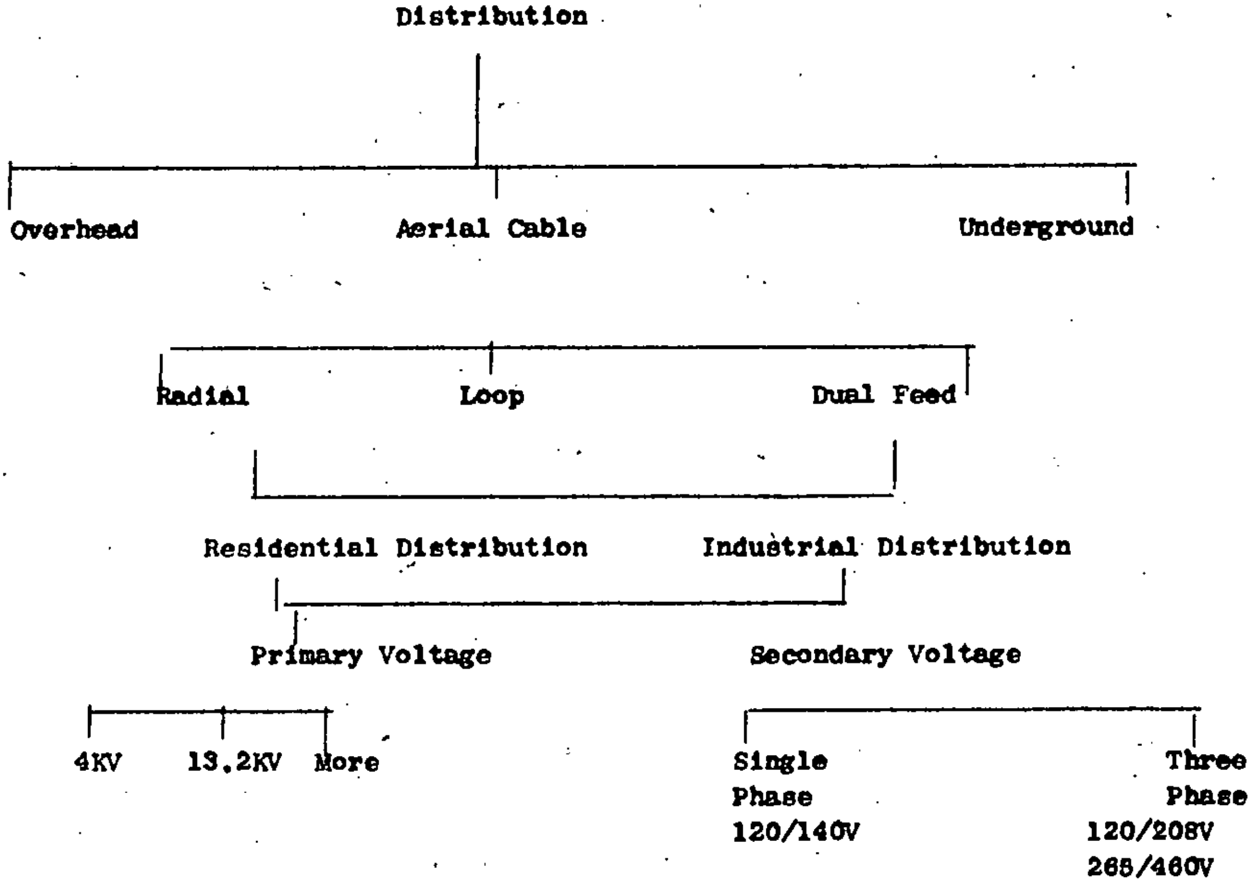
The problem of distribution of electric power becomes more complicated and the efficiency of distribution becomes more important as the electrical load increases with the growth of industry.

The author has made a critical study of the primary and secondary distribution system practices in use in the United States of America with reference in particular to the adaptation to Pakistan.

Faced with such a vast problem of studying American distribution practices, the author of necessity is forced to limit his discussion on many of the topics given below. He realizes that many accepted practices in America would not be economically feasible in Pakistan. However, many American practices and trends are recorded in the thesis since future developments may warrant their consideration.

Use is made of confidential information not available in the general literature but released to the author for this thesis; consequently, statements concerning certain practices and studies may be found in the thesis without source references. Wherever available published material or current trends are used references are given.

Since Pakistan may enjoy phenomenal growth in its distribution systems, it was deemed advisable to investigate American practices which might even be new to many areas in America.


Distribution
Overhead
Aerial Cable
Underground
Radial
Loop
Dual Feed
Residential Distribution
Industrial Distribution
Primary Voltage
Secondary Voltage
4KV
13.2KV
More
Single Phase 120/140V
Three Phase 120/208V 268/460V

II OVERHEAD ELECTRICAL DISTRIBUTION SYSTEM

In designing a distribution system, an engineer should consider the cost of the material which he is going to use. It is not always practical to use concrete or steel poles in order to obtain a permanent installation, as it may be more practical and economical to use wood poles which have been properly treated with preservatives. The price of the different materials, of course, will depend almost entirely upon the geographical location of the installations, the abundance of material at hand, freight and drayage costs, and various other expenses necessary in delivering the material to the job.

American practice has shown that material savings may be made by using bare conductor of high tensile strength. By omitting the weatherproof covering commonly used on the line conductors, approximately one third of the price of the conductor may be saved. The elimination of the weatherproof wrapping or braiding on the conductors decreases both the weight and the overall surface area of the conductor, thereby adding a greater mechanical safety factor to the construction. Another item of saving is in the labor cost where bare conductors are used for over head distribution. This difference is on account of the decreased weight and the cleanliness of the bare conductors, in addition to the labor saving devices for making splices and taps. The labor costs for bare conductors is considerably less than the labor costs for weather proof conductor. Bare-wire construction lends itself to longer spans and therefore fewer poles. Joints and splices are made on the bare wire construction by the use of splicing sleeves and solderless connections, thereby effecting a great saving over the method of soldering all joints. The cost of pulling slack on distribution systems built of bare wire is relatively small compared with the similar distribution systems where weather-proof conductor is used. In areas subject to ice loading bare conductor usage is very desirable.

In making a system more permanent, perhaps as much depends upon the method of construction or the installation of line material as upon the kind of material. Nothing can take the place of a good set of specifications for the installation of a distribution system, and established good methods should be followed unless sound engineering judgment warrants a change. This does not mean that where conditions warrant that new methods should not be tried.

The most economical voltage for an overhead distribution system in most cases is determined by the immediate load to be cared for by the system. The next thought is given to future possibilities in order to design a system with sufficient surplus capacity. Then the type of construction is chosen to fit the voltage. If the most economical voltage is chosen it must be considered in connection with an economical type of construction.

Too often the system voltage is not given sufficient consideration, and engineers have been too prone to use the voltage with which they are already acquainted. This is probably true for two reasons. One reason can be attributed to the fact that there are a number of recognized voltages which have been giving satisfactory service in the past. The other reason is that practically all the pole line material equipment has been designed to operate at these recognized voltages. Economy usually dictates the use of one of the standard voltages.

The voltage used on the first distribution systems was 220. This was considered the most economical voltage for the old direct-current systems before the advent of alternating-current distribution. The 220 volt direct-current systems served their purpose at the time they were inaugurated because there was only a small lighting load to be cared for and this load was concentrated in a very small area. As the bulk of their load increased it was found impossible to put in conductors of sufficient size to carry the load economically.

The advent of alternating-current for use on distribution systems presented the possibility of extension of the system at a very great saving in line conductors. The primary voltage for distribution systems was gradually raised from 220 volts to 1100 or 2200 volts. With additional load increase the primary distribution voltage increased to 13.2 kv with some secondary systems operating at 440 volts instead of the standard 220-110 volt system. Such system voltages not only eliminate the multiplicity of substations but also provide possibilities for future extensions either for large blocks of industrial load or for small scattered rural prospects.

√Single phase 11,500-115/230 volt distribution transformers are used on most of the 11 kv distribution systems where these systems serve a widely scattered territory. A considerable saving might be obtained by installation of the neutral and 6600-7200 volt transformers. However, in sparsely settled territories the cost of a neutral conductor amounts to more than the difference in price of the 6600 volt and 11000 volt transformers. One of the first objections which is always raised to 11 kv distribution is that the distribution transformers cost approximately 40% more than 2300 volt transformers. The greatest difference in cost of 2300 volt and 11 kv distribution systems is in the price of the protective equipment.

In the design of a distribution system, it is necessary to choose materials and methods of installation which will give the greatest safety to linemen and construction crews. This can be accomplished by providing proper clearances and safe equipment. Due thought should be given to the safety of the man who has to operate the distribution system after it is completed.

Any kind of temporary construction should be discouraged, as it is not an easy matter to replace a temporary installation while it is in operation. It must be remembered that equipment once installed is to be operated and maintained with the least possible number of interruptions to service. It must be operated and maintained to avoid hazards to life and property.

III UNDERGROUND DISTRIBUTION

Practices and Trends In Service For Residential Customers

The use of underground distribution in residential areas dates back many years. Early installations made use of the components associated with high load density design practices utilizing conduit, manholes, lead covered cables, usually paper insulated and submersible equipment. In residential areas involving relatively light load density, the cost of conventional duct and manhole type of construction cannot normally be justified and tbe use of cable suitable for direct earth burial is essential.

The latest innovation, buried cable and buried transformers without vaults, is being tried by two utilities and may extend underground distribution to areas normally supplied by overhead distribution system or aerial cable.

Factors Which Influence Demand For Underground

The tendency to use underground cable is not only influenced by the long established demand on the part of the owners and subdividers to avoid the use of poles, anchors and wires associated with overhead construction because of aesthetic considerations, but has been intensified by factors that have developed in recent years. In towns densely populated areas, overhead lines are clearly impossible. The use of curvilinear streets and irregular property lines, inherent in many new sub-division developments, have been influential in increasing the preference for underground construction in such areas because of the congestion of poles and guys required. As the cost ratio of underground and overhead construction becomes smaller, certain operational advantages of underground should be evaluated in determining its use from the utilities viewpoint.

Ordinarily, underground systems are not subject to major damage and prolonged outages during severe storms to which overhead lines are susceptible. Continuity of service in underground areas, which are in most instantances supplied from overhead lines, are often related to overhead line hazards. Generally speaking, underground lines avoid the major problems of service restoration and repairs over wide areas which are associated with overhead construction under extreme emergency conditions. Tree trimming cost constitutes one of the most important items in the installation and maintenance of overhead lines in some areas. These costs are eliminated by the use of underground distribution.

Furthermore, the underground system might be expected to have a longer life than the poles and cross-arms of an overhead system. These considerations may make the use of underground attractive in many localities.

It should be pointed out that failures do occur in underground cables and that such failures require longer repair time than that generally required on most kinds of damage to overhead conductors. However, total outages will probably be less on underground due to the smaller number of faults that occur.

General Installation Requirements

Cable installation practices vary widely from that of using conventional conduit systems to the least costly direct burial methods.

The use of conventional conduit systems, normally associated with high load density areas, for residential underground installations, has been largely replaced (in the interest of cost reduction) to an increasing extent by direct buried cables.

The trouble free operation of buried cable depends largely upon the depth of burial and the protection provided against mechanical damage. These two factors are closely related. Burial of cable deep in the ground is one of the most effective means of preventing mechanical damage. Cables should always be placed below the frost line to avoid mechanical stress resulting from heaving or shifting of the earth caused by freezing and thawing. Buried cable should be deep enough to be free from interference and possible damage from such operations as deep plowing, post hole digging, driving of fence posts, road maintenance, drainage installation, and gardening. A good covering of earth to place the cables below the level at which such interference is likely to occur provides better assurance against mechanical damage than metallic armor on the cable itself in shallow ground. For good results the depth of burial should be from 30 to 42 inches depending upon the location and the probability of mechanical disturbance. In addition to the natural protection of the earth coverage, it is highly desirable in some locations to provide further mechanical protection over the cables, such as creosoted wood planks or concrete slabs, after they have been covered with about 6 inches of backfill.

Extra protection is of particular importance at road crossings and driveways, where damage could result from driving over the cables with heavy loads. For such locations the installation of the cable in buried conduit is highly recommended. In addition to the mechanical protection provided by the conduit, it also affords a convenient means of replacing the cable without the necessity of digging up the roadway.

The most satisfactory way of installing buried cables is to lay them in a trench with proper bedding and backfill. The trench method as compared with cables installed by means of cable plow, results in less bending and distortion of the cable, less danger of stone cutting, greater uniformity in the depth of burial and better control of conditions throughout the entire length. Where cable is plowed in, there is no way of controlling the condition of the bedding and backfill since this depends entirely upon the contents of the soil.

Where cables are laid in a trench the bottom should be free from sharp stones and have a sandy loam layer at least three to four inches deep to provide a smooth bedding. The cable or cables can then be laid in the trench. If the sandy loam contains relatively large stones or pebbles, it should be screened before using under or over the cable. The sandy loam, which contains both sand and loam, provides protection from possible injury from the crushing effect of stones or rocks which sometimes occurs as the back fill settles. In addition, soil of this type tends to hold moisture and provide better heat transfer away from the cable than with sand alone or with clay alone. Sand dries out quickly as it permits water to drain off readily and clay bakes out in dry seasons and in this condition it has high thermal resistance.

Multiple primary cables, such as the three phases of a single feeder where single phase cables are used, may be layed in a trench without special attention to separation. Where more than one circuit is involved, some separation is required to permit work on one circuit with the other alive. Where primary and secondary cables are directly buried in the same trench, they can be separated by being laid on opposite sides of the trench or with the secondary 6 or more inches above the primary. The latter arrangement is probably less costly since it can be accomodated by a narrow trench and offers the advantage of the secondary cables providing some protection from the primary in case of excavation, as well as facilitating the direct connection of services without the risk of digging into the primary.

Choice of design depends primarily upon the utility's viewpoint regarding operating requirements and service quality. It is also dictated by local conditions, many of which are beyond the control of the utility, such as local governmental restriction, soil conditions, local terrain, and landscaping, as well as area layouts.

Where low cost is the objective, it is important to evaluate simplification as it effects operating, maintenance, and service restoration; particularly in view of the long term life of the installation. It is also important to consider the adaptability of the design to the load growth as capacity increases. Direct buried cable installations at minimum costs can be designed to satisfy all these requirements.

Design Objectives

What are the design objectives that should be the goal in underground residential distribution?

There are certain objectives that are common to most residential underground installation.

1. The quality of service with respect to continuity and voltage should be at least equal to that provided by the usual overhead system.

2. The component parts must be reliable and inherently protected from the operational hazards inherent in underground installations such as moisture, damage from digging, corrosion, freezing, lightning, etc.

3. The installation should make the maximum use of overhead system components such as transformers and switching equipment. This is in the interest of low cost and simplification as well as adaptability to operation by normal operating personnel, whose training and experience usually contains and centers around overhead system practices.

4. The system should be capable of serving increased loads without cable replacement throughout its useful life.

5. Service restoration normally should be made by overhead trouble-men without digging and in a minimum of time.

6. Cost should be kept to a minimum consistent with the above considerations.

Primary System

The primary voltage used in underground distribution system is that generally used for general distribution in the area.

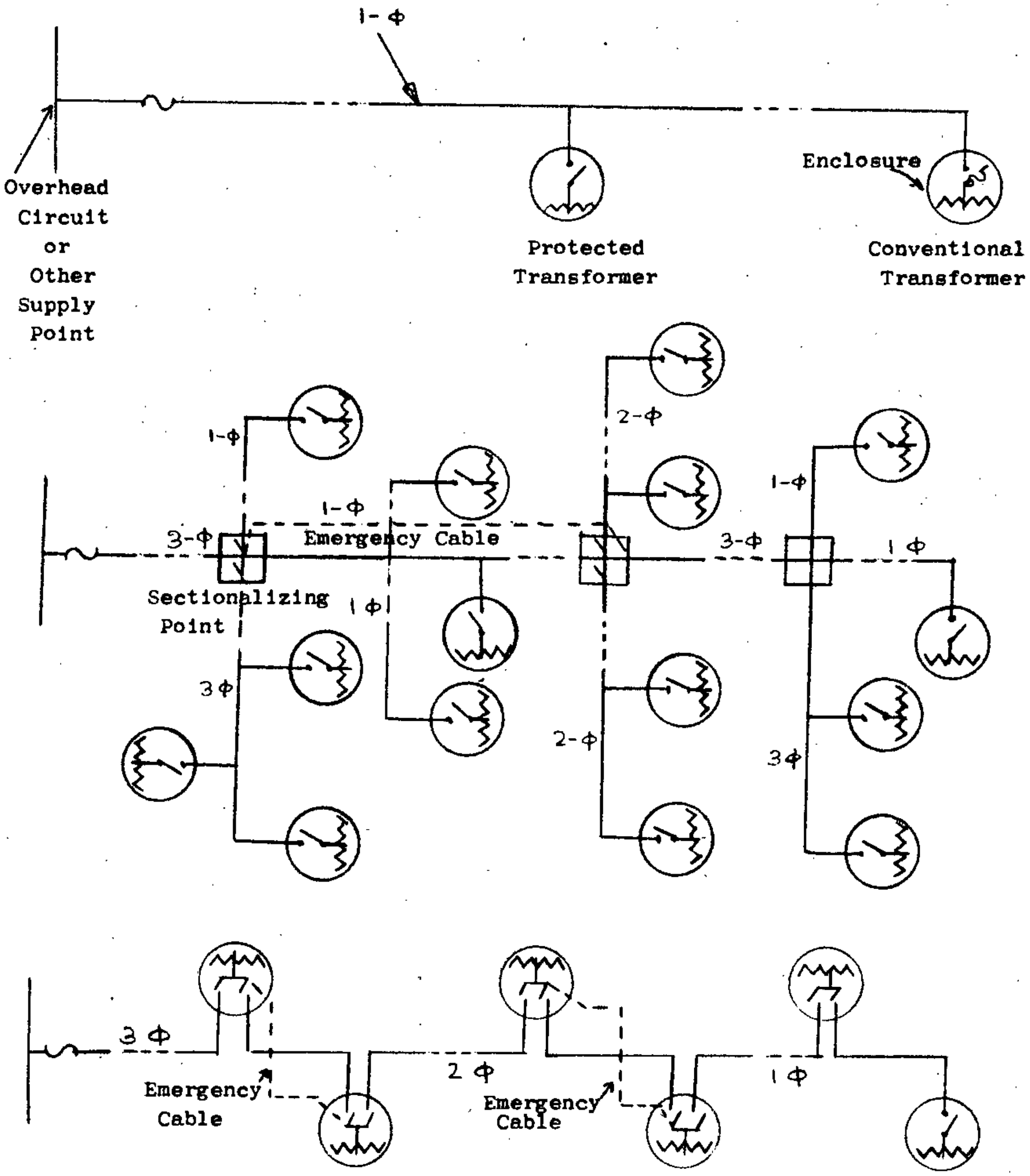
Existing installations range from 2.4 kv underground to 7.2/12 kv multi-grounded systems with by far the majority of system supplied at 2.4/4.16 kv with multi-grounded neutrals.

Underground distribution is normally confined to small areas such as a single sub-division and is usually provided by single phase branches from three phase circuits used for general service in the area. Where required by the loads, two or three phases may be used.

The general features of various circuit arrangements fall into three general categories:

1. Radial
2. Loop
3. Dual Feed.

The first of these, which is the simplest arrangement, as shown by figure 1, is similar to the familiar radial overhead layout. In this simplest form, single phase branches serve one or more transformers without sectionalizing or reserve connections at the ends of the laterals. These laterals may be more extensive with branches and sub-branches along a three phase system depending upon the extent of the area to be served and where justified by the load requirements. Sectionalizing may be provided at the lateral take-off or at frequent intervals on more extensive layouts to allow for the removal of several laterals between sectionalizing



Radial Primary Layout

Figure 1

points. It is usually considered more essential to provide sectionalizing where the main is underground than where it is overhead.

Since most underground areas are supplied from adjacent overhead lines, it is the usual practice to provide fused disconnects at the junction point to give protection to the remainder of the service area for faults on the underground.

The simple radial layout can be improved by providing sectionalizing at all transformer installations with provision for disconnecting the cable in either direction. In case of cable failure, service can be promptly restored ahead of the failure by sectionalizing, and the use of a portable emergency cable between any two transformer installations can temporarily restore service to the remainder of the load. The use of emergency cable is facilitated when single conductor cable, such as concentric, is used on such a system.

One of the most frequently used primary layout is the open primary loop as shown in figure 2. The loop arrangement provides a supply to each transformer installation from either direction and permits the prompt restoration of operation. The two ends of the loop are usually supplied at different points. These points may be on different circuits, or, if single phase, from different phases of the same circuit. The additional cable

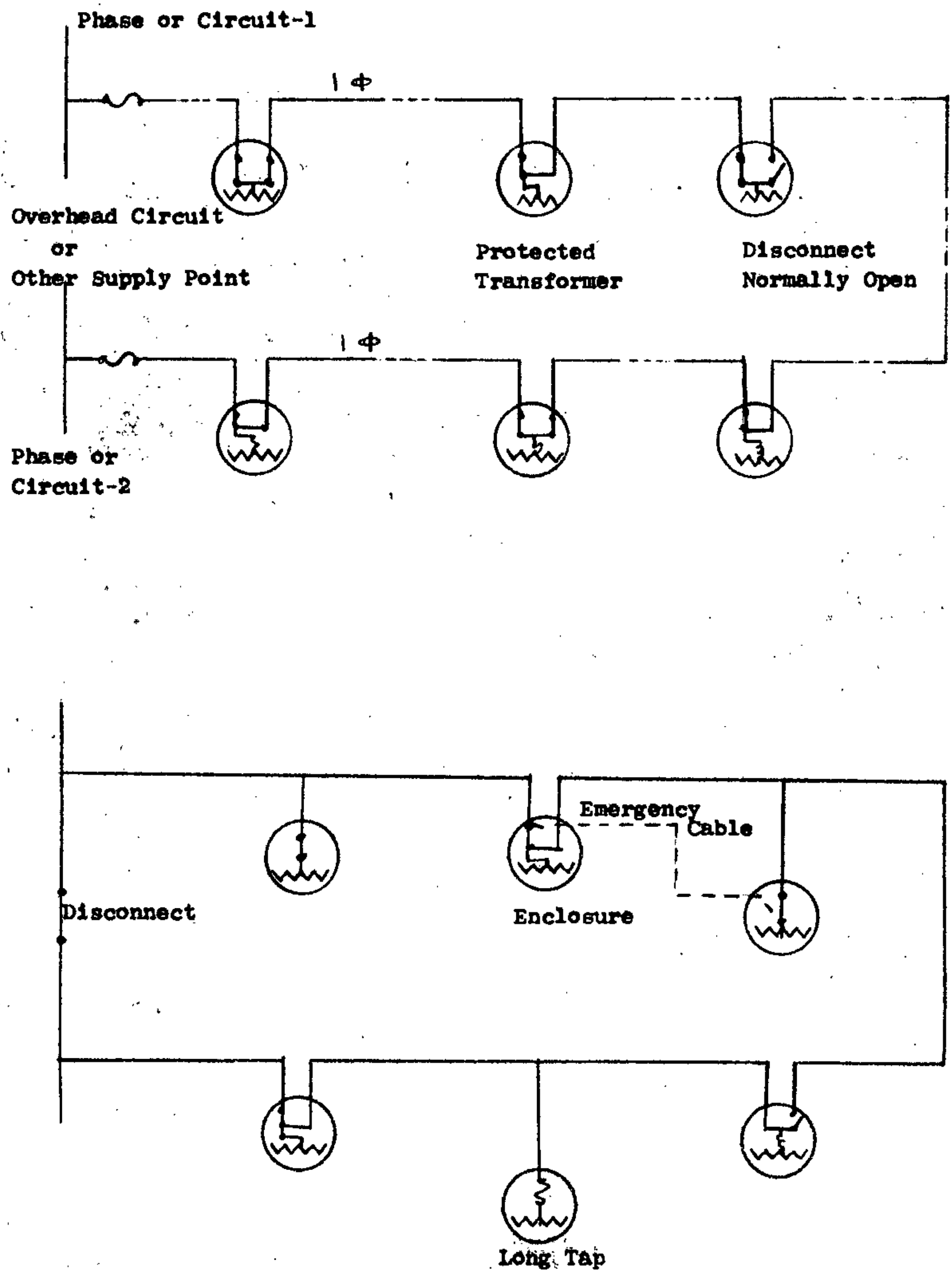


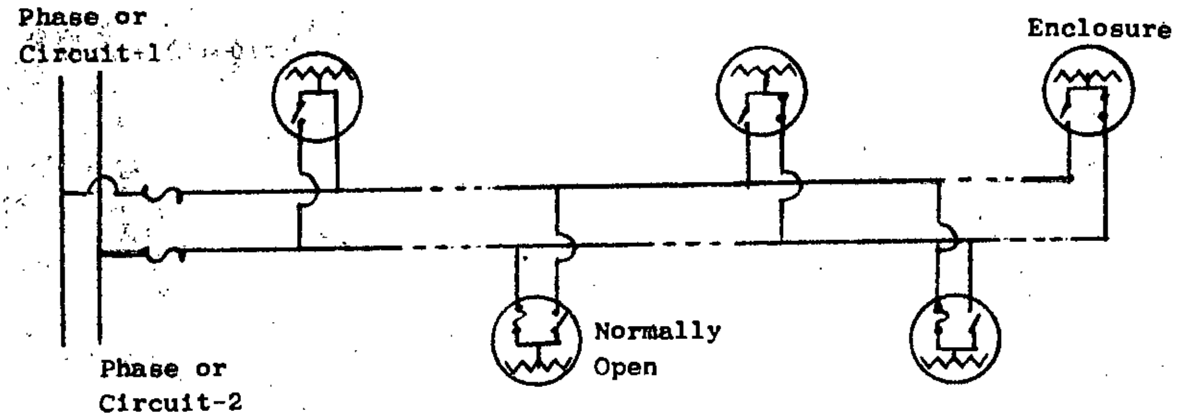
Fig. 2 Loop Primary Layout

required to supply loop service over that under the simple radial layout is usually nominal and may be adequately justified by the improvement in operation provided.

One arrangement which will provide some savings in investment is to alternately loop and tap adjacent transformers. This is particularly true where the transformers are located at a distance from the cable run. Under this arrangement, the tapped transformer is subject to interruption for cable failure between two adjacent looped transformers and the use of the temporary cable must be resorted to for service restoration.

Another arrangement which is also used in the primary circuit is shown in figure 3. This arrangement, which may be used under certain circumstances, provides duplicate feeds to each transformer location with facilities to switch each transformer, manually, from the normal to its alternate cable supply. In some instances, two cables might be available for such use along the same route and separate phases of a three phase circuit could be used where the circuit is made up of separate cables for each phase. It is doubtful if this arrangement can be justified if the two cables have to be provided as a part of the installation. Also under this arrangement, the number of transformers must be limited because of the excessive amount of time required for switching at all transformer locations.

DUAL FEED PRIMARY LAYOUT



Half of Transformers Normally
Feed From Each Circuit.

Figure 3

Remarks

Many variations of these three basic arrangements are possible and the choice of the plan is dependent on the relation between the cost of additional refinements and the benefits they will provide. The benefits that must be evaluated are improvement in quality of service as related to operating time for service restoration, and operating manpower requirement.

The industry tendency is toward some form of loop arrangement with two way supply, since it appears that such a system most economically provides the degree of service continuity consistent with the requirements of most utilities.

Primary Cable

The types of cable used in residential underground distribution systems depend mostly upon the methods of installation, as previously discussed, but is also influenced by the established practices of the individual utility.

Present practice throughout the United States generally makes use of some type of single conductor cable, although there are some installations of multiple conductors. Types of conductors vary from lead and paper or lead and cambric through all the various types of rubber and synthetic compound installations. Lead sheathed cables are generally installed in some form of duct system and are not normally directly buried unless constructed with a jacket over the lead. There is a trend in the newer installations to use of ozone resistant rubber with a neoprene jacket for use in duct or direct burial.

A considerable amount of concentric cable is in use and its use, both for direct burial and in ducts, is increasing. This cable, insulated with rubber, and having a neoprene jacket, is used in the 5 kv class. It is similar to single conductor cable but is classified as a two conductor cable.

An important advantage in the use of rubber or synthetic compound insulated cables, or cables without shielding taps at 5 kv, is the simplicity of termination. Overhead type equipment, such as porcelain box cut-outs, may be used at transformer installations and sectionalizing points. This results in lower costs and improved operating procedures, by crews trained in the use of overhead equipment, as compared to the usual type of termination and expansive switching facilities required with metallic sheathed paper or cambric insulated cables.

A recent development which holds promise of considerable cost reduction is the low cost moulded thermoplastic cable splice which is available in kit form for use in non-metallic sheath cable. Its use eliminates the need for joint taping and results in a considerable reduction in labour costs. After making the proper connection, a mould is fitted over the joint area and filled with a compound which, through chemical action, fills the mould and insulates the complete splice. Its use is particularly adaptable to single conductor cable and is adequate for direct burial.

Secondary System

The load circuits or secondary mains from which consumer services are tapped generally follow the geographical pattern of the load area because the mains are located under the streets or alleys in the area so that the services to the consumer can be as short as possible. This arrangement facilitates access to the mains for repairs, maintenance, and service connections. In underground systems the secondary main as well as other circuits are generally carried in duct systems and the service connections are made in manholes, vaults, or shallow junction boxes. At the inter-connections of the secondary mains the corresponding phase conductors of the intersecting mains are connected together so that, in most city areas where the low-voltage secondary work is applicable, the system of secondary mains takes the form of a grid. In an ideal case the grid forms a regular pattern such as shown in figure 4.

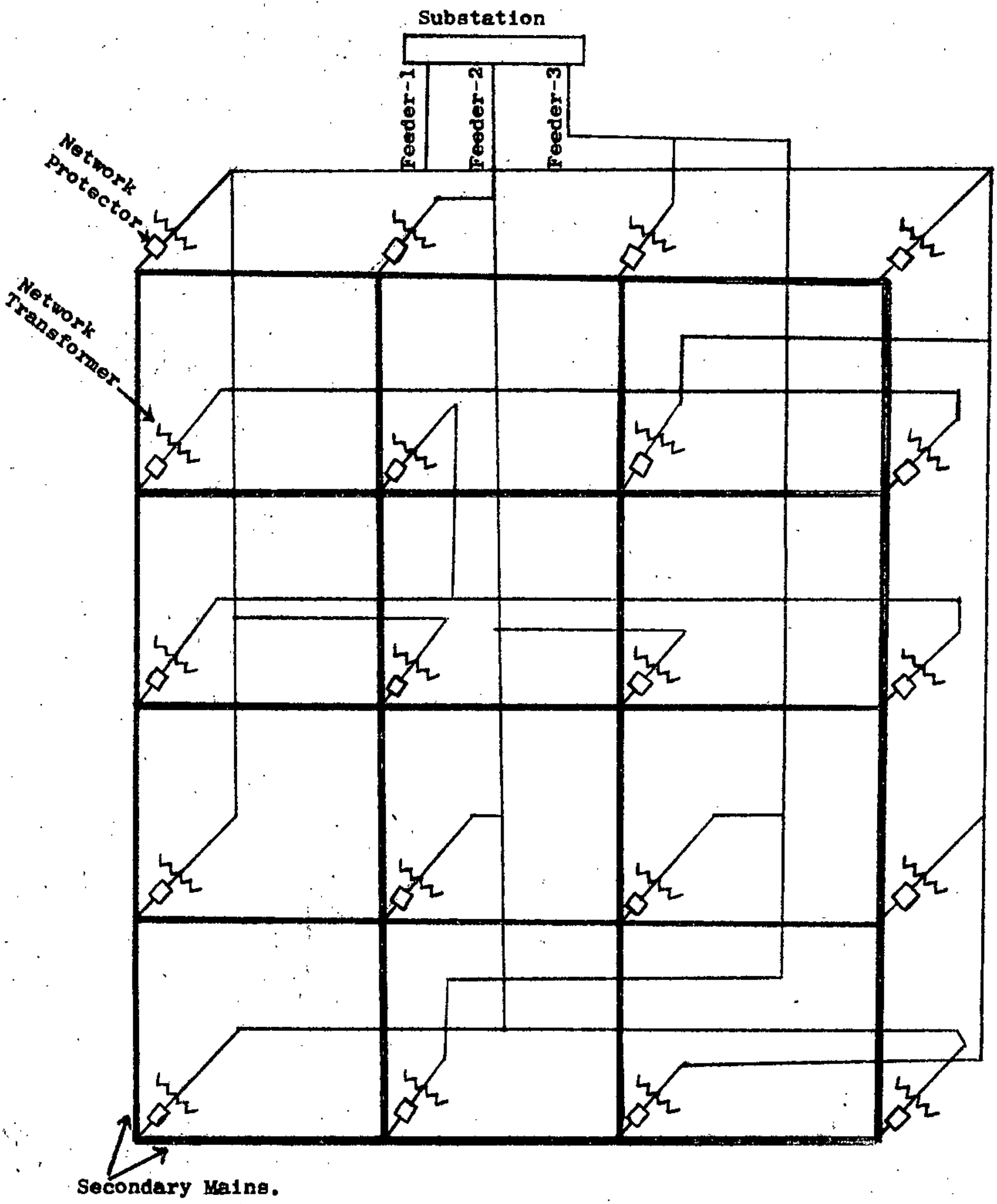


Fig. 4 Schematic Diagram Showing the Basic Arrangement Of Primary Feeders, Network Transformers, and Secondary Mains In a Low Voltage Secondary Network.

Single phase, three wires 120/240 volt secondary circuits with grounded neutral is the general practice throughout the United States. However, in some areas three phase four wire Y 127/208 volt secondary is being used where heavy load concentrations are being experienced. Three phase power load and single phase lighting load are readily served from such a system. In the future 240/480 volt three wire secondary might also be provided to serve heavy residential loads.

The layout of the underground secondary is much the same as that used on overhead. Radial secondaries are used predominently but there has been some use of banking and looping. These latter arrangements are justified by improved regulation and reduced motor starting flicker.

The advantages of single phase banked secondaries over the radial system becomes more important underground. It not only provides the usual advantages of diversifying loads between transformers, thereby permitting smaller installed capacity, improved normal voltage levels, and reduced flicker which is a factor in spacing between transformers, but it also provides capacity to handle new and growing loads. Cables, once buried, are expensive to replace if it is found that conductor size is inadequate. The use of a double breaker self protected transformer constitutes a most desirable method, from a cost standpoint, of banking underground secondaries, although fused tie points installed above ground between adjacent transformers may be used.

Secondary and Service Cable

In underground systems the secondary mains generally are made up of single-conductor cables because of many interconnections and service taps required in a secondary network can be made more easily and less expensively on single-conductor cables than multi-conductor cables. Within the last decade, improved insulating materials have resulted in extensive use of non-metallic sheathed cables because splices can be made more easily and less expensively on single-conductor cables than multi-conductor cables. Within the last decade, improved insulating materials have resulted in extensive use of non-metallic sheathed cables because splices can be made more easily. Although three conductor cables generally are not used, it is common practice to twist all the conductors of a three phase circuit together to keep to a minimum the reactance of the circuit and thus improve voltage regulation.

The size of the conductors in the secondary main depends primarily on the required carrying capacity. However, the voltage drop from a transformer to any load along the mains under normal operating conditions should not exceed about two percent.

The conductor sizes most frequently used in underground low-voltage networks are 4/0 and 250-, 350-, and 500-MCM. However, because of relatively high voltage drop, difficulty of handling and the difficulty of burning clear faults on 500-MCM cable, two 4/0 or 250-MCM cables in parallel are frequently used in place of one 500-MCM conductor.

Conclusion on Underground System

Underground residential distribution costs vary from about 1.5 to as much as 10 times those of an overhead system required to serve the same area. This variation is dependent upon the practices of the individual utility with regard to overhead standards as well as the underground design standards acceptable in the particular locality. By the utilization of available components and simplified installation practices, and operating standards and requirements, underground 4 kv residential distribution can be provided in most localities at costs in the range of 2 to 2.5 times that required for an equivalent overhead supply.

With the ever increasing demand for and increased utilization of electric service, coupled with the public demand for service improvements and improved appearances of utility service facilities, future use of underground distribution in residential areas will undoubtedly increase substantially.

IV AERIAL CABLE

The real economies of aerial cable become more apparent when compared with open wire on the basis of dollars per KVA of load area coverage instead of on the cost per mile of line.

This point is often overlooked while emphasis is being placed on the more obvious advantages of improved appearance, greater reliability, and reduced tree trimming.

When open wire construction costs are compared with those for aerial cable, mile for mile the aerial cable costs from 50 to 150% more, the exact percentage figure depending on local conditions and what items are included in the total outlay.

But such a comparison leaves unrevealed an important part of the economic picture. It fails to take into account the greater load carrying ability of aerial cable construction on voltage limited circuits.

Cable Size Important

Much of the voltage drop in an open-wire feeder is the result of line reactance. The ratio of reactance to resistance increases directly with conductor size and spacing. For a 4/0 open-wire line with an equivalent delta spacing of 33.6 inches, a conductor size representative of the construction often used on 6 KV premary feeder mains, the ratio is about 2-1.

It is not customary to transpose the phase conductors on primary circuits. Hence, the reactance and effective resistance and consequently the voltage drop in the line, is different for each phase. The limiting load on a voltage limited circuit is determined by the voltage drop in the phase with the greatest impedance.

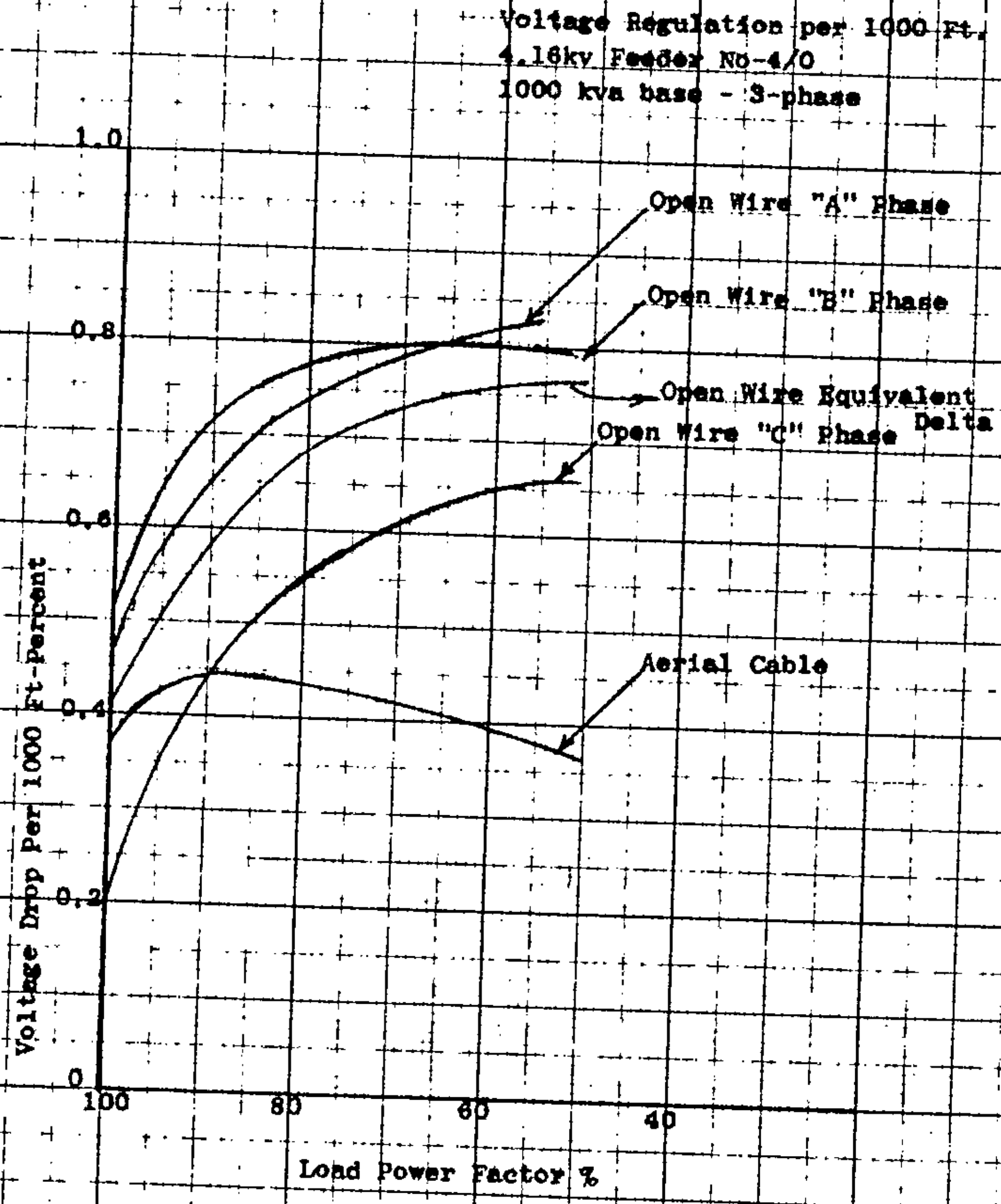


Fig. 3 Voltage Drop In Aerial Cable and In Open Wire of Corresponding Sizes Is Charted As A Faction of Load Power Factor

Figure 5 shows the spread in voltage drop in the various phases of a 4-KV feeder with 4/0 open-wire conductor as a function of the load power factor.

Voltage Regulation Better

The conductors of a 3-phase aerial cable are closely grouped in equilateral triangular formation. This arrangement results in balanced reactances much lower in value than those obtained with open-wire construction. This improves voltage regulation.

For the larger conductor sizes the resistance is low, and the reactance becomes a considerable part of the circuit impedance. Thus aerial cable becomes more advantageous as the conductor size increases.

Figure 5 also shows a comparison of the voltage drop in 4/0 aerial cable feeders with the voltage drop in 4/0 open wire feeders. Thus it is shown graphically that aerial cable becomes more advantageous as the load power factor decreases.

Comparison of Load Carrying Ability
At 4.16 KV of 4/0 Aerial Cable
With 4/0 Open Wire With
Equal Percent Drop.

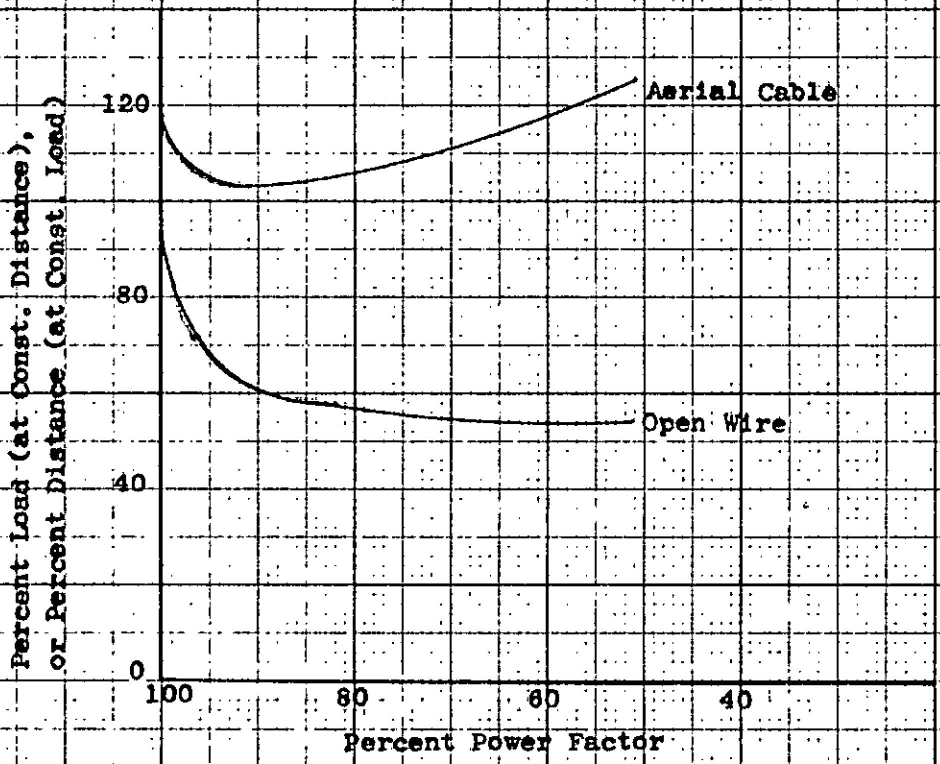


Fig. 6 Lower Voltage Drop Affords An Edge In Load Carrying Ability. Load and Distance Are Shown As Functions Of Power Factor.

Load Carrying Greater

Figure 6 illustrates the greater load carrying ability of aerial cable for voltage limited feeders. Aerial cable's lower voltage drop will carry the same load further, or a greater load the same distance.

Power factor effects the load carrying ability of aerial cable less than it does that of open wire. In fact the load that can be carried via aerial cable increases as the power factor drops below about 85%.

Some new residential loads coming on power systems today have very low power factors. As this trend continues, the greater load capability of aerial cable should prove even more important in the future.

Best Application

Three phase primary mains afford the most attractive application of aerial cable. On these the largest conductor sizes are used and consequently in this usage lies the greatest opportunity to increase feeder load carrying capability. Other advantages of aerial cable take on importance in this field.

Service reliability is most critical on the mains. An outage here effects all or most of the customers on a feeder, while an outage on a simple phase lateral effects only a rela tively few customers.

Tree-trimming expense is greatest where large space is required for open-wire, 3-phase circuits. Trees must be trimmed around aerial cable, but the amount of trimming is reduced. Aerial cable used for primary mains has an attractive appearance and relieves congestion on lines carrying more than one feeder.

An important consideration for any utility company is the fact that aerial cable reduces the chances of trouble spreading from feeder to feeder. Aerial cable will and has given continuous operation when knocked down from the messenger and totally submerged in water.

Secondary networks with units in underground vaults and aerial cable secondaries along the street can solve the distribution problems in small business districts. For small and medium sized cities and for the outlying shopping centers around different areas such combined light and power net work minimizes the congestion of conventional overhead service. Moreover, this system facilitates conversion to underground network if future growth demands removal of poles and wires.

Small business areas generally are supplied from 4 KV overhead radial feeders with separate power and light transformers, secondaries, and services. Many buildings require both power and lighting services. Over the years, increasing load has required more and larger transformers at closer spacing. Pole congestion and the maze of overhead wires not only impede pole replacement and maintenance but promote municipal demands for underground distribution.

Long range forecasts in many cases do not justify conversion to a completely underground secondary network capable of serving the high load densities of many areas. A solution of this problem is a secondary network with units in underground vaults and aerial cable secondaries on poles along both sides of the street.

Some of the high-lights of the system are: (1) Vaults are located directly in front of largest loads with underground cable ties between vaults on opposite sides of the street; (2) Short underground services from the vault to nearby loads and riser cable feeding aerial secondary for the other loads still remaining; (3) 500 KVA Network units and 350 MCM secondary cables produce a system capable of handling 25 to 50 KVA of load per 100 feet on each side of the street; (4) If the need for a fully underground secondary network system develops, network voltage has been established, and the already installed underground equipment can be fully utilized.

Network Combines Overhead and Underground

The combination of overhead and underground cable secondaries with network units in vaults will satisfy the demand for improved appearances in many cases. Three phase aerial cable secondary mains on each side of the street replace the separate light and power wires. A few larger transformers in vaults eliminate many pole-mounted lighting transformers and power banks to improve greatly the appearance of the overhead system. Further improvement in appearance and reliability may be attained by using aerial cable for the primary feeders.

Vaults on opposite sides of the street should be tied together with underground cables. The network protection then functions to permit each unit to back up the other in emergency.

Aerial Cable Affords Flexibility

(1) The cost of a few test installations of aerial secondary cable was 1.49% below that of the conventional type.

(2) The cable secondary system appears to be more resistant to wind and ice storms than open wire construction.

Maintenance Less

(3) As cable secondary design requires fewer poles, maintenance cost per KVA of customers served is reduced and along with it the occasions for disturbing a customer's premises for pole replacement.

(4) Physical characteristics of the line improves and the cable withstands more wind than open wire and even it comes down sometimes maintains service.

(5) It has better electrical characteristics than open-wire construction, steady voltage drop reduces to 80% and flicker voltage drop to 50%. Such improvements afford higher quality service and permit use of large transformers.

Faults Are Fewer

(6) More clearance for services is available as a service can be attached at any point. Service poles for clearing buildings or other obstructions are no longer necessary.

(7) Neoprene-covered secondary cable is less subject to faults caused by tree conditions which themselves are obstructive because of the greater flexibility in locating services.

Has Extra Clearance

(8) Replacing a tangent pole costs considerably less. It does not involve work on the services. When secondaries are open wire, some service must be rearranged during transfer to a new pole. Moreover, the pole for cabled secondaries is clear for hot-stick work in transferring primaries.

(9) Extra clearance for transformer replacements is available because service connections can be kept away from the pole.

Compared with open-wire construction there are these advantages in the use of aerial cable secondaries.

1. Although fewer, faults are difficult to locate and the different companies have yet to acquire "trouble-shooting" experience with this relatively new construction.

2. Aerial cable installation requires a special spinning tool for lashing in the field.

3. Operation of spinner requires special training of personnel.

4. As aerial cable is 20 to 30 feet above ground, making service connections in any sort of wind necessarily involves use

of the long extension ladder with hooks at the upper end.

Other Disadvantages

5. The present method of installing services costs a little more.

6. Adding a fourth wire for 3-phase service or as a streetlight conductor is more difficult.

7. Additional anchoring and keeping the same pole location make replacement of dead-end poles more expensive.

More Training Needed

8. Two or more men are needed to locate and repair secondary faults.

9. As services are connected to the line, there is less service clearance from the ground. Service clearance still exceeds the minimum code requirements, and the services themselves are usually shorter.

10. Secondary cable system installation and maintenance call for new training of service crews.

Competitive Position

Aerial cable can compete with open-wire construction in areas where it can use its greater load carrying ability to advantage. Where local costs are low the cost ratio drops below that assumed in the calculations, and the cost differential is considerably reduced. Then reliability, appearance, service continuity and the tree-trimming element becomes the basis of comparison. These may justify the remaining cost differential.

This study was based on 4.16 KV distribution as this system is widely used and is quite vulnerable to tree interference. Aerial cable is easily applied to 4.16 KV.

Aerial cable for distribution feeders is not limited to 4.16 KV. It may also be used at 12.0 KV and 13.2 KV. At these voltage levels shielded cable is required and this increases the difficulty of making taps. The advantages resulting from the extra load carrying ability of aerial cable are also present at the higher voltages.

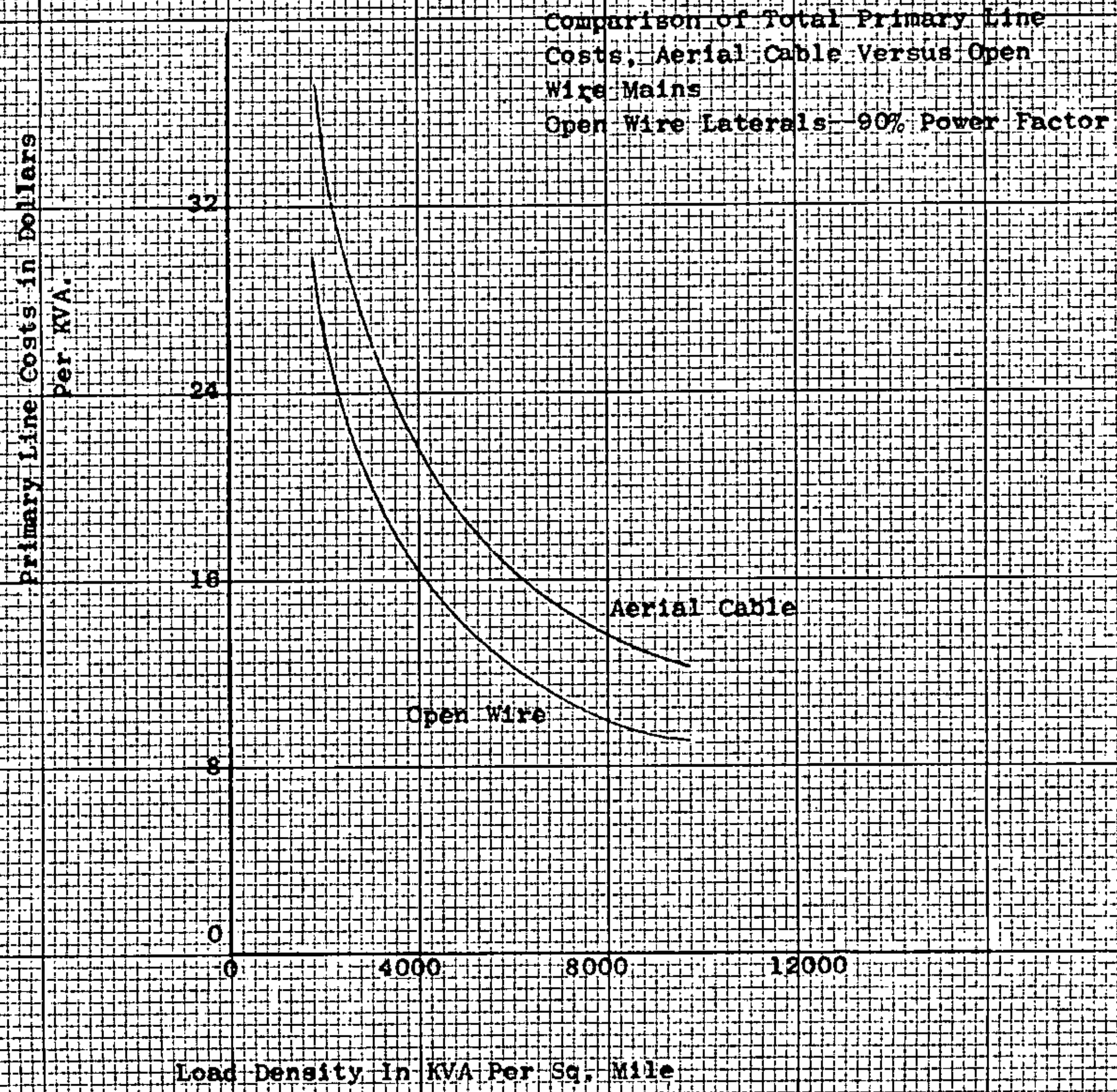


Fig. 7 Total Costs of Primary Lines In Dollars Per KVA Are Functions Of Load Density When A 90% Power Factor Is Assumed Constant.

Comparison Of Total Primary Line And Substation Costs--Aerial Cable Versus Open Wire Mains--Open Wire Laterals 90% Power Factor

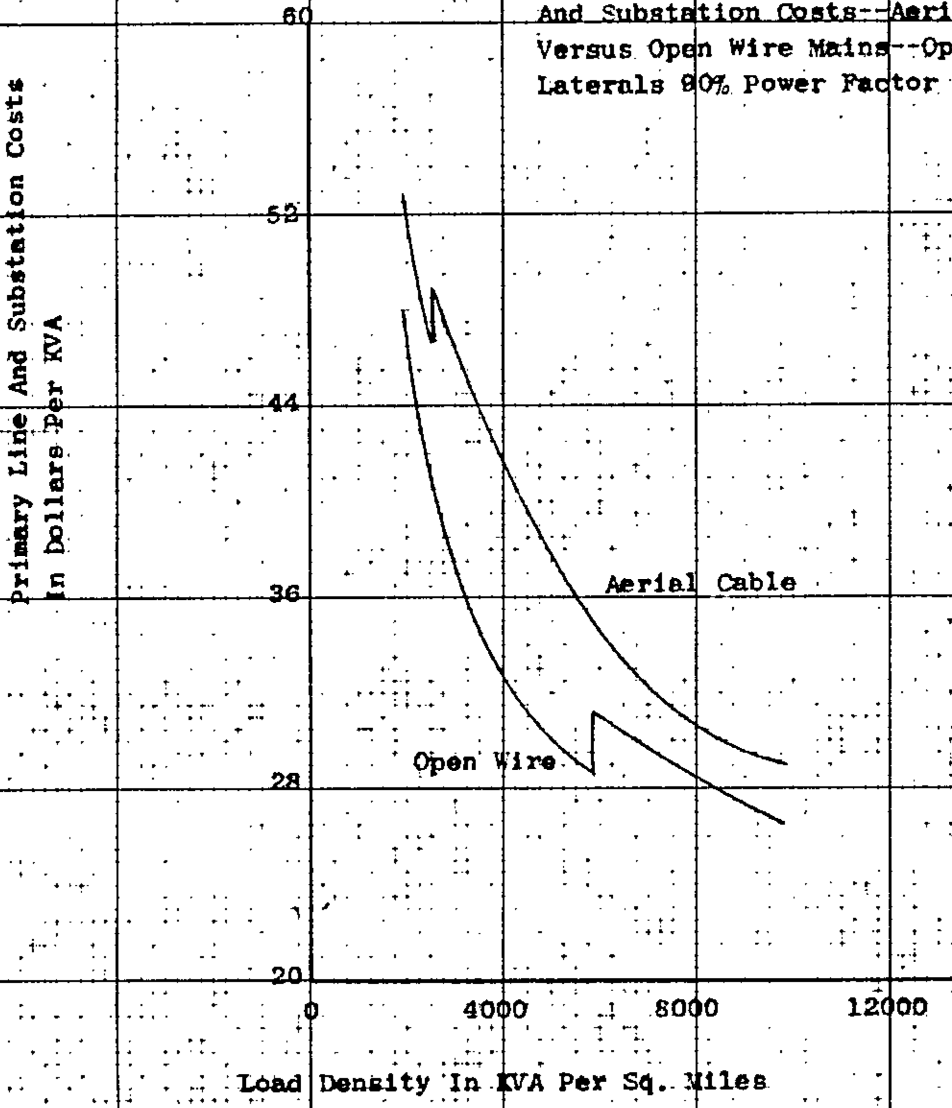


Fig. 8 Substation Costs Are Correlated With Total Expenditures For Primary Lines In Dollars Per KVA, And Breaker Positions Are Provided.

V RESIDENTIAL DISTRIBUTION

The present, and long-standing, distribution system for residential service in the United States is the 120/140 volt three wire system, which could conceivably continue to be used indefinitely. However, conditions have changed materially from the time this system first became standard, and developments are on the horizon which can be expected to produce large increases in residential load in the future. The plant investment in residential distribution systems is estimated currently at 20% (percent) of the total investment of the budget for the electrical utilities. The indications are that this investment will continue to grow, both in percentage and dollar value. The residential distribution is the most important single problem facing the electrical utility industry today. The time is ripe for a decision with respect to new construction as to whether a fundamental change shall be made in distribution systems or whether present practices should be continued.

What are the advantages in distribution economy resulting from the use of higher voltages? The most obvious advantage is that the distribution secondaries and service drops can use small copper. It might further appear that there is no other saving but this. However, reduction of copper cross-section is not the whole answer, as this involves only the thermal capacity of the citcuits. In most practical situations, regulation is more important in influencing costs than thermal capacity.

The determining regulation may be voltage dip due to motor starting or it may be the spread in service entrance voltage from light load to full load. Which one of these forms of regulation is determining from a cost standpoint can be ascertained only by analyzing the particular situation. Both forms of regulation are improved according to the square of the operating voltage, for a given conductor size and given kilo-volt amperes of load. Thermal loading is improved only according to the first power of voltage.

If the secondary voltage level is changed, the proportioning of the system will change. The improvement in voltage regulation permits a greater "reach", i.e., a given distribution transformer can serve more residences. It then has a higher kilovolt-ampere rating with lower cost per kilovolt ampere. It also suffers a smaller drop in voltage from motor starting inrushes, which minimize another limitation on system design. Another and important advantage occuring to higher voltage and greater "gathering power" is the improvement is diversity due to summing up of individual home demands.

It should be noted that the following results sum up the advantages of going to a higher secondary voltage:

1. Saving in secondary and service entrance copper.

2. Reduction in total installed kilovolt amperes of distribution transformers.

3. Reduction in cost per kilovolt ampere of installed transformer capacity due to the use of larger standard transformer.

Economy of 3 Phase Secondaries

To evaluate the relative economy of 3-phase and single phase distribution secondaries, it is first necessary to consider the role of the grounded neutral conductor on both types of system. Theoretically, it might seem possible to omit the neutral conductor on both the 3-phase and single phase systems. Thus the mid-point of a 120/240 volt transformer could be grounded, and only the two outside wires carried away as secondaries. At each home the house circuits would consist of a connection to ground and to one or the other of the outside wires. Unbalances due to differences in loading of the two outside wires would be expected to find their way back to the transformer mid-point via ground.

With street water mains and house service water connections both of copper with soldered joints, this system should be workable, although it can be expected that the voltage regulation from line conductor to neutral will be higher than when a neutral conductor is used.

Rightly or wrongly, the utilities have settled upon the practice of not depending upon water pipes for the return of neutral currents, and neutral conductors of the same size as the line conductors are frequently used. The neutral conductor may be common to both the primary and secondary systems. Consider the case of a neutral used for secondaries only. With unit current in each line wire and unit voltage to neutral, the power capacity of the single 3-wire system is two or two thirds of a power unit per conductor. In a similar manner, a 3 phase 4-wire system has three units of power handling ability, or three fourths of a power unit per conductor. Under the most favorable conditions, the 3-phase system permits a maximum improvement of copper utilization by the ratio of three-fourths to two thirds or 1.125. On the other hand, neglecting the neutral in the single and three-phase systems results in no gain in utilization of copper. The actual gain on the three phase system is therefore somewhere between zero and 0.125, depending upon the actual role of the neutral conductor in the system under consideration. Therefore a three-phase four-wire system is as much as 12½% more efficient in use of secondary copper than a single phase three wire system. If a higher secondary voltage than the present 120/240 volt standard is used, the general concept of distribution system design is changed, leading to larger transformers at wider spacings. The individual transformers may be as large as 250 k.v.a. with present load densities to over 2000 k.v.a. for communities saturated with heat pumps.

Different Types of Distribution

System-1 is the conventional radial system used to provide single phase 120/240 volt service in most residential areas today. Figure 9 is a single line diagram of this system.

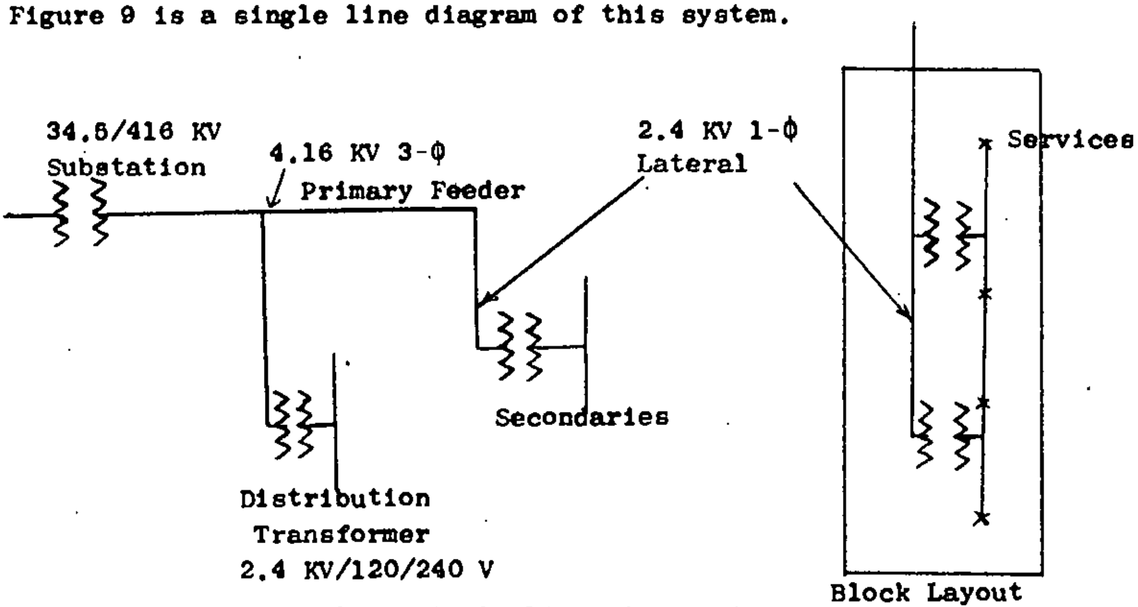


Fig. 9 Single Line Diagram For Conventional 120/240 Volt Radial System.

In the studies made using this system arrangement, the distribution substations were assumed to step down from a subtransmission voltage to a distribution voltage of 4.16 kv three-phase distribution circuits run through the area and are sectionalized so as to provide loop feed under emergency conditions. Single-phase 2400 volt laterals were tapped off the 4160 volt feeders, and run down the back lot line of each block to supply the single phase distribution transformers. Single phase three-wire 120/240 volt secondary circuits run in two directions from the transformers to the service take-off points.

System 2 provides single phase 120/240 volt service through distribution transformers supplied by single phase common neutral laterals from 24.5 kv 3-phase primary feeders. This is shown in figure 10.

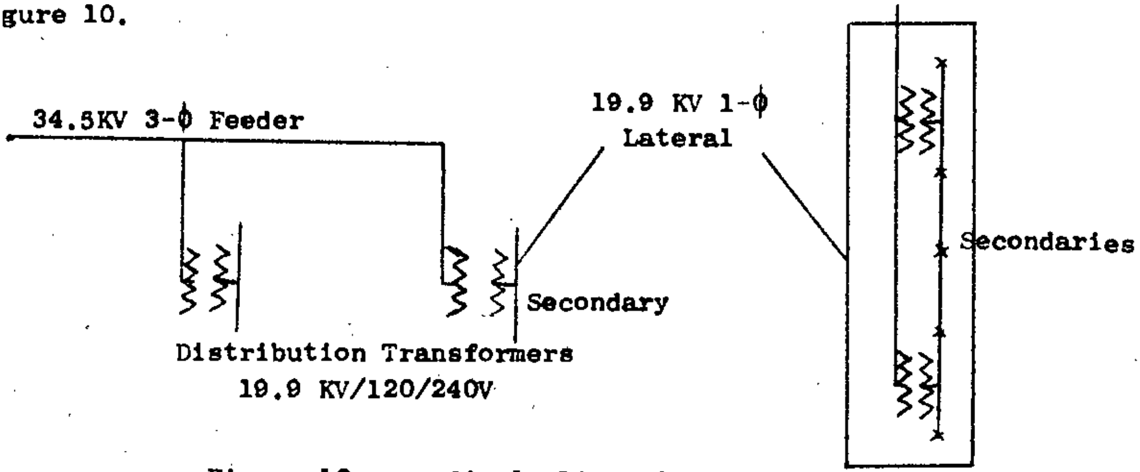


Figure 10 Single Line Diagram For Higher Primary Voltage Conventional 120/240 Volt Radial System.

*If three-phase 120/208 volt secondaries used, laterals would be 3-phase 34.5 kv, and distribution transformers 34.5 kv 120/208 volt.

The 34.5 kv circuits are sectionalized so as to provide loop service under emergency conditions.

Section 3 provides 3-phase 4-wire 120/208 volt secondaries served from 3-phase distribution transformers supplied from 34.5 kv primary circuits; see figure 10, sectionalized loop primary feeders are used.

System 4 uses 265/460 volts as the secondary voltage. The long three phase 4-wire secondary circuits made possible by the higher voltage permit more load to be served by a single transformer. In this system shown in figure 11, the large three-phase transformers are supplied from a 3-phase primary operating at a voltage in the 34.5 class. The secondary circuits carry power away from the transformers in four directions. The primary feeders provide loop supply.

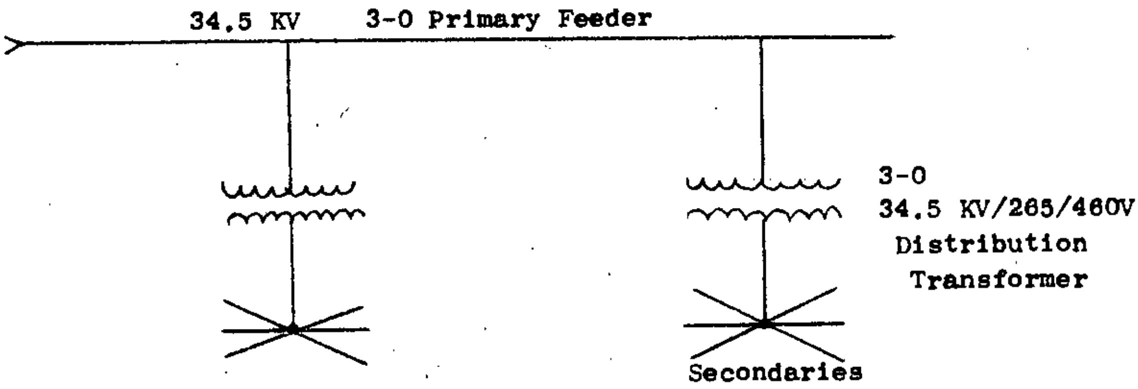


Fig. 11 Single Line Diagram For Higher Secondary Voltage Radial System

*If single phase 240/480 volt secondaries used, distribution transformers would be 34.5 kv 240/480 volts.

System 5 makes use of a higher single phase secondary voltage. The 3-wire 240/480 volt secondaries are served through relatively large transformers as shown in figure 11. The secondaries run in four directions from the transformer. The transformers are 3-phase with each phase on the secondary side center tapped and isolated from the other two phases. The primary voltage for the system is in the 34.5 kv class. These primary feeders provide loop supply. The 265/460 volt is not the only higher voltage to use. Other 3-phase voltages that could be considered for this type of an application are those of 220/380, 240/416, and 254/440.

Services

The service to each house for the conventional 120/240 volt system is the well-known 3-wire service for both overhead or underground systems. For the higher voltage secondary systems, whether single-phase 240/280 volt, or 3-phase 265/460 volt, a 2 wire service is used. The two wires are a line conductor and a neutral. The service entrance facilities for the higher voltage system are shown in figure 12.

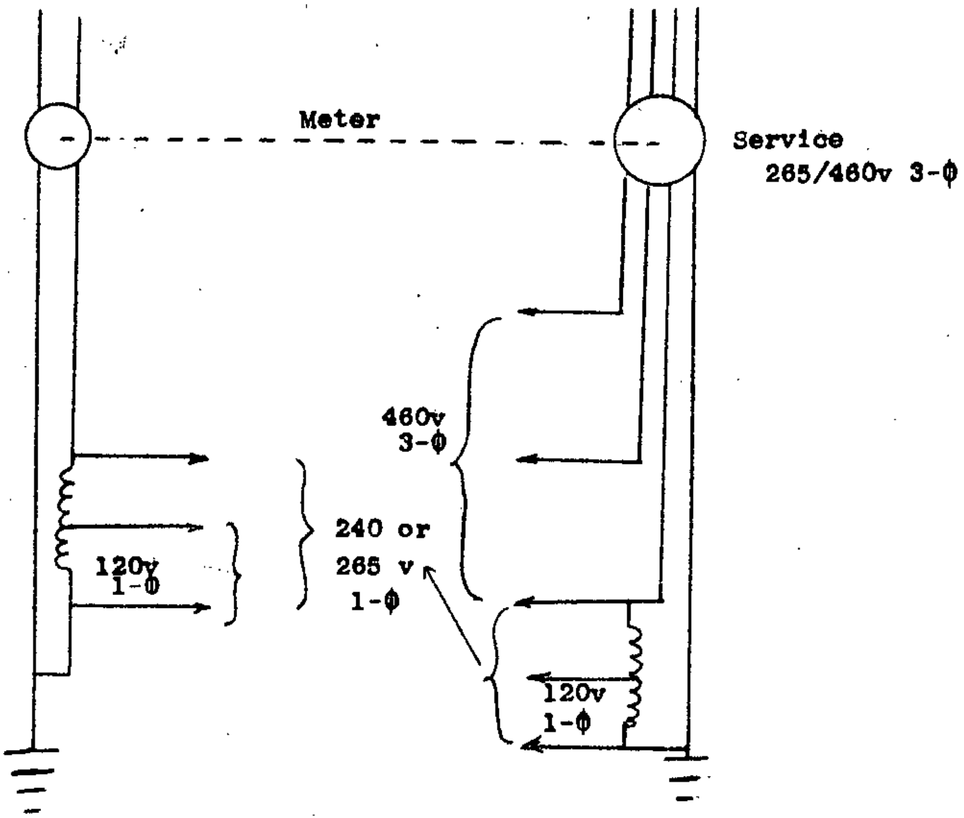


Fig. 12 Service Entrance Facilities For Residences, Higher Secondary Voltage System.

All houses served from 240 volt or 265 volt secondaries will have an auto-transformer to step down to 120 volts for lighting and convenience outlet circuits. The higher single-phase voltage (240 or 265 volts), is assumed to serve all the fixed high-voltage appliances such as ranges, water heaters, clothes dryers, and room coolers. These appliances will not be served through the auto-transformers.

Cost Data

The costs used in the studies are believed to be reasonably typical of the costs for many operating companies.

Overhead

Large distribution substations were employed in the conventional 120/240 volt system using 4-kv primary feeders. The substation stepped down from the subtransmission voltage of 34.5 kv to 4.16 kv.

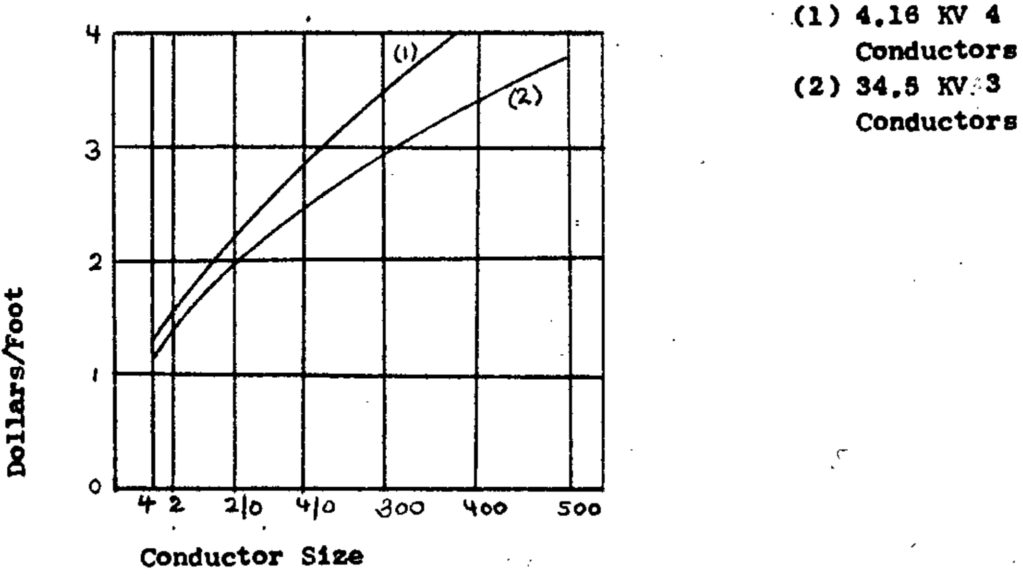


Figure 13 shows the cost of the overhead primary circuits. The figure includes both 4.16 kv and 34.5 kv primary circuits. Figure 14 shows the cost data of 3-wire and 4-wire secondary circuits. Full sized neutrals are carried for all low-voltage circuits whether single phase or 3-phase.

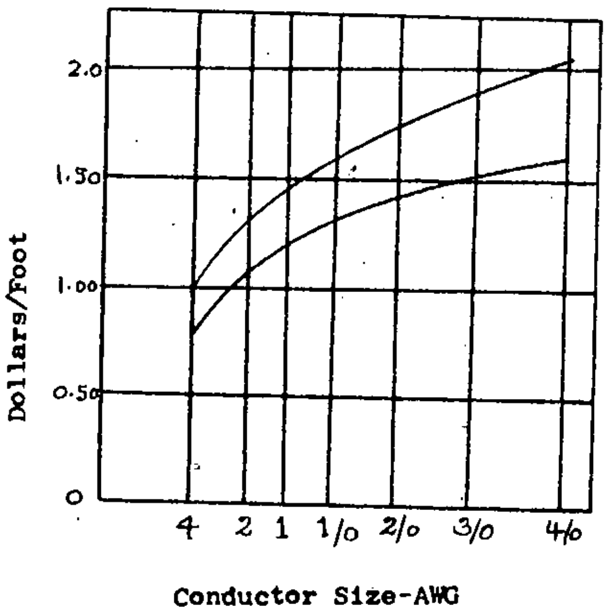


Fig. 14 Overhead Secondary Installed Costs, Including Poles

The installation costs of distribution transformers used in the conventional system are given in Figure 15.

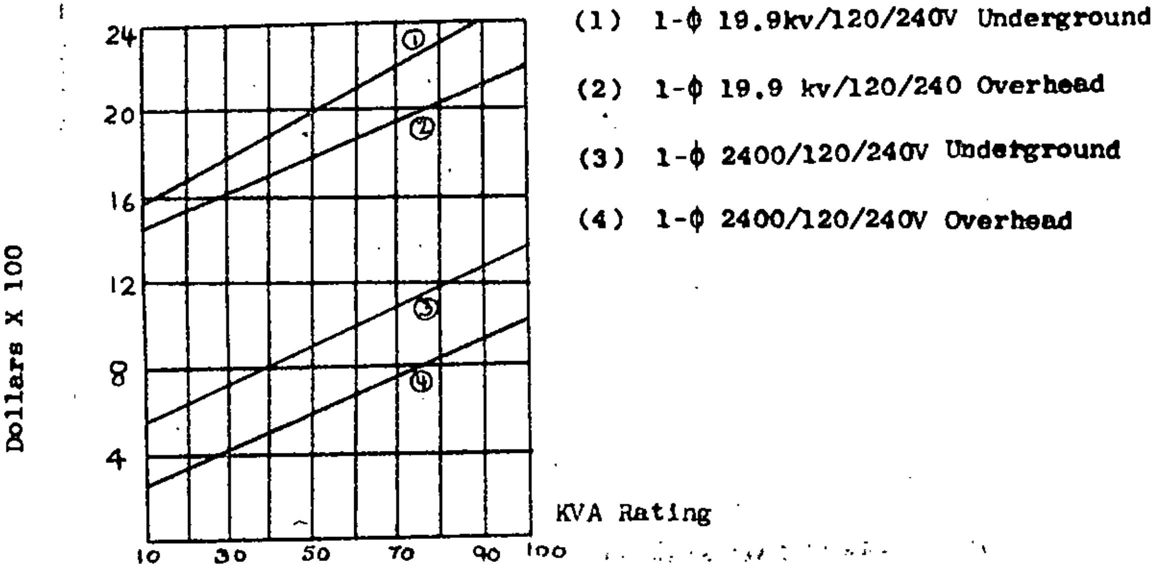


Fig. 15 Installed Cost Of Distribution Transformers For Conventional 120/240 V Studies

Figure 16 gives the installed costs of the transformers used for the 240/480 volt single phase systems and for the 265/460 volt 3-phase systems.

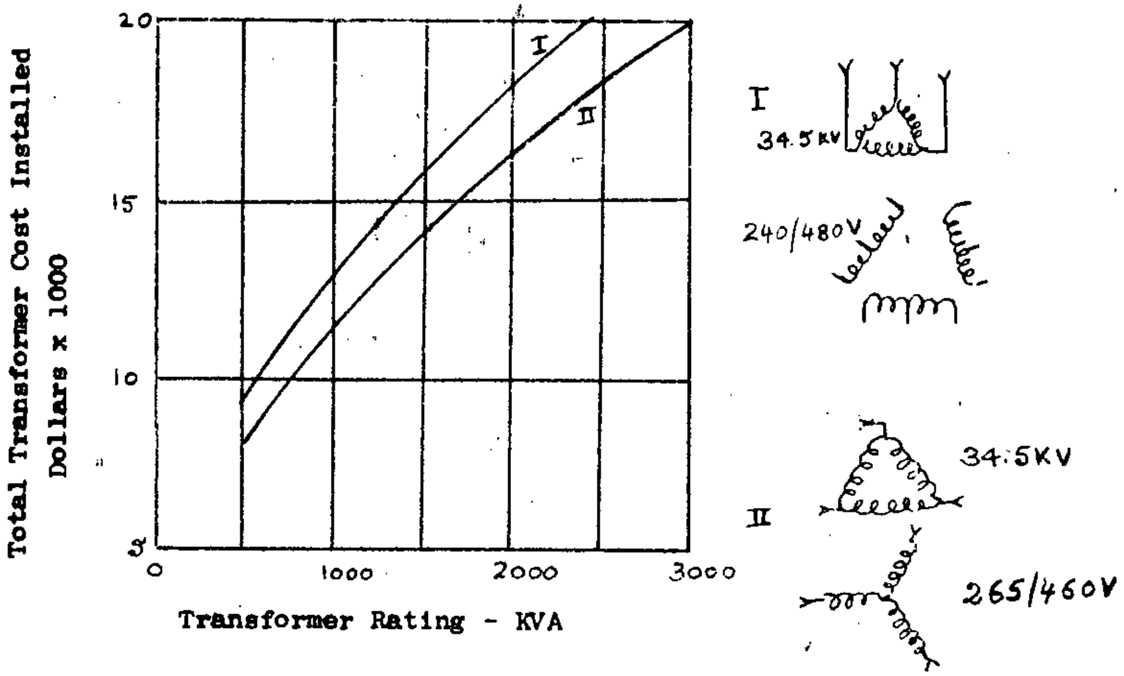


Fig. 16 Installed Cost of Two Types Of Higher Secondary Voltage 3-ϕ Distribution Transformer

The cost of overhead service drops to each house as shown in Table III (See Appendix). For the 1.6 and 2.5 kva load densities, it was assumed that No. 8 conductors would be used. For 5 and 10 kva cases, No. 4 conductors were assumed.

Results And Evaluations

Table IV and V (Appendix) present the results of the overhead system optimizations. The totals and the breakdown of costs are given in terms of dollars per house for each of the four load densities and for each of the five systems. The results are plotted in figure 17. Figure 18 shows the results plotted in terms of dollars per kilovolt-ampere.

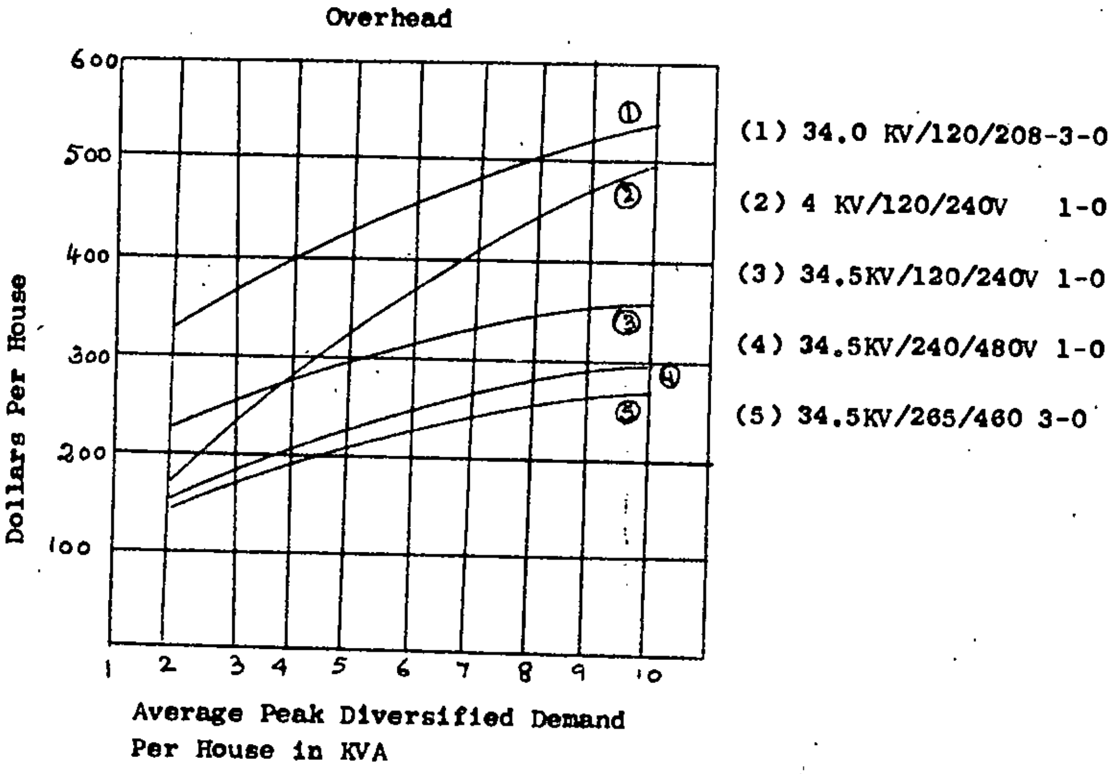


Fig. 17 Overhead System Investment In Dollars Per House Versus Average Peak Diversified Demand Per House.

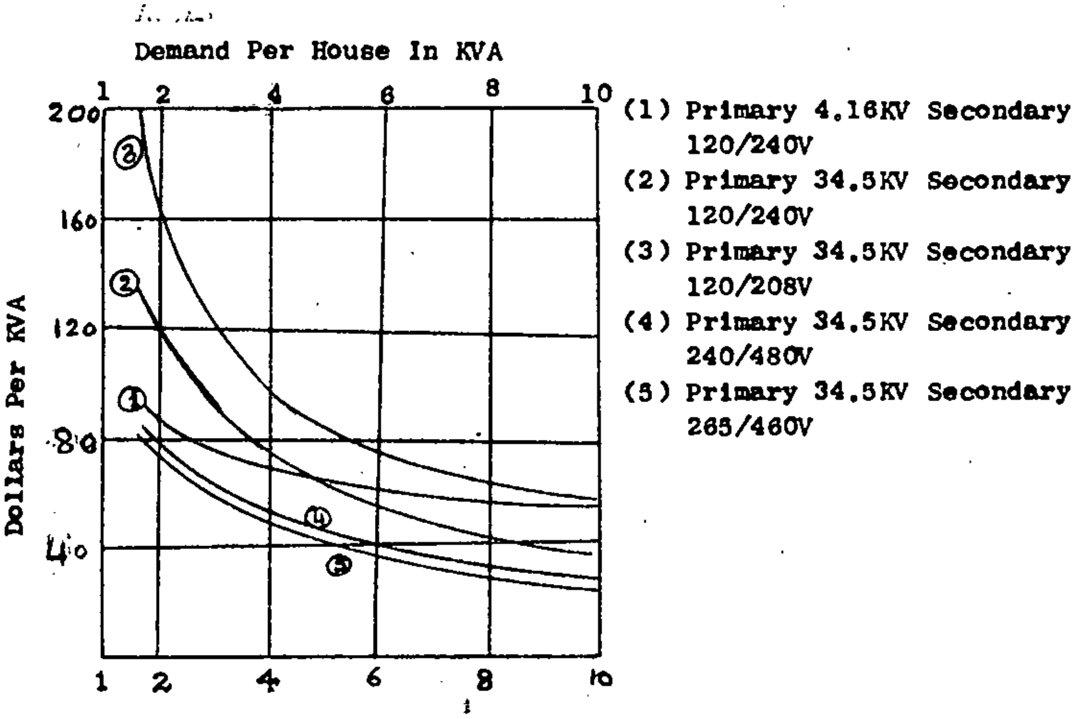


Fig. 18 OverHead System Investment In Dollars Per Kilovolt Ampere Versus Average Peak Diversified Demand Per House.

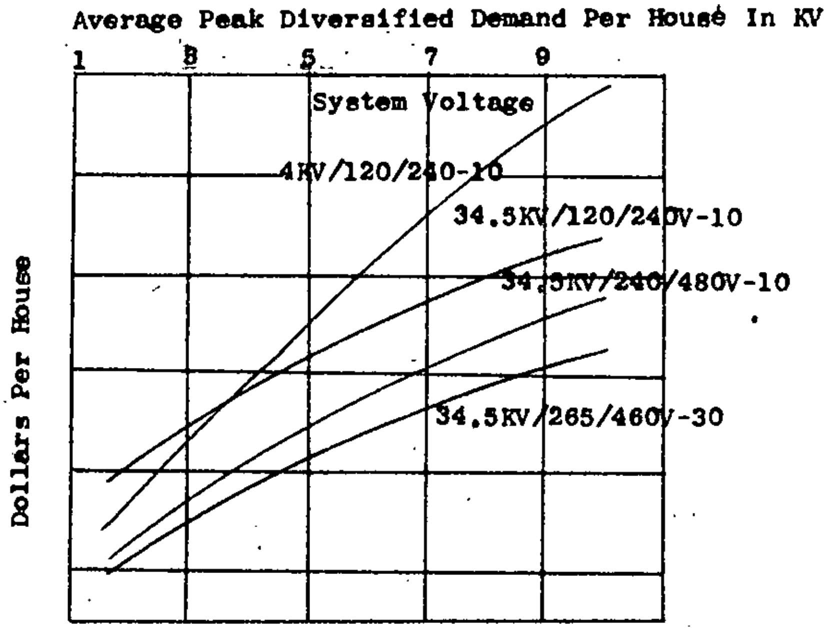


Fig. 19 Underground System Investment In Dollars Per House Versus Average Peak Diversified Demand Per House; Diversified Demand Based On 1,000 Houses.

The results of the underground system studies are presented in Table VI and VII (Appendix). Figure 18 and 19 show these results plotted in terms of dollars per house and dollars per kilovolt-ampere respectively.

The curves of figures 17 and 19 show that 265/460 volt system offers the greatest economy for both the overhead and underground installations. The overhead curves of figure 17 show that the 265/460 volt system provides savings over the conventional system utilizing 4-KV primaries of 47% at the highest load density studied.

The percent savings available in the background systems through the use of a higher secondary voltage are not as great as they are in the overhead systems, but they nevertheless represent an appreciable amount. Underground the 265/460 volt system provides savings of 39% at the highest load density, as shown in figure 19.

Overhead the 265/460 volt system provides savings over the 34.5 kv to 120/240 volt system of 26% at highest load density studied. Underground, the 265/480 volt system permit savings over the 36.5 kv to 120/240 volt system of 22% at the highest density. In both the overhead and underground systems, the 34.5 kv to 120/240 volt system provides the lowest conventional system costs at the high load densities. At the low load densities the 4 kv to 120/240 volt system provides the lowest conventional system cost.

The 3-phase higher voltage system offers savings over the single phase higher voltage system. The savings largely results from the increase in power-handling ability of the 3-phase secondaries.

The largest part of the savings of the 265/460 volt system over the 4-kv to 120/240 volt system is due to the elimination of the 4-kv substation. It is this saving, complemented by the savings available through the use of the 265/480 volt secondaries, that makes the 265/480 volt system most economical.

VI ECONOMIC TRENDS IN THE USE OF ALUMINUM

Conductors

More than half the investment of an electrical utility is in transmission and distribution, and of that major division the greater part will be found in distribution while construction cost has been increasing generating station operating economics and substation simplification have operated to stabilize the cost of electric service to the customer.

Much has been done to check the spiraling transmission and distribution costs, such as the following: use of higher voltages for transmission, relating of existing equipment to secure the maximum use, and eliminating non-essentials. However, in 1950 new extensions for new customers and replacement of existing facilities were involving double the costs of 1940.

To prevent that portion of distribution between the substation and the customer's meters from assuming a disproportionate share of the expense of supplying electricity, engineers concentrated on the use of new materials and new design for increased economy. Appealing possibilities lay in the use of aluminum but, because of lack of information about such application of the material and because of the pressure to keep construction apace with community growth, there was reluctance to change. On two or three occasions prior to 1950, experimental installations had been planned for the system, but in each instance because of inability to clear up important details these plans were abandoned.

It is quite obvious that there have been certain economic advantages in the use of aluminum conductors over a period of many years. This fact is easily demonstrated by the installation of aluminum transmission lines starting in the 1890's and on through the years at such an accelerated pace that today, we know that there are nearly three million miles of aluminum cable (mostly steel-reinforced aluminum cable--A.C.S.R.--) in service in the United States. Furthermore, somewhat over 80% of the high voltage power in North America is transmitted over aluminum lines.

The high electrical conductivity of aluminum has made it a logical competitor with copper, as a conductor material.

Let us examine the reasons for this ever-increasing expansion of aluminum use, largely at the expense of copper. It might be well to point out the relative abundance of aluminum in the earth's crust as compared with that of copper. Although aluminum is not found in metallic form in nature, according to geological surveys there is approximately 900 times as much aluminum in the earth's crust as there is copper and it is also believed that it is somewhat over five times as plentiful as iron--on a volumetric basis. Copper on the other hand, although plentiful, is not plentiful to nearly the same extent, and what is more important, is not plentiful where we need it most.

Aluminum is the only commercial rival to copper as a good conductor of electricity in the ever-increasing challenge to the electrical industry in keeping pace with the demand for electrical energy. It has excellent resistance to corrosion in most environments, it has physical characteristics which are preponderantly good, and it is easy to handle. Its light weight and relatively high electrical conductivity permit the engineers to figure, as a rule of thumb, that for equal performance, one pound of aluminum will do the job of two pounds of copper. The ratio is frequently even higher.

Various applications of aluminum have multiplied so rapidly that the industry has had to make prodigious strides in production capacity to keep pace with requirements. As a result of the heavy pressure, the price of the aluminum ingot today is substantially at the pre-war level.

The introduction of ACSR (aluminum conductor, steel reinforced) some forty years ago was a most important factor in bringing aluminum conductors into competition with copper conductors. ACSR with its higher strength and lighter weight than the electrically equivalent copper conductors introduced the undeniable economic factor of "span advantage", that is to say, for some clearance between conductor and ground the use of AGSR rather than copper conductors requires either fewer structures, insulators, clamp, etc. or in some instances where the line profile is unfavorable for such economics, at least require shorter poles or structures. The longer spans attainable with ACSR have shown such strong span advantage in many instances that copper conductors were simply "not in the running", even though on a conductor foot basis they were much lower in price than their ACSR counterparts. Today the design engineers and the purchasing agents jointly enjoy the saving derived from both span advantage and the lower price of aluminum conductors.

Many technical developments and improvements through the years, such as compression type joints and dead-ends, an impressive assortment of reliable accessories and the solution to fatigue breakage of conductor strands, have contributed in a major way to the economic dominance of aluminum conductors in the transmission and primary distribution fields. In recent years the introduction of higher operating voltages has required cables of larger diameters. The field has been a "natural" for ACSR in either the expanded form with impregnated paper fillers or in the multilayer design. Aluminum conductors in secondary distribution, in the field of open and enclosed busses, in reactors, in building wiring and communication cable are all active uses.

EC aluminum which means electrical conductor grade aluminum, has a minimum purity of 99.45%, has a conductivity equal to a minimum of 61% of the international Annealed Copper Standard. It is apparent that for equivalent resistances, aluminum conductors must have a cross-sectional area 62% greater than annealed copper wire, and 59% greater than hard-drawn copper as used for overhead lines. Because of the differences in specific gravity of the two metals, however, the aluminum conductor will weigh only about half as much as a copper conductor for equivalent lengths. Therefore, a pound of copper will make a #8 wire 20 feet long, while a pound of aluminum will make a #6 wire 41 feet long and these two wires will have the same resistance per foot. The resistances of hard drawn copper and aluminum are two AWG gauge members apart; that is, a #12 wire in aluminum is equivalent to a #14 in copper.

The tensile strength of EC aluminum depends upon the amount of cold work to which the material has been subjected, and the selection of the proper temper is dependent to a large extent upon the service of the conductor. Most multi-strand cable is manufactured from ASTM Spec. EC-H 19 material having a tensile strength from 25,000 to 3,000 psi, depending upon the size. Intermediate tempers, such as EC-H16 or EC-H26 are available where higher flexibility and workability are problems. In general, aluminum insulated wire, either stranded or solid, from #8 and smaller utilizes one of these intermediate tempers so that the tensile properties will be in the range from 17,000 to 22,000 psi. These intermediate tempers were chosen so that aluminum would be more nearly comparable to flexibility to annealed copper wire of equivalent current carrying capacities. In other words, aluminum #12 solid wire employing EC-H26 or EC-H16 temper will have approximately the same breaking strength as a #14 wire fabricated from annealed copper.

Covered and Insulated Conductors

The use of covered cable for power and feeder circuits goes back to 1905 when a 1,590,000 CM cable was installed in one of the Aluminum Company of America plants. It is still in operation on 400 volts. About 1916 a large installation of covered cable was made in which there was some 1700 aluminum to aluminum soldered connections.

In the early period of its manufacture, covered aluminum conductor was often used as insulated conductor, although installation value of the covering was minimum. Today covered conductor is a major aluminum conductor product with ever-growing quantities in use as distribution, service and drop cable.

Connectors

The choice of aluminum for insulated power and feeder cable came when the favorable price advantage of aluminum over copper made its choice almost mandatory. Problems of connecting and terminating which had been so successfully solved in the use of aluminum for overhead conductor work could not be applied to insulated cable in all cases. The size of fittings and splicing sleeves and connectors of all types had to be scaled down because of span limitation. It has been necessary to study this entire field of connectability with the idea of producing efficient means of terminating insulated cable and at the same time consume the smallest amount of space.

Conductor Materials

The most important material is copper because of its high conductivity and great tensile strength. Aluminum is used to a large extent, especially with steel core, for high voltage lines. Among the other materials used are copperweld, cadmium, copper, phosphor bronze, galvanized steel. The choice of material depends upon the cost, the required electrical and mechanical properties and on local conditions. The conductivities of copper and aluminum are decreased greatly by very small quantities of impurities: their alloys, with the exception of cadmium copper, have too low a conductivity to be used. For this reason composite conductors are used, which consist of pure copper or aluminum with a galvanized steel core for mechanical strength.

Copper

Hard-drawn copper has a high conductivity and a great tensile strength; cold working decreases conductivity slightly but increases the strength considerably. Within the range of 20 to 30 tons per inch^2 tensile strength, the conductivity is lovered by T/10 percent where T is the tensile strength in tons per inch^2; thus at 20 tons the conductivity is 98 percent, at 30 it is 97 percent.

Cadmium Copper

An addition of about 1 percent of cadmium increases the tensile strength 50 percent and reduces the conductivity by 15 percent only. The effects of the cold working are the same as for pure copper. Thus 0.9% cadmium produces an alloy of tensile strength 45 tons per inch^2, 85 percent conductivity, with the same modulus of elasticity and co-efficient of linear expansion as for copper. Cadium copper is relatively expensive, and is most useful for long spans with a line of small cross-section.

Steel-Cored Aluminum

Steel-cored aluminum conductors have a core of galvanized steel strands and a layer or layers of aluminum wires outside. Usually the aluminum and steel wires are of the same diameter. There may be one wire of steel surrounded by six wires of aluminum, or seven of steel by twelve or thirty of aluminum. There are many types of such conductors.

The conductivity of the steel-cored aluminum conductor is taken as that of the aluminum portion alone, since the steel wires have high resistance to alternating currents.

The strength is taken as 85 percent of the sum of the steel wires plus 95 percent of the sum of the strength of the aluminum wires. The factors 85 percent and 95 percent allow for the stranding.

The total strength of a steel-cored aluminum conductor is normally 50 percent greater than that of the equivalent copper conductor, and the weight only three-quarters as much (one half due to aluminum and a quarter to steel). It is claimed that the result is a conductor with a smaller ratio of loading to strength than any other conductor, even allowing for the increased wind and ice load due to the increased diameter as compared with that of the equivalent copper conductor. The sag is therefore the least so that the supporting towers may be shorter, or the span length greater for a given sag, than for any other conductor. The larger diameter is useful in very high voltage lines, as the corona losses are then less.

VII VOLTAGE CONTROL, POWER FACTOR CORRECTIONS AND USE OF DWIGHT CHART

Importance of Voltage Control

One of the most troublesome features associated with the operation of overhead transmission systems is the inherent variation of voltage at the receiving end, due to changes in the load. The fluctuations of voltage must be prevented from reaching the distributing network for the following reasons.

1. In the case of lighting load, the lamp characteristics are very sensitive to changes of voltage. For example, a 5% decrease in the applied voltage results in a decrease of 15-20% in the illuminating power of metallic-filament lamps. On the other hand, if the voltage is 5% above the correct value, the lamps deteriorate at a rapid rate, their life being shortened by about 60%

2. When a power load consisting mainly of induction motors is supplied, rather larger variations may be permitted than on a lighting circuit, and in order to take advantage of this it is customary to supply power loads and lighting loads from two distinct local circuits. Even in this case, however, it is distinctly undesirable to have more than a small percentage voltage variation. For, if the voltage is above normal, the motor operates with a saturated magnetic circuit, with consequent large magnetizing

current and heating and lower power factor. If the voltage, on the other hand, is low, its effect is to very considerably reduce both the starting torque and pullout torque.

3. If the exciting voltage impressed on the distributing transformers is carried above normal, the exciting currents and core losses begin to increase rapidly, and excessive heating is thereby occasioned. Also, due to saturation of the iron, very prominent third harmonics are introduced either in the voltage or current.

Economics of Secondary Capacitors

There are many benefits to be gained from the application of shunt capacitors to distribution circuits. Most of the benefits are made possible by that quality of the capacitor which in effect reduces the magnitude of the line current in a circuit having a lagging power-factor load. A capacitor will draw a current which leads the impressed circuit voltage by 90 degrees. This leading current can be provided to cancel part or all of the magnetizing current which lags the impressed circuit voltage by 90 degrees. Thus while the in phase component of the line current remains essentially constant, the magnitude of the resultant line current is reduced.

The reduction in line current lowers the thermal loading on all series-circuit components, such as conductors, transformers, regulators, circuit breakers, etc. and thereby permits the addition of more revenue-producing load on the circuit. If an overload condition exists in these circuit components, shunt capacitors may be applied to reduce the thermal loading to a tolerable level.

In some cases, the voltage drop to the end of a circuit may be high enough to cause trouble at the consumer's utilization devices. In other cases, the voltage drop may prohibit the addition of more load in order to avoid these consumer problems. Shunt capacitors can be used to raise the voltage level to a practical operating value and thus alleviate these low-voltage problems.

In general there are two ways to describe a shunt capacitor. First of all, since a capacitor draws a leading current, it may be considered as a leading load. With this concept, the voltage at a capacitor installation may be considered as a resolution of a voltage rise and a voltage drop; the rise being due to the leading current flowing through the series reactances of the circuit, and the drop due to the lagging current flowing through these same reactances.

The other description, the one which is becoming more widely accepted, is that a shunt capacitor is a generator of lagging kilovars. In this respect, capacitors do the same job as overexcited synchronous condensers, in that they supply the lagging kilovars close to the loads and reduce kilovar demand on the source. Capacitors offer the advantages of being available in relatively small kilovar ratings, being more easily moved to meet changing system conditions, and having lower operating losses.

Comparison of Secondary and Primary Capacitors

The installation of shunt capacitors on a circuit is justified by the revenue-producing load that can be added to the circuit as a direct result of the capacitor application. Improving power factor, raising circuit voltage, and reducing line current are benefits that are obtained in the process of increasing load with capacitors.

The problem then becomes one of determining where and how these capacitors are to be applied. This problem involves not only the questions of whether they are to be in large banks as distributed, fixed or switched, but the question of whether they should be applied at primary voltage or secondary voltage. If it is determined that part of the capacitors should be switched, they will be necessarily primary capacitors, inasmuch as it is impractical to switch secondary capacitors.

The secondary capacitor has a very distinct advantage over the primary capacitor in that it releases load capacity in the distribution transformers. If a given kilovar of capacitors were installed on the secondary of a feeder circuit, load capacity is released in in the primary feeder as before. But since the loading of the distribution transformers has not been reduced more distribution transformer capacity must be added in order to utilize released capacity of the primary feeder.

There are other advantages of the secondary capacitor over the primary capacitor. However, they are small when compared to the released capacity in the distribution transformers. Some of these increased benefits given by secondary capacitors are: reduced losses in the distribution transformer, reduced losses in that part of the secondary between the transformer and the capacitor, slightly increased revenue due to a higher voltage at the consumers watt-hour meter, and released capacity in the secondary conductors between the capacitor and the distribution transformer.

Although the capacitor is limited in its functional use only to its ability to generate a wattless kva, its justification may be used on any one or combination of the following:

1. Reduction in kva or loading of the distribution facilities, or expressed conversely, increasing the capacity of facilities.

2. Reduction in voltage regulation.

3. Increasing the emergency ability of the system (or a part of the system).

4. Increasing generation by releasing ampere capacity in the generator to fully utilize the prime mover's capacity.

Power Factor Correction & Increase
In Load Capacity

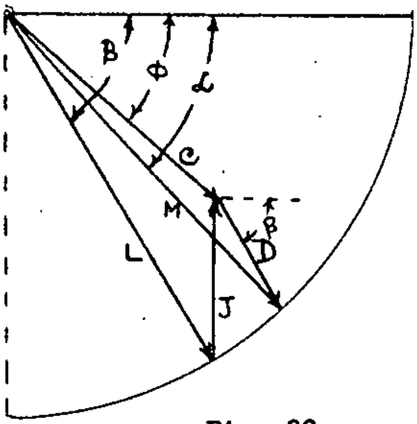


Fig. 20

Assuming a lagging load, such as the one represented by the unit Vector L at an angle B in Fig. 20, the addition of a given kilovar of shunt capacitor on the circuit will reduce the lagging component of unit vector L by a quantity represented by the vector J. Vector C at angle is the vector sum of L and J, or the resultant load. From the diagram it can be seen that the magnitude of C is less than unity. To utilize the released capacity of the circuit it has been assumed that the load will be added at the initial power factor angle B until a unit load of M at some new angle is obtained. This load addition is represented by Vector D.

For any given initial power factor angle B and a correction to any given power factor angle, , the ratio of the magnitude D and

J can be calculated. This ratio of kilovolt-ampere of load capacity released for load at the initial power angle B for each kilovar of shunt capacitors added.

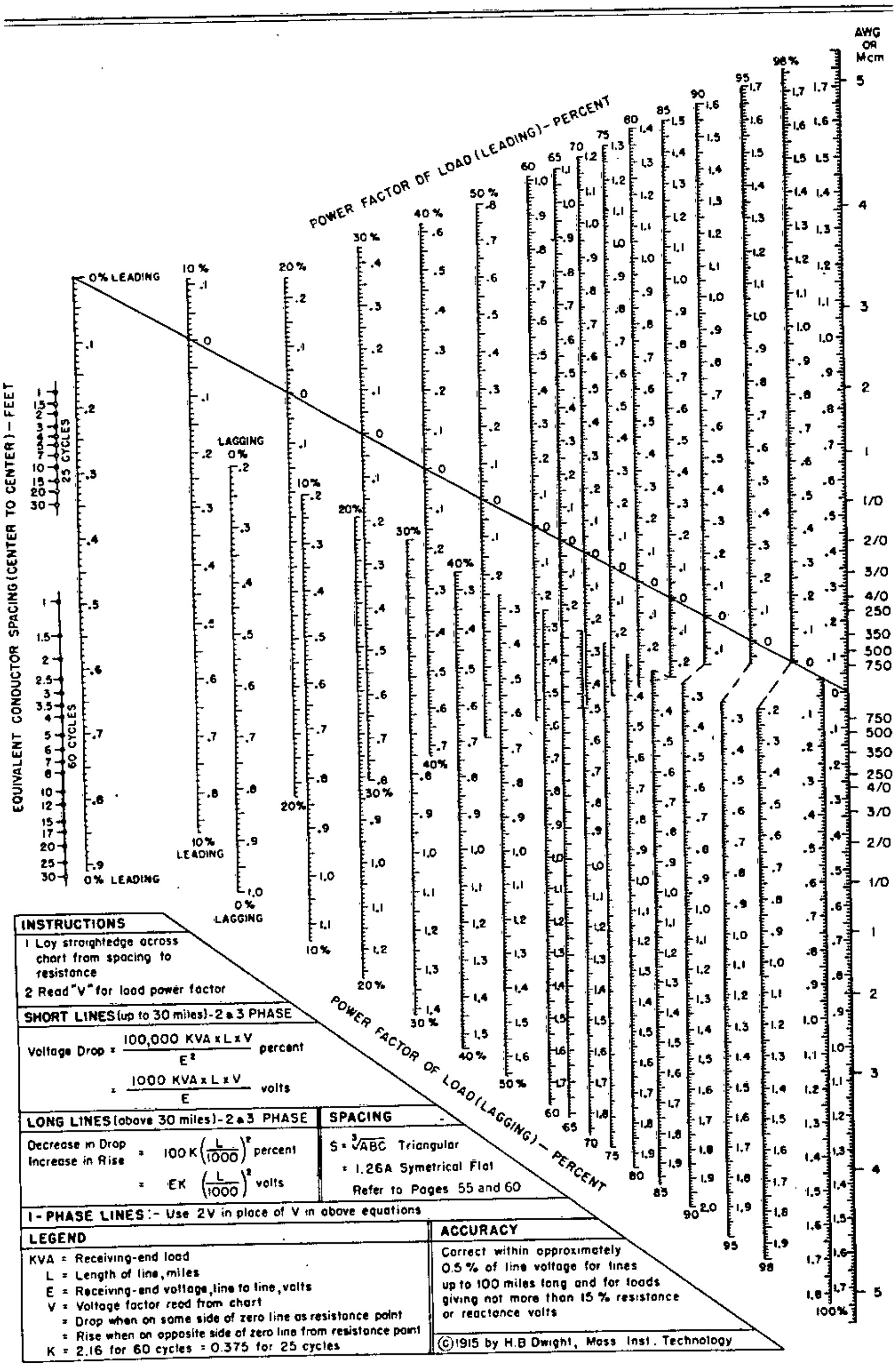
Graphical Solution (Of Voltage Drop Calculation)
By Dwight Chart

Mr. H. B. Dwight has worked up a straight line chart shown as chart I and II (see appendix) in which the resistance and the reactance of the circuit have been taken into account through the medium of spacing lines marked for various conductors. The use of this chart does not, therefore, require the calculation of the resistance and reactance or the use of tables of such constands. The Dwight Chart is equally good to loads of leading and lagging power factor. Another feature of this chart is that formulas are given which take capacitance effect into account with sufficient accuracy for circuits with a length up to approximately 100 miles.

VOLTAGE REGULATION

DWIGHT CHART

COPPER CONDUCTORS



INSTRUCTIONS

1 Lay straightedge across chart from spacing to resistance

2 Read "V" for load power factor

SHORT LINES (up to 30 miles) - 2 & 3 PHASE

$$\text{Voltage Drop} = \frac{100{,}000\ \text{KVA} \times L \times V}{E^2}\ \text{percent}$$

$$= \frac{1000\ \text{KVA} \times L \times V}{E}\ \text{volts}$$

LONG LINES (above 30 miles) - 2 & 3 PHASE

Decrease in Drop
Increase in Rise

$$= 100K\left(\frac{L}{1000}\right)^2\ \text{percent}$$

$$= EK\left(\frac{L}{1000}\right)^2\ \text{volts}$$

SPACING

$S = \sqrt[3]{ABC}$ Triangular

$= 1.26A$ Symetrical Flat

Refer to Pages 55 and 60

1 - PHASE LINES :- Use 2V in place of V in above equations

LEGEND

KVA = Receiving-end load
L = Length of line, miles
E = Receiving-end voltage, line to line, volts
V = Voltage factor read from chart
= Drop when on same side of zero line as resistance point
= Rise when on opposite side of zero line from resistance point
K = 2.16 for 60 cycles = 0.375 for 25 cycles

ACCURACY

Correct within approximately 0.5 % of line voltage for lines up to 100 miles long and for loads giving not more than 15 % resistance or reactance volts

Reproduced by permission from *The Standard Handbook for Electrical Engineers*, 8th Edition, 1949 published by McGraw-Hill Book Co., Inc., New York.

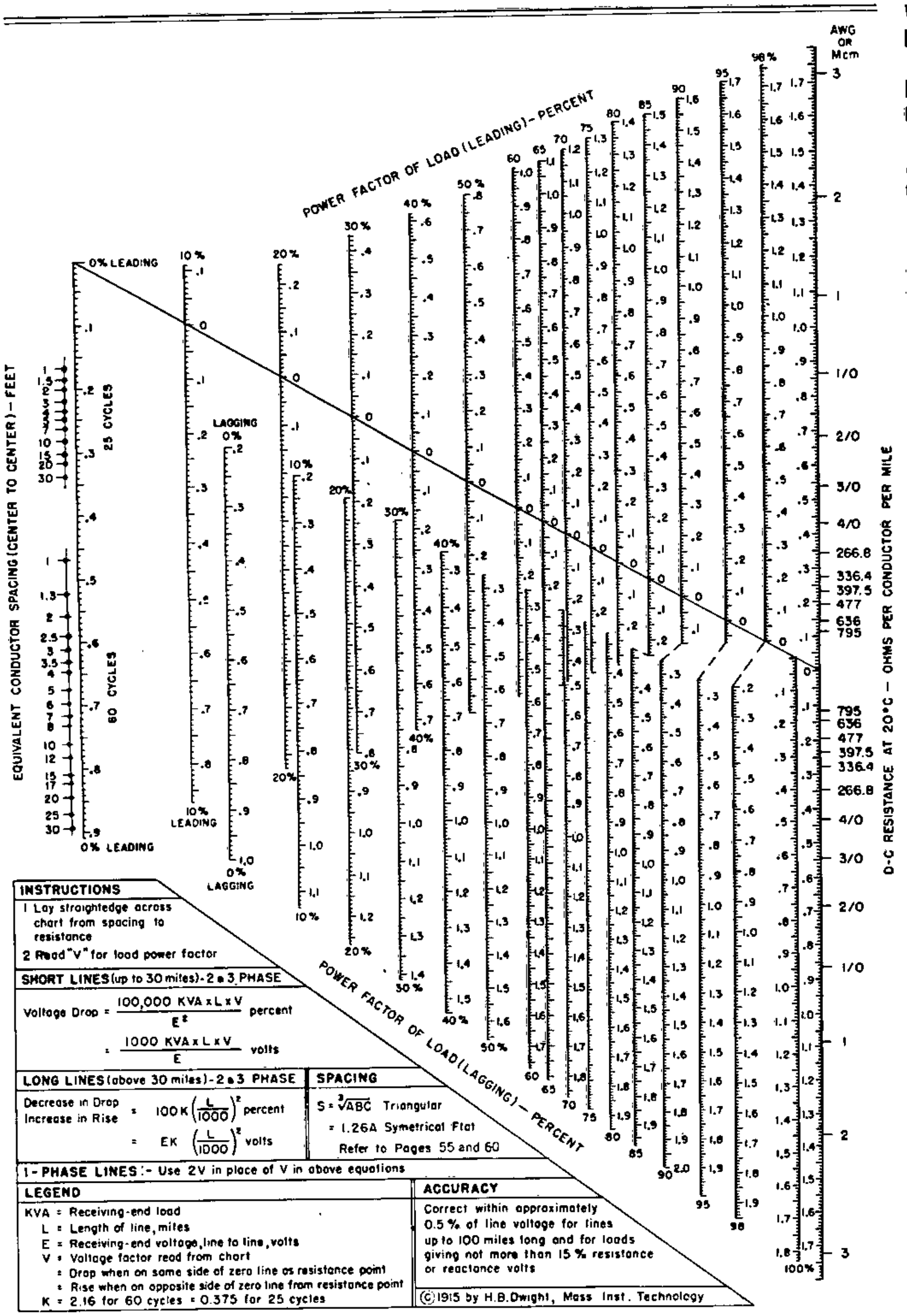
For conductor temperatures other than 20 C, locate t actual resistance on the resistance (right-hand) line a use it instead of the conductor-size marking.

VOLTAGE REGULATION

DWIGHT CHART

ACSR CONDUCTORS

ALL-ALUMINUM CONDUCTORS



INSTRUCTIONS

1 Lay straightedge across chart from spacing to resistance

2 Read "V" for load power factor

SHORT LINES (up to 30 miles) - 2 & 3 PHASE

$$\text{Voltage Drop} = \frac{100{,}000\ \text{KVA} \times L \times V}{E^2}\ \text{percent}$$

$$= \frac{1000\ \text{KVA} \times L \times V}{E}\ \text{volts}$$

LONG LINES (above 30 miles) - 2 & 3 PHASE

Decrease in Drop
Increase in Rise

$$= 100K\left(\frac{L}{1000}\right)^2 \text{percent}$$

$$= EK\left(\frac{L}{1000}\right)^2 \text{volts}$$

SPACING

$S = \sqrt[3]{ABC}$ Triangular

$= 1.26A$ Symetrical Flat

Refer to Pages 55 and 60

1-PHASE LINES :- Use 2V in place of V in above equations

LEGEND

KVA = Receiving-end load
L = Length of line, miles
E = Receiving-end voltage, line to line, volts
V = Voltage factor read from chart
= Drop when on same side of zero line as resistance point
= Rise when on opposite side of zero line from resistance point
K = 2.16 for 60 cycles = 0.375 for 25 cycles

ACCURACY

Correct within approximately 0.5 % of line voltage for lines up to 100 miles long and for loads giving not more than 15 % resistance or reactance volts

The aluminum conductors are ACSR but also apply to all-aluminum cable within the stated accuracy of the chart.

For conductor temperatures other than 20 C, locate the actual resistance on the resistance (right-hand) line and use it instead of the conductor-size marking.

Conclusions

The study of distribution practices in America has shown the author that no one scheme is the best for all problems and he now realizes that each local area to be served in Pakistan should be viewed as a new problem. With established American ties Pakistani engineers will be utilizing American manufactured electrical equipment, consequently expansions to existing distribution systems should be planned for economical use of available standard voltage equipment.

Although not mentioned in detail in studies made, sound thought should be given to the manufacture of pre-stressed concrete poles in Pakistan for overhead distribution systems.

In addition to the studies made, the author has had the opportunity of acquiring detailed plans and specifications of good engineering installation practices for distribution systems, which should prove of great value in system layout.

For special problems of lines serving definite loads at available voltages, he believes it will be advantageous to instruct his engineering students and associates in the use of the "Dwight Chart" for rapid and accurate calculations.

To solve the problems which will face Pakistan in the distribution of electrical energy, the training of engineers is perhaps the most important need of the country. Perhaps devotion of the author's life to the broad training of many young men in the field of electrical engineering may do more good for the over-all distribution problem than devoting time and effort to the solution of a particular system problem. It is to the training of these men that material such as has been presented will be of great value.

TABLE I LISTS OF CIRCUIT RATING AND IMPEDANCES FOR THE COMMON SIZES OF AERIAL SECONDARY CABLES

TABLE I AERIAL CABLE

CHARACTERISTICS, 3-PHASE SECONDARY

COND. SIZE	CIRCUIT RATING AMP.	K.V.A.	CIRCUIT IMP.	SPECIAL COPPERWELD MESSENGER	ULTIMATE STRENGTH 16	60F SAG IN 100 FT SPAN
No. 4/0	245	92	7.65%	No. 1/0 Equiv Type K	14,490	0.93 Ft
350 MCM	333	125	5.42%	No. 4/0 Equiv Type G	15,640	1.39 Ft
500 MCM	408	153	4.48%	250 MCM Equiv Type EK	17,840	1.65 Ft

3-1/c 600V, Heavy Neoprene Jacket
Maximum Conductor Temp.--75° C
Maximum Ambient Temp.----40° C
Impedance On 500 KVA Base, 216V, 100 Ft. Lengths

TABLE II CHARACTERISTICS OF TYPICAL THREE CONDUCTOR RUBBER INSULATED NEOPRENE SHEATHED 5KV GROUNDED NEUTRAL AERIAL CABLE

Insulation Thickness 10/64 (Inches)

COND. SIZE (B&S)	SHEATH THICKNESS (INCHES)	MESSENGER SIZE (B&S)	ULTIMATE STRENGTH (LB)	APPROX. TOTAL WT. LB/FT	125 FT SPAN FINAL SAG 60° F (INCHES)	RESULT. SAG HEAVY LOADING (INCHES	COND. RESIST. 75° C 60 C/S Ohms/Mile	REAC. TO NEUTRAL 60 C/S /M	CURRENT CARRYING CAP. PER CONDUCTOR 50° C AMPS
6	4/64	7/No. 10	7121	1.01	14	23	0.50	0.050	64
4	4/64	7/No. 10	7121	1.22	16	25	0.32	0.046	85
2	4/64	7/No. 10	7121	1.53	20	28	0.20	0.043	116
1	4/64	7/No. 9	8616	1.80	20	26	0.16	0.041	133
1/0	5/64	7/No. 8	10460	2.25	20	26	0.13	0.040	156
2/0	5/64	7/No. 7	12670	2.64	20	24	0.10	0.039	182
3/0	5/64	19/No. 10	19350	3.20	16	19	0.080	0.038	216
4/0	5/64	19/No. 9	23390	3.83	15	18	0.060	0.036	244

TABLE III FIXED COSTS OF OVERHEAD SERVICES

System Secondary Voltage	Service Volts	# of Conductors	Conductor size A.W.G.#	Installed Cost of Conductors	Installed Cost of Auto Transformers	Total
120/240V	120/240V	3	8	$22.80		$22.80
120/240V	120/240V	3	4	$45.60		$45.60
120/208V	120/208V	3	8	$22.80		$22.80
120/208V	120/208V	3	4	$45.60		$45.60
240/480V	240	2	8	$15.20	$28.00	$43.20
240/480V	240	2	4	$30.40	$28.00	$58.40
265/460V	265	2	8	$15.20	$28.00	$43.20
265/460V	265	2	4	$30.40	$28.00	$58.40

TABLE IV OVERHEAD DISTRIBUTION SYSTEM COSTS, DOLLARS PER HOUSE

	Load Density Per House									
	1.6 KVA					2.5 KVA				
	A	B	C	D	E	A	B	C	D	E
Service Cost	22.80	22.80	22.80	43.20	43.20	22.80	22.80	22.80	43.20	43.20
Dist. Transformers	33.33	131.00	203.00	37.21	21.11	44.42	143.00	216.00	42.21	32.56
Secondary Mains	16.46	16.87	50.80			16.46	16.87	50.80		
Sec. Mains & Trunks				43.27	59.80				53.80	57.70
Primary Feeders	37.09	39.71	41.55	8.10	4.57	43.45	40.21	42.05	8.90	8.54
Substations	40.00					62.50				
Voltage Regulators		8.00	8.00	8.00	8.00		13.20	13.20	13.20	13.20
TOTAL	149.68	218.38	326.15	139.78	136.68	189.63	236.08	344.85	161.31	155.20

A = Secondary Voltage 120/240 volts, 1-phase; primary voltage 4 KV
B = Secondary Voltage 120/240 volts, 1-phase; primary voltage 34.5 KV
C = Secondary Voltage 120/208 volts, 3-phase; primary voltage 34.5 KV
D = Secondary Voltage 240/480 volts, 1-phase; primary voltage 34.5 KV
E = Secondary Voltage 265/480 volts, 3-phase; primary voltage 34.5 KV

TABLE V OVERHEAD DISTRIBUTION SYSTEM COSTS, DOLLARS PER HOUSE

	Load Density KVA Per House									
	5 KVA					10 KVA				
	A	B	C	D	E	A	B	C	D	E
Service Cost	45.60	45.60	45.60	58.40	58.40	45.60	45.60	45.60	58.40	58.40
Dist. Transformers	84.60	171.00	248.90	57.01	52.31	140.00	201.00	396.00	118.02	106.73
Secondary Mains	24.47	22.95	60.70				31.60	34.20		
Sec. Mains & Trunks				67.80	65.60				81.10	53.80
Primary Feeders	60.53	44.74	46.47	13.10	13.10	68.14	51.30	57.80	22.80	26.50
Substations	125.00					250.00				
Voltage Regulators		15.30	15.30	15.30	15.30		23.00	23.00	23.00	23.00
TOTAL	340.20	299.59	416.97	211.61	204.71	503.74	352.50	566.60	303.32	268.43

A = Secondary Voltage 120/240 volts, 1-phase; primary voltage 4 KV
B = Secondary Voltage 120/240 volts, 1-phase; primary voltage 34.5 KV
C = Secondary Voltage 120/208 volts, 3-phase; primary voltage 34.5 KV
D = Secondary Voltage 240/480 volts, 1-phase; primary voltage 34.5 KV
E = Secondary Voltage 265/480 volts, 3-phase; primary voltage 34.5 KV

TABLE VI UNDERGROUND DISTRIBUTION SYSTEM COSTS, DOLLARS PER HOUSE

LOAD DENSITY, KVA PER HOUSE

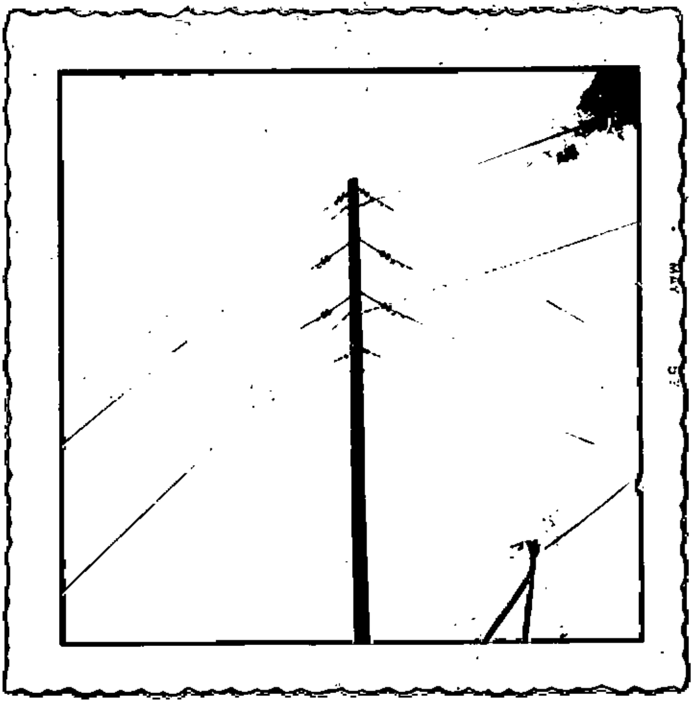
	5 KVA				10 KVA			
	A	B	C	D	A	B	C	D
Service Cost	92.85	92.85	100.05	100.05	82.85	92.85	100.05	100.00
Distribution Transformers	105.00	182.00	58.01	43.87	236.25	241.00	80.01	72.90
Secondary Mains	30.60	29.90				49.05		
Secondary Mains & Trunks			129.86	105.48			197.47	152.66
Primary Feeders	93.52	101.07	41.45	40.52	121.99	126.77	75.95	75.95
Substations	125.00				250.00			
Voltage Regulator		15.30	15.30	15.30		23.00	23.00	23.00
TOTAL	446.97	421.75	344.67	305.22	691.09	532.67	476.48	424.56

A = Secondary Voltage 120/240 volts 1-phase; Primary Voltage 4 KV
B = Secondary Voltage 120/240 volts 1-phase; Primary Voltage 34.5 KV
C = Secondary Voltage 240/480 volts 1-phase; Primary Voltage 34.5 KV
D = Secondary Voltage 265/480 volts 3-phase; Primary Voltage 34.5 KV

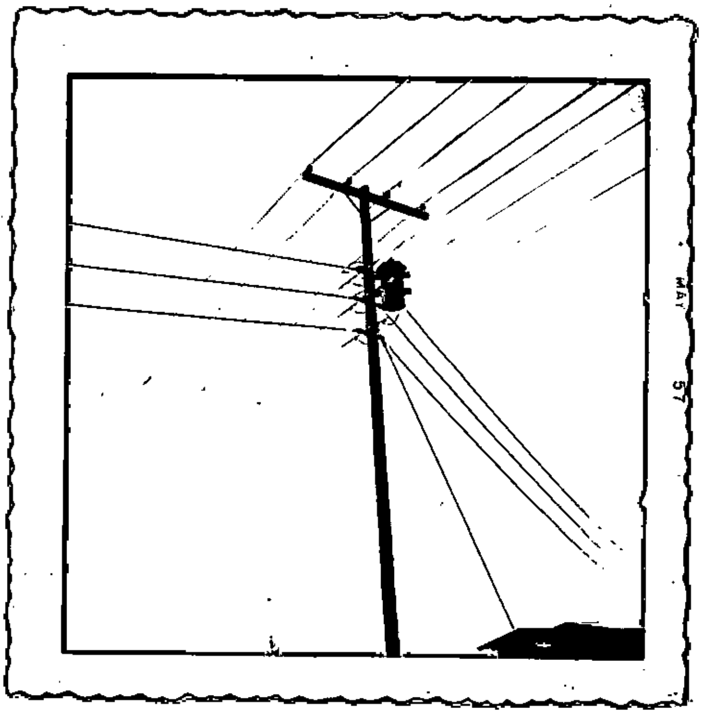
TABLE VII UNDERGROUND DISTRIBUTUON SYSTEM COSTS, DOLLARS PER HOUSE

	Load Density, KVA Per House							
	1.6 KVA				2.5 KVA			
	A	B	C	D	A	B	C	
Service Cost	68.27	68.27	86.12	86.12	68.27	68.27	86.12	86.12
Distribution Transformers	55.75	89.00	23.07	21.07	59.18	113.50	42.15	28.31
Secondary Mains	28.88	45.30			45.30	45.30		
Secondary Mains & Trunks			67.85	62.91			77.10	71.79
Primary Feeders	50.76	81.18	22.66	22.66	64.41	82.58	24.71	21.79
Substations	40.00				62.50			
Voltage Regulator		8.00	8.00	8.00		13.20	13.20	13.20
TOTAL	243.66	291.75	207.70	200.76	299.66	322.85	243.28	221.21

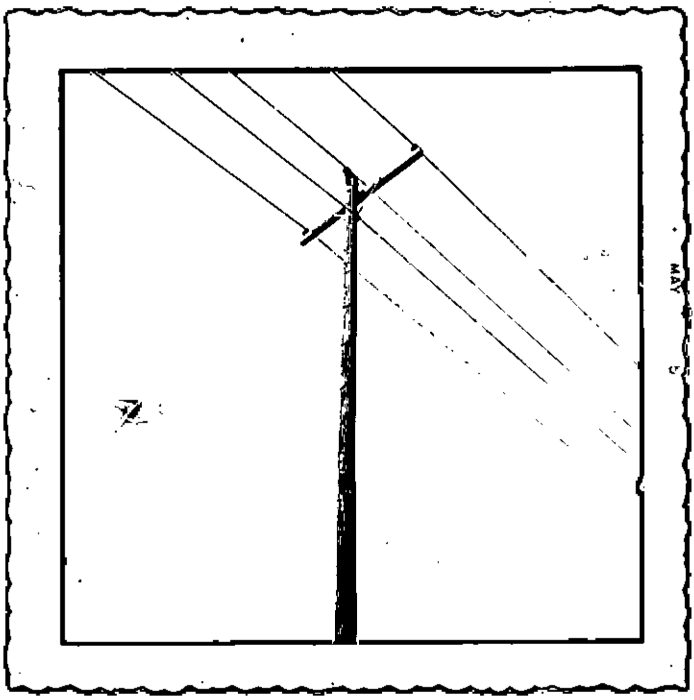
A = Secondary Voltage 120/240 Volts 1-phase; Primary Voltage 4 KV
B = Secondary Voltage 120/240 Volts 1-phase; Primary Voltage 34.5 KV
C = Secondary Voltage 240/480 Volts 1-phase; Primary Voltage 34.5 KV
D = Secondary Voltage 265/460 Volts 3-phase; Primary Voltage 34.5 KV



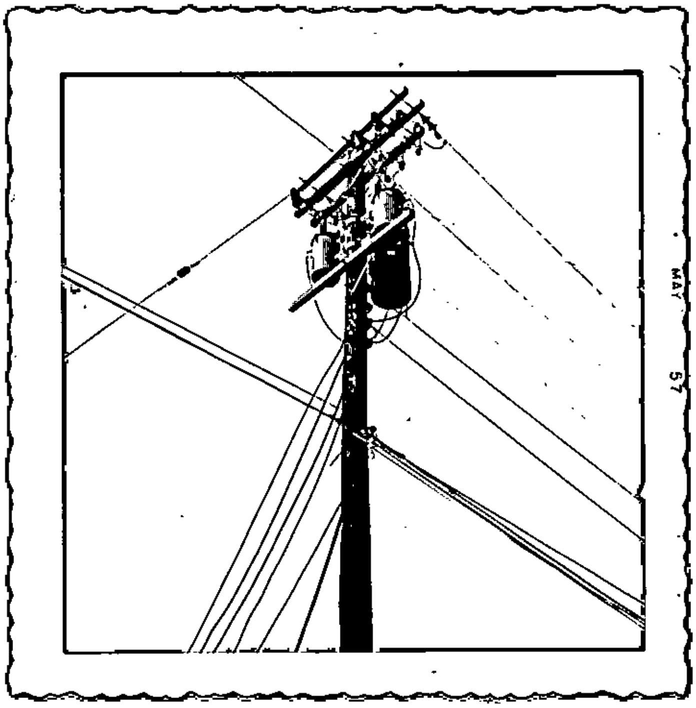
(a) Typical 90° Angle Pole (Three Phase Four Wire Distribution)



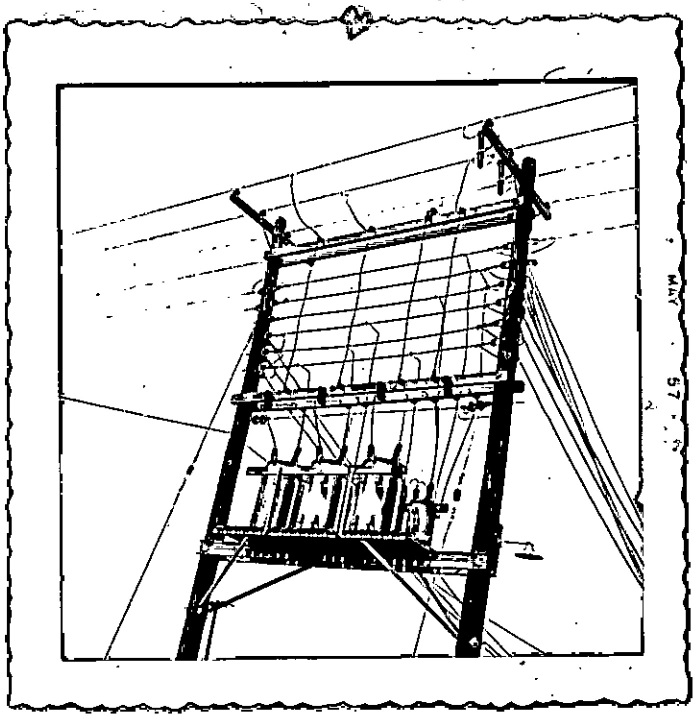
(b) Typical Pole Mounted Single Transformer (Street Lighting and 3-Phase Distribution).



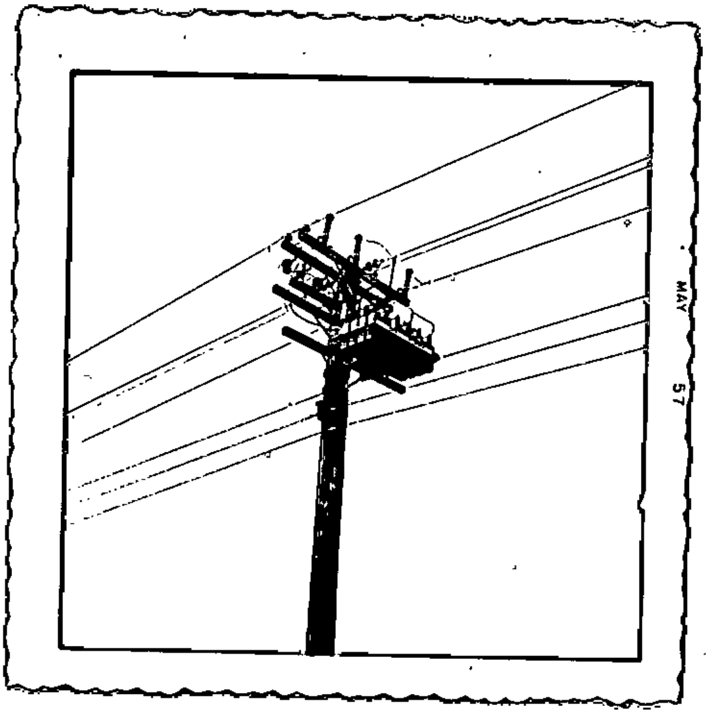
(c) Typical Pole Line Construction In A 3-Phase 4-Wire Distribution Line.



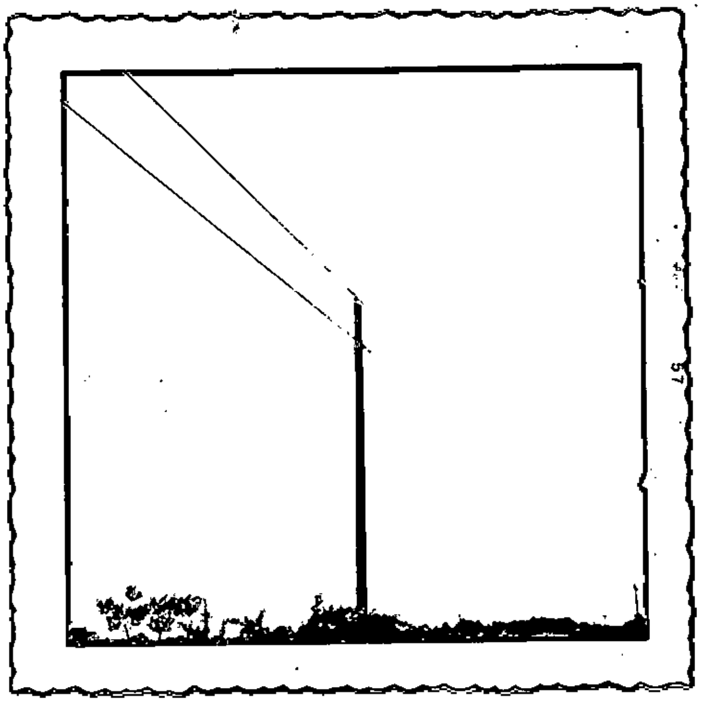
(d) Typical End Pole Mounting of Three Transformers (3-Phase Primary and Secondary Distribution).



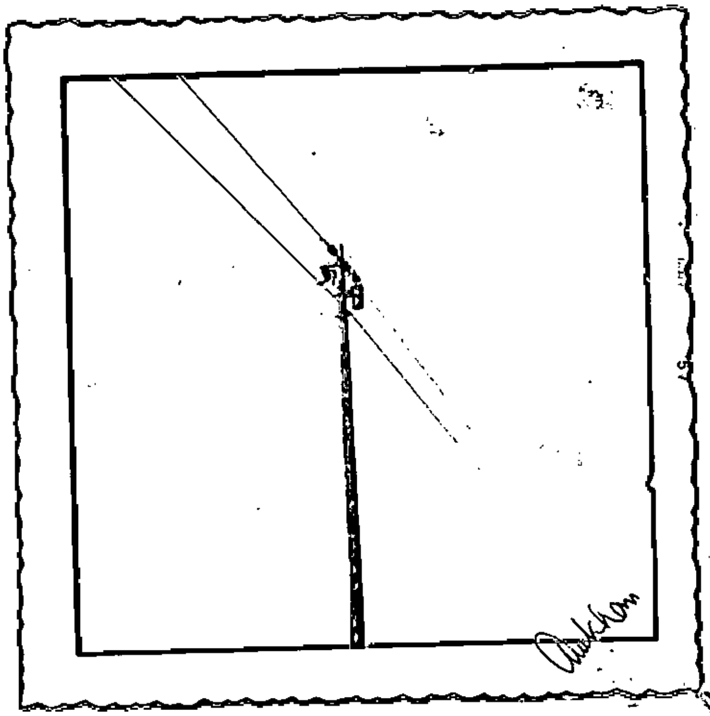
(e) Typical plateform mounted transformer substation using three transformers for power load and one transformer for auxilliary power (3-phase distribution)



(f) Typical 3-phase Capacitor Bank for Power Factor Correction



(g) Typical Single Phase Ridge Pin Pole Line Construction.



(h) Typical Transformer Substation on Single Phase Distribution Line.

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