Electrical, Electronics
Engineering Department

Design overhead distribution systems

UETTDRDS05B
(Vol 1 of 2)

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MODULE TITLE	**Design overhead distribution systems**
Nominal Duration	**40 hours**
Module Code or Number	**UETTDRDS05A**

T2.2.2 Transmission, distribution and rail power systems
T2.2.4 Powerline distribution installation
T2.4.6 High voltage SWER system

List of essential resources

- Voltage regulation relay - typical working sample
- Line drop compensator
- Phantom line circuit - simulating a typical transmission or distribution feeder
- Sample VT and CT
- Local distribution system diagrams - with fault levels indicated
- Low voltage AC supply
- Extra low voltage AC supply
- Low voltage DC supply

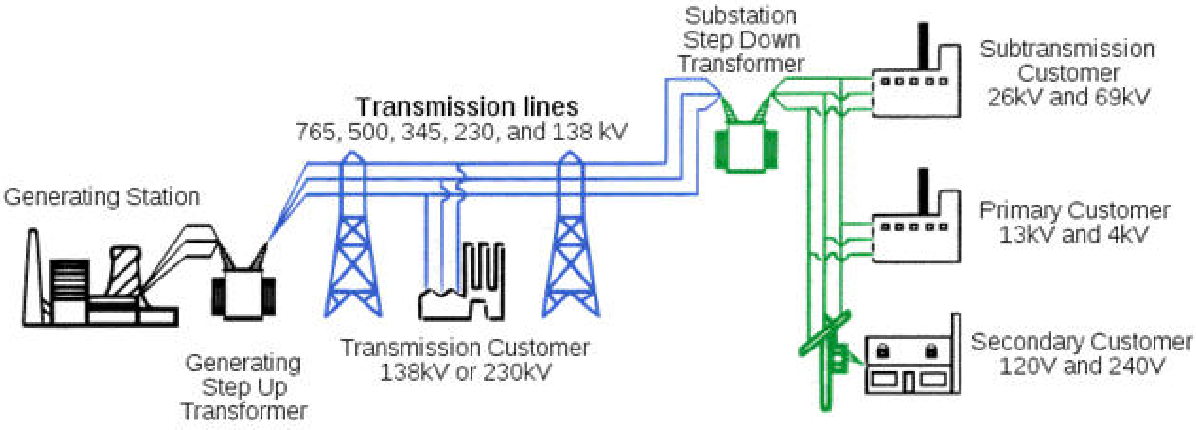
Items such as the voltage regulation relay, line drop compensator and VT may be difficult to obtain, student exposure to this equipment may be obtained with the aid of industrial visits.

Electric power transmission

Electric power transmission is the bulk transfer of electrical energy, a process in the delivery of electricity to consumers.

A power transmission network typically connects power plants to multiple substations near a populated area.

The wiring from substations to customers is referred to as electricity distribution, following the historic business model separating the wholesale electricity transmission business from distributors who deliver the electricity to the homes.



Electric power transmission allows distant energy sources (such as hydroelectric power plants) to be connected to consumers in population centres, and may allow exploitation of low-grade fuel resources such as coal that would otherwise be too costly to transport to generating facilities.

Transmission lines

Usually transmission lines use three phase alternating current (AC). Single phase AC current is sometimes used in a railway electrification system. High-voltage direct current systems are used for long distance transmission, or some undersea cables, or for connecting two different ac networks.

Electricity is transmitted at high voltages (110 kV or above) to reduce the energy lost in transmission.

Power is usually transmitted as alternating current through overhead power lines. Underground power transmission is used only in densely populated areas because of its higher cost of installation and maintenance when compared with overhead wires, and the difficulty of voltage control on long cables.

A power transmission network is referred to as a "grid". Multiple redundant lines between points on the network are provided so that power can be routed from any power plant to any load center, through a variety of routes, based on the economics of the transmission path and the cost of power.

Much analysis is done by transmission companies to determine the maximum reliable capacity of each line, which, due to system stability considerations, may be less than the physical or thermal limit of the line.

Deregulation of electricity companies in many countries has led to renewed interest in reliable economic design of transmission networks.

A power station (also referred to as a generating station, power plant, or powerhouse) is an industrial facility for the generation of electric power.

Power plant is also used to refer to the engine in ships, aircraft and other large vehicles. Some prefer to use the term energy centre because it more accurately describes what the plants do, which is the conversion of other forms of energy, like chemical energy, gravitational potential energy or heat energy into electrical energy. However, power plant is the most common term in the U.S., while elsewhere power station and power plant are both widely used, power station prevailing in many Commonwealth countries and especially in the United Kingdom.

At the center of nearly all power stations is a generator, a rotating machine that converts mechanical energy into electrical energy by creating relative motion between a magnetic field and a conductor.

The energy source harnessed to turn the generator varies widely. It depends chiefly on which fuels are easily available and on the types of technology that the power company has access to.

Hydroelectric Station

Steam Electric Station

Overhead transmission

Overhead conductors are not covered by insulation.

The conductor material is nearly always an aluminium alloy, made into several strands and possibly reinforced with steel strands.

Copper was sometimes used for overhead transmission but aluminium is lower in weight for equivalent performance, and much lower in cost.

Overhead conductors are a commodity supplied by several companies worldwide. Improved conductor material and shapes are regularly used to allow increased capacity and modernize transmission circuits.

Conductor sizes range from 12 mm² (#6 American wire gauge) to 750 mm² (1,590,000 circular mils area), with varying resistance and current-carrying capacity.

Thicker wires would lead to a relatively small increase in capacity due to the skin effect, that causes most of the current to flow close to the surface of the wire.

Today, transmission-level voltages are usually considered to be 110 kV and above.

Lower voltages such as 66 kV and 33 kV are usually considered sub-transmission voltages but are occasionally used on long lines with light loads.

Voltages less than 33 kV are usually used for distribution.

Voltages above 230 kV are considered extra high voltage and require different designs compared to equipment used at lower voltages.

Since overhead transmission lines are uninsulated, design of these lines requires minimum clearances to be observed to maintain safety.

Adverse weather conditions of high wind and low temperatures can lead to power outages: wind speeds as low as 23 knots (43 km/h) can permit conductors to encroach operating clearances, resulting in a flashover and loss of supply.

Oscillatory motion of the physical line can be termed gallop or flutter depending on the frequency and amplitude of oscillation.

An overhead power line is an electric power transmission line suspended by towers or poles. Since most of the insulation is provided by air, overhead power lines are generally the lowest-cost method of transmission for large quantities of electric power.

Towers for support of the lines are made of wood (as-grown or laminated), steel (either lattice structures or tubular poles), concrete, aluminum, and occasionally reinforced plastics. The bare wire conductors on the line are generally made of aluminum (either plain or reinforced with steel or sometimes composite materials), though some copper wires are used in medium-voltage distribution and low-voltage connections to customer premises.

The invention of the strain insulator was a critical factor in allowing higher voltages to be used. At the end of the 19th century, the limited electrical strength of telegraph-style pin insulators limited the voltage to no more than 69,000 volts.

Today overhead lines are routinely operated at voltages exceeding 765,000 volts between conductors, with even higher voltages possible in some cases.

Overhead power transmission lines are classified in the electrical power industry by the range of voltages:

Low voltage – less than 1000 volts, used for connection between a residential or small commercial customer and the utility.

Medium Voltage (Distribution) – between 1000 volts (1 kV) and to about 33 kV, used for distribution in urban and rural areas.

High Voltage (Subtransmission if 33-115kV and transmission if 115kV+) – between 33 kV and about 230 kV, used for sub-transmission and transmission of bulk quantities of electric power and connection to very large consumers.

Extra High Voltage (Transmission) – over 230 kV, up to about 800 kV, used for long distance, very high power transmission.

Ultra High Voltage – higher than 800 kV.
Lines classified as "High voltage" are quite hazardous. Direct contact with (touching) energized conductors still present a risk of electrocution.
A major goal of overhead power line design is to maintain adequate clearance between energized conductors and the ground so as to prevent dangerous contact with the line.
This is extremely dependent on the voltage the line is running at.

Structures

Structures for overhead lines take a variety of shapes depending on the type of line. Structures may be as simple as wood poles directly set in the earth, carrying one or more cross-arm beams to support conductors, or "armless" construction with conductors supported on insulators attached to the side of the pole.
Tubular steel poles are typically used in urban areas. High-voltage lines are often carried on lattice-type steel towers or pylons. For remote areas, aluminium towers may be placed by helicopters.
Concrete poles have also been used. Poles made of reinforced plastics are also available, but their high cost restricts application.
Each structure must be designed for the loads imposed on it by the conductors.
A large transmission line project may have several types of towers, with "tangent" ("suspension" or "line" towers, UK) towers intended for most positions and more heavily constructed towers used for turning the line through an angle, dead-ending (terminating) a line, or for important river or road crossings.
Depending on the design criteria for a particular line, semi-flexible type structures may rely on the weight of the conductors to be balanced on both sides of each tower.
More rigid structures may be intended to remain standing even if one or more conductors is broken.
Such structures may be installed at intervals in power lines to limit the scale of cascading tower failures.
Foundations for tower structures may be large and costly, particularly if the ground conditions are poor, such as in wetlands.
Each structure may be considerably strengthened by the use of guy wires to resist some of the forces due to the conductors.
Power lines and supporting structures can be a form of visual pollution. In some cases the lines are buried to avoid this, but this is more expensive and therefore not usual.
Insulators
Insulators must support the conductors and withstand both the normal operating voltage and surges due to switching and lightning. Insulators are broadly classified as either pin-type, which support the conductor above the structure, or suspension type, where the conductor hangs below the structure. Up to about 33 kV (69 kV in North America) both types are commonly used.
At higher voltages only suspension-type insulators are common for overhead conductors. Insulators are usually made of wet-process porcelain or toughened glass, with increasing use of glass-reinforced polymer insulators.
Suspension insulators are made of multiple units, with the number of unit insulator disks increasing at higher voltages.
The number of disks is chosen based on line voltage, lightning withstand requirement, altitude, and environmental factors such as fog, pollution, or salt spray. Longer insulators, with longer creepage distance for leakage current, are required in these cases. Strain insulators must be strong enough mechanically to support the full weight of the span of conductor, as well as loads due to ice accumulation, and wind.
Porcelain insulators may have a semi-conductive glaze finish, so that a small current (a few milliamperes) passes through the insulator.

This warms the surface slightly and reduces the effect of fog and dirt accumulation. The semiconducting glaze also insures a more even distribution of voltage along the length of the chain of insulator units.

Insulators for very high voltages, exceeding 200 kV, may have grading rings installed at their terminals.

This improves the electric field distribution around the insulator and makes it more resistant to flash-over during voltage surges.

Conductors

Aluminum conductors reinforced with steel (known as ACSR) are primarily used for medium and high voltage lines and may also be used for overhead services to individual customers. Aluminum conductors are used as it has the advantage of better resistivity/weight than copper, as well as being cheaper. Some copper cable is still used, especially at lower voltages and for grounding.

While larger conductors may lose less energy due to lower electrical resistance, they are more costly than smaller conductors.

An optimization rule called Kelvin's Law states that the optimum size of conductor for a line is found when the cost of the energy wasted in the conductor is equal to the annual interest paid on that portion of the line construction cost due to the size of the conductors.

The optimization problem is made more complex due to additional factors such as varying annual load, varying cost of installation, and by the fact that only definite discrete sizes of cable are commonly made.

Since a conductor is a flexible object with uniform weight per unit length, the geometric shape of a conductor strung on towers approximates that of a catenary.

The sag of the conductor (vertical distance between the highest and lowest point of the curve) varies depending on the temperature.

A minimum overhead clearance must be maintained for safety.

Since the temperature of the conductor increases with increasing heat produced by the current through it, it is sometimes possible to increase the power handling capacity (uprate) by changing the conductors for a type with a lower coefficient of thermal expansion or a higher allowable operating temperature.

Bundled conductors are used for voltages over 200 kV to avoid corona losses and audible noise.

Bundle conductors consist of several conductor cables connected by non-conducting spacers.

For 220 kV lines, two-conductor bundles are usually used, for 380 kV lines usually three or even four. American Electric Power is building 765 kV lines using six conductors per phase in a bundle.

Spacers must resist the forces due to wind, and magnetic forces during a short-circuit.

Overhead power lines are often equipped with a ground conductor (shield wire or overhead earth wire).

A ground conductor is a conductor that is usually grounded (earthed) at the top of the supporting structure to minimise the likelihood of direct lightning strikes to the phase conductors.

The ground wire is also a parallel path with the earth for fault currents in earthed neutral circuits.

Very high-voltage transmission lines may have two ground conductors.

These are either at the outermost ends of the highest cross beam, at two V-shaped mast points, or at a separate cross arm.

Older lines may use surge arrestors every few spans in place of a shield wire, this configuration is typically found in the more rural areas of the United States.

By protecting the line from lightning, the design of apparatus in substations is simplified due to lower stress on insulation.

Shield wires on transmission lines may include optical fibers (OPGW), used for communication and control of the power system.

Medium-voltage distribution lines may have the grounded conductor strung below the phase conductors to provide some measure of protection against tall vehicles or equipment touching the energized line, as well as to provide a neutral line in Wye wired systems.

While overhead lines are usually bare conductors, rarely overhead insulated cables are used, usually for short distances (less than a kilometer). Insulated cables can be directly fastened to structures without insulating supports.

An overhead line with bare conductors insulated by air is typically less costly than a cable with insulated conductors.

A more common approach is "covered" line wire. It is treated as bare cable, but often is safer for wildlife, as the insulation on the cables increases the likelihood of a large wing-span raptor to survive a brush with the lines, and reduces the overall danger of the lines slightly. These types of lines are often seen in the eastern United States and in heavily wooded areas, where tree-line contact is likely.

The only pitfall is cost, as insulated wire is often costlier than its bare counterpart.

Many utility companies implement covered line wire as jumper material where the wires are often closer to each other on the pole, such as an underground riser/Pothead, and on reclosers, cutouts and the like.

Aerial bundled cable

Low voltage overhead lines may use either bare conductors carried on glass or ceramic insulators or an aerial bundled cable system.

The number of conductors may be anywhere between four (three phase plus a combined earth/neutral conductor - a TN-C earthing system) up to as many as six (three phase conductors,

separate neutral and earth plus street lighting supplied by a common switch).

Train power

Overhead lines or overhead wires are used to transmit electrical energy to trams, trolleybuses or trains.

Overhead line is designed on the principle of one or more overhead wires situated over rail tracks. Feeder stations at regular intervals along the overhead line supply power from the high voltage grid. For some cases low-frequency AC is used, and distributed by a special traction current network.

Further applications

Overhead lines are also occasionally used to supply transmitting antennas, especially for efficient transmission of long, medium and short waves.

For this purpose a staggered array line is often used.

Along a staggered array line the conductor cables for the supply of the earth net of the transmitting antenna are attached on the exterior of a ring, while the conductor inside the ring, is fastened to insulators leading to the high voltage standing feeder of the antenna.

Usage of area under overhead power lines

Use of the area below an overhead line is restricted because objects must not come too close to the energized conductors. Overhead lines and structures may shed ice, creating a hazard.

Radio reception can be impaired under a power line, due both to shielding of a receiver antenna by the overhead conductors, and by partial discharge at insulators and sharp points of the conductors which creates radio noise.

In the area surrounding overhead lines it is dangerous to risk interference; e.g. flying kites or balloons, using ladders or operating machinery.

Overhead distribution and transmission lines near airfields are often marked on maps, and the lines themselves marked with conspicuous plastic reflectors, to warn pilots of the presence of conductors.

Construction of overhead power lines, especially in wilderness areas, may have significant environmental effects.

Environmental studies for such projects may consider the effect of brush clearing, changed migration routes for migratory animals, possible access by predators and humans along transmission corridors, disturbances of fish habitat at stream crossings, and other effects.

Electricity Power Supply Systems

The generation and supply of electrical energy to customers is an important part of the community in which we live to-day.

Within Australia, this is generally separated into the sections of generation, transmission (with subtransmission) and distribution. Figure 1 shows a simple sketch of a system to help you visualise these various sections.

In most states, the management and control of generation transmission and distribution are being separated as a matter of governmental policy, to provide competition between various generating authorities and supply authorities and to improve service.

As shown in Figure 1, the extent of voltages falling within the responsibility of supply authorities is generally 132kV and below, with some 66kV in rural areas.

Another aspect of the supply of electrical energy to customers is the increase in supplementary generation, sometimes by individual customers.

This can be either local generation or cogeneration, both of which are operated in conjunction with the supply from the transmission system or the supply authority.

The many features of cogeneration (which includes heat recovery from spent fuel) are covered in another subject.

Distribution Systems and Voltage Levels

Various Voltage Levels in Distribution

In older systems the supply authority collects the bulk energy at 66 kV or less from the transmission substation.

As indicated in Figure 1, there are specific voltage values used in the distribution of electrical power.

These voltage values, which are all ‘line to line’ values are 66kV, 22kV, 11kV, 6.6kV and 400/230V.

Some of these values are rarely used in public distribution networks but are common in private networks in large industrial sites (eg 3.3kV, 6.6kV).

Considered in its most simple form, electric power distribution consists of two main elements (i) the retail function, or buying and selling of electrical energy and (ii) the distribution function, which is the transport and dissemination of the power.

These functions have been recognised as being quite separate and financially separated from one another in the new competitive electricity market which has been set up in Australia in recent years.

As electricity is not ‘stored’, many aspects of distribution are influenced by minimising the costs associated with the (instantaneous) ‘buy and sell’ operation.

The choice of voltage to be used on any particular section in the distribution system will be influenced, among other factors, by:

- decisions associated with voltage drops resulting from large current loads
- capital cost of transformers used to change voltage levels
- capital costs of construction of distribution lines and associated switchgear to operate at the chosen voltage
- environmental aspects of the system installation.

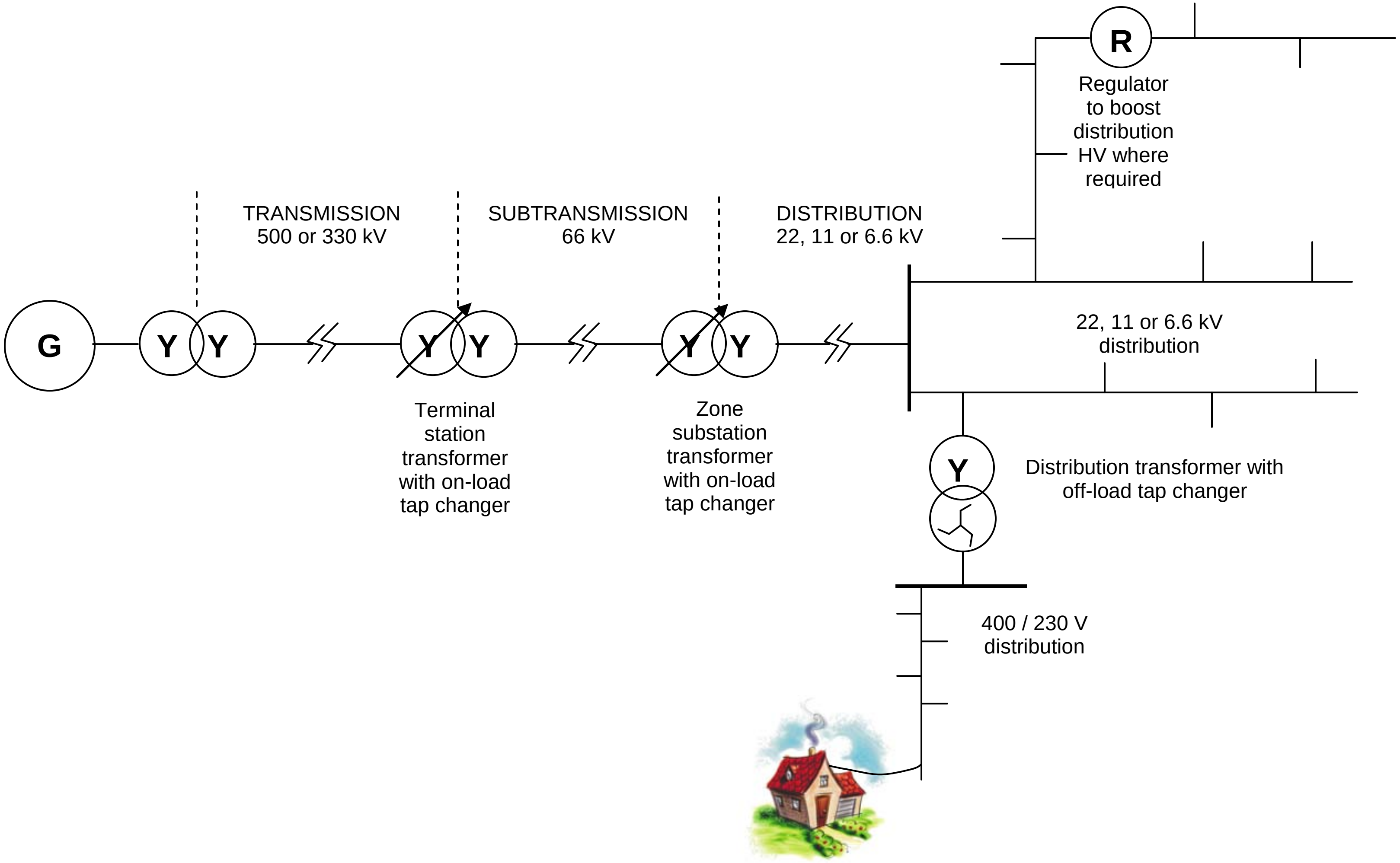


Figure 1. A simple power system

For any given electrical load (in kVA), the higher the load voltage the lower will be the resultant current required.

As it is the current flowing in the supply cabling which creates the voltage drop and the heating (I2R) loss, to minimise losses we try to keep the values of line current as low as possible. In this way the necessary distribution line voltage level can be determined, along with the resultant cost of constructing the line.

This explains why bulk generation and transmission, where large quantities of power are produced in big 'base-load' generation stations and transmitted to major load centres, is done at very high voltages.

This also explains why, with the exception of the low voltage distribution network, where voltages are set at 230 volts single phase/400 volts three phase, the highest voltages practical are used throughout all distribution, subtransmission and transmission systems.

Because of the large cost differential between having electricity cables (conductors) overhead, suspended on insulators fixed to poles, or underground, in heavily insulated cables, many distribution systems are overhead, this being the cheaper system.

However, current design tends toward placing distribution assets underground for both aesthetic and practical reasons – communities prefer a "cleaner" skyline and underground assets are less likely to be damaged (car accidents, building site cranes, etc).

Types of distribution feeder systems

Radial

Many distribution systems operate using a 'radial feeder' system. A typical radial feeder system is shown schematically in Figure 2.

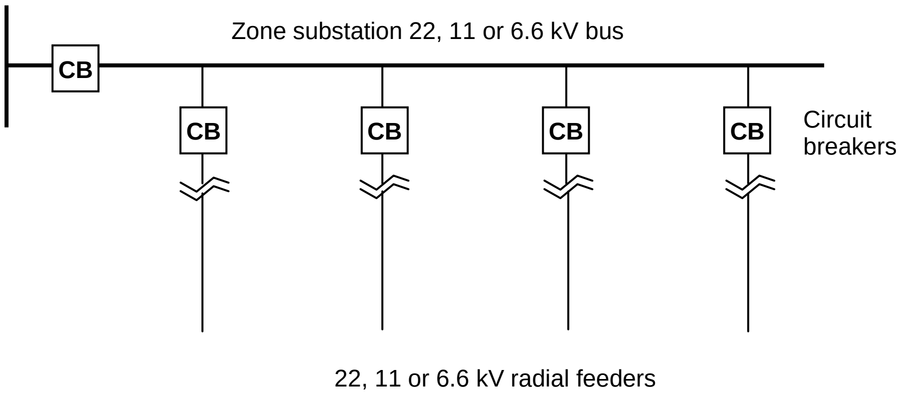


Figure 2. Radial feeder system

Radial feeders are the simplest and least expensive, both to construct and for their protection system.

This advantage however is offset by the difficulty of maintaining supply in the event of a fault occurring in the feeder.

A fault would result in the loss of supply to a number of customers until the fault is located and cleared.

The next level of reliability is given by a 'parallel feeder' system.

Parallel feeders

A greater level of reliability at a higher cost is achieved with a parallel feeder. A typical parallel feeder system is shown schematically in Figure 3.

In the event of a line fault only one of the feeder sets of cables will be affected, thus allowing the remaining parallel feeder to continue to supply the load.

To improve the reliability factor it may be possible to have the separate sets of cables follow different routes.

In this case the capital cost is double that of a radial feeder but there is a greater reliability factor for the line.

This may be justified if the load is higher, more customers are being supplied, or there are loads such as hospitals which require high levels of reliability.

Parallel feeders are more common in urban areas or for feeders to large single customers, where load shedding in an emergency may be possible.

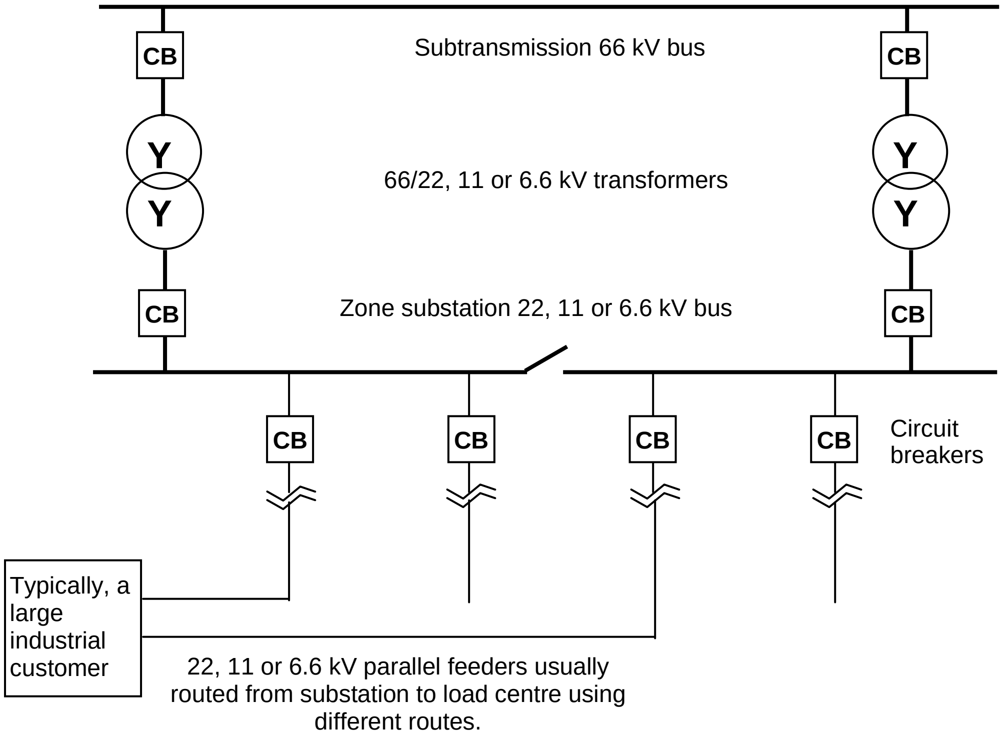


Figure 3. Parallel feeder system

Ring main

A similar level of system reliability to that of the parallel arrangement can be achieved by using 'ring main' feeders.

This usually results from the growth of load supplied by a parallel feeder where the cabling has been installed along different routes.

These are most common in urban and industrial environments.

Whilst the start and finish ends of the ring are at the same location, power is delivered by both pathways of the ring into substations located around the ring.

Should a fault occur on a feeder cable at any point around the ring the faulty section may be isolated by the operation of the protecting circuit breakers, at the same time maintaining supply to all substations on the ring.

In typical urban/suburban ring-main arrangements, the open ring is operated manually and loss of supply restored by manual switching.

Current practice is to use 'distribution automation', where operation and supply restoration in the feeder rings is done automatically by centrally-controlled supervisory systems.

This gives the advantages of ring main systems as line voltage drops are reduced at the various load Substations there is a 'firm' supply (ie an alternative path is available if the primary one fails) to each load substation.

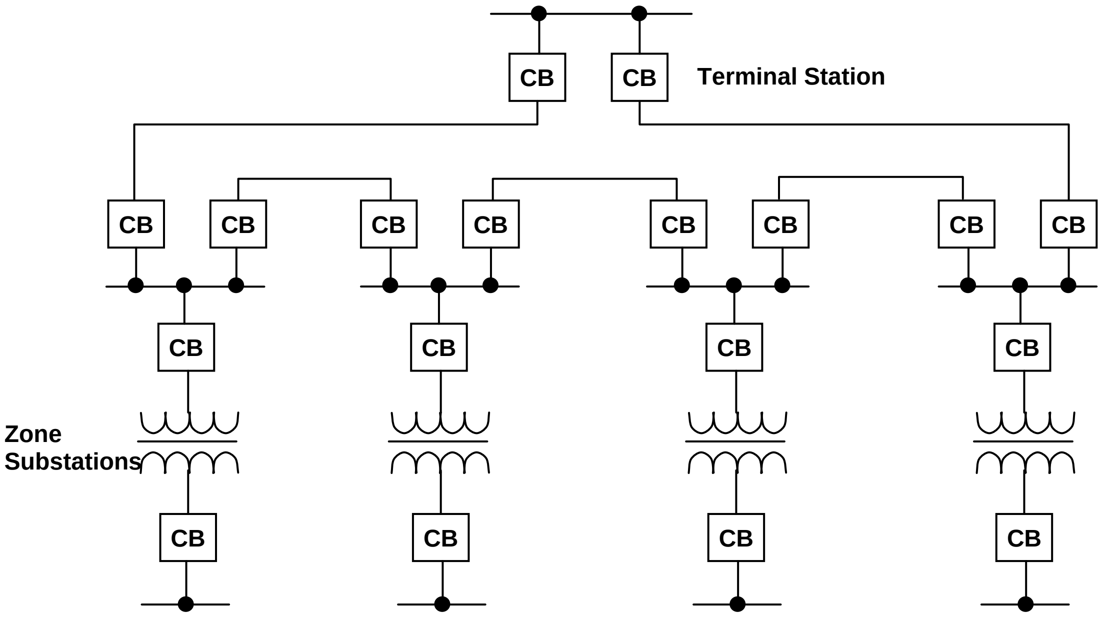


Figure 4. A ring main feeder system

Meshed systems

In transmission and sub-transmission systems, usually parallel, ring or interconnected ('mesh') systems are used.

This ensures that alternative supply can be made to customers in the event of failure of a transmission line or element.

The extra expense can be justified because of the much greater load and number of customers that are affected by failure of lines at transmission or sub-transmission levels. The general rule is that where large loads or numbers of customers are involved, then some form of standby, in the form of deliberate redundancy, is built into the network design, through the use of parallel, meshed or ring type feeders.

Only in outer rural areas would one consider using only radial supply at a sub-transmission level.

On the other hand, simple radial supply is almost universally used for low voltage (400V) feeders, even in urban areas, because they supply relatively few customers.

Revision exercise 1

1. List the voltage levels used in the various stages of transmission and distribution in electric power systems.

2. List the main sections of a power system, starting with the generators and ending with the customer's load?

3. State where one would use each of the following types of feeders. Give reasons in each case.
    a. Radial feeders

    b. Parallel feeders

    c. Ring feeders

    d. Meshed feeders

4. How can the cost of the higher-level feeder systems be justified?

Overhead and Underground Power Systems

As stated previously, initial overhead line construction is less expensive than underground cabling for the same kVA load. In rural or semi-rural areas, the sheer cost of underground cabling would make it impossible for customers to be able to afford the cost of supply.

The down side is that overhead lines operate under continual mechanical stress with exposure to varying climatic conditions.

This results in progressive deterioration in time as a result of corrosion, mechanical wear and fatigue, timber rot, etc.

All components must be periodically inspected and replaced as required. They are exposed to environmental impacts such as storms, lightning, wind-blown debris and traffic impact (of poles) which means overhead systems are rarely as reliable as underground ones.

The greater spacing of overhead line conductors generally results in higher system inductance than for a cable system.

This means an overhead line has a greater voltage drop than an underground cable of equal current-carrying capacity and hence cannot supply power over as long a distance as the underground equivalent, particularly for lower voltage distribution systems.

Even though poles are considered unsightly in urban locations, the capacity of an overhead feeder can be readily increased by replacing it with larger conductors and/or increasing the voltage insulation/operating level.

This flexibility is one big advantage of overhead systems.

The reliability of underground distribution is greater than for overhead systems because of the lower number of fault interruptions, as discussed above.

However, when interruptions do occur they are generally of much longer duration than those associated with overhead lines.

Underground cables have comparatively higher capacitance, and under light load conditions can affect system power factor.

In some cases, high charging currents and high transient voltages may accompany switching of cable systems that are open-circuited (especially at the higher distribution voltages, eg 22kV). This light-load performance can limit total underground feeder length.

On the other hand, this does mean they can supply heavy load, especially when it is inductive in nature, over longer distances than overhead lines.

The cost of underground cabling includes:

- the cost of trenching (and sometimes compensation for private amenity) coping with obstructions from other utilities such as gas, water, sewerage / drainage, telephone, etc

- the reinstatement of footpaths and road surfaces.

- The subsequent installation of another underground cable along the same path for system reinforcement by a parallel or ring feeder, generally only exacerbates these difficulties.

Overhead Insulated Conductors

A more recent development has been the use of overhead conductors which are insulated.
These conductors are more expensive than bare overhead but cheaper than full underground, as full cable outer mechanical protection is not needed, nor is expensive trenching and restoration. Being insulated provides some protection against wind-blown debris short-circuiting conductors together or conductor clashing.
There are two basic types:

1. Aerial bundled cable, or ABC for short, consisting of fully insulated (ie safe to touch) conductors tightly wrapped around a mechanical bearer wire (usually steel).
2. Covered conductors, consisting of ‘partly insulated’ conductors mounted on insulators similar to bare overhead lines. These are cheaper than ABC and offer most of the protection features against wind-blown debris as does ABC but are not touch safe.

ABC in particular is heavy and unsightly requiring more poles than bare-wire overhead, but trees can grow around it and hide it almost completely from view in due course. Covered conductor can also tolerate trees near it, but not to the same extent as ABC. It is less heavy and less unsightly when not shielded by trees.

Revision exercise 2

1. What are the three main types of conductor/cable systems used in distribution?

2. What are the advantages and disadvantages of underground distribution cable networks?

3. Where would one use aerial insulated conductor systems instead of either bare wire overhead or underground systems?

Three Phase, Single Phase and Single Wire Earth Return Systems

By far the majority of customers have electricity supplied to their homes, offices, factories, etc. as a three phase and/or single phase supply at voltages of 400 volts and/or 230 volts.

Most houses are supplied at 230 volt single phase, as this is cheapest for light loads, involving only two wires.

Medium sized ‘business’ customers (ie, factories, shops) will normally be supplied at 400 volt three-phase.

This involves running four wires into the customer and is still cost effective in urban areas because the street supply is always three phase.

The low voltage consists of three 230 Volt active phases and one ‘neutral’.

The neutrals are then connected to the customers load using the MEN system of earthing.

This provides a low resistance connection to earth providing protection to both the customers and the supply system in the event of faults.

Large customers cannot be supplied economically at 400/230 volts because of the high cost of providing all the cabling that would be required.

nstead, such customers (eg mines, large industrial sites, large commercial centres) are usually supplied at a high voltage instead of the conventional 400/230 Volts.

In this case the customer would usually own (or lease) the power transformer or transformers needed to reduce the high voltage supply, and in return the customer would have a lower tariff for energy consumed.

High voltage single phase systems are commonplace in rural areas, where the cost of supplying customers with relatively small loads at remote locations is a major problem. In such areas, the high voltage (usually 22kV or 11kV) feeder has only two wires and substations only supply one customer or a small group of customers close together, eg a farm and its associated out-buildings).

There is no real low voltage network, other than single phase supply direct to the farm buildings.

In such situations, the method used is to arrange the 22/11 kV overhead line to pass as close as practical to most of the customers.

At the nearest pole to a customer a double wound single phase pole mounted transformer is connected with the primary across the two high voltage wires and the secondary providing nominally 230 volts, as a single phase to neutral supply.

Single wire earth return (SWER) or single wire ground return is a single-wire transmission line for supplying single-phase electrical power from an electrical grid to remote areas at low cost.

It is principally used for rural electrification, but also finds use for larger isolated loads such as water pumps, and light rail.

Single wire earth return is also used for HVDC over submarine power cables.

Description

SWER is a choice for a distribution system when conventional return current wiring would cost more than SWER’s isolation transformers and small power losses.

Power engineers experienced with both SWER and conventional power lines rate SWER as equally safe, more reliable, less costly, but with slightly lower efficiency than conventional lines. Some single wire transmission proposals have used radio-frequency AC.

SWER uses conventional 50Hz or 60Hz AC power, and is therefore much less expensive.

Conventional low frequency 50Hz or 60Hz power is supplied to the SWER line by an isolating transformer of up to 300 kVA.

This transformer isolates the grid from ground or earth, and changes the grid voltage (typically 22 kilovolts line to line) to the SWER voltage (typically 12.7 or 19.1 kilovolts line to earth).

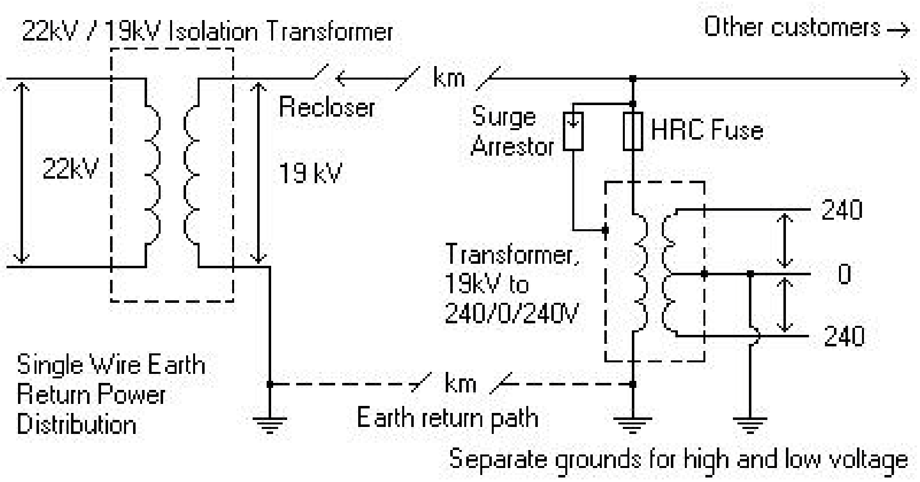
SWER line

The SWER line is a single conductor that may stretch for tens or even hundreds of kilometres, visiting a number of termination points.

At each termination point, such as a customer's premises, current flows from the line, through the primary coil of a step-down transformer, to earth through an earth stake.

From the earth stake, the current eventually finds its way back to the main step-down transformer at the head of the line, completing the circuit.

SWER is therefore a practical example of a phantom loop.



SWER burns up grounding poles or may fail to reset breakers in areas with high resistance soil.

In Australia, locations with very dry soils need the grounding poles to be extra deep.

Experience in Alaska shows that SWER needs to be grounded below permafrost, which is high-resistance.

The secondary winding of the local transformer will supply the customer with either single ended single phase (N-0) or split phase (N-0-N) power in the region’s standard appliance voltages, with the 0 volt line connected to a safety earth that does not normally carry an operating current.

A large SWER line may feed as many as 80 distribution transformers.

The transformers are usually rated at 5 kVA, 10 kVA and 25 kVA. The load densities are usually below 0.5 kVA per kilometer (0.8 kVA per mile) of line.

Any single customer’s maximum demand will typically be less than 3.5 kVA, but larger loads up to the capacity of the distribution transformer can also be supplied.

Some SWER systems in the USA are conventional distribution feeders that were built without a continuous neutral (some of which were obsoleted transmission lines that were refitted for rural distribution service).

The substation feeding such lines has a grounding rod on each pole within the substation; then on each branch from the line, the span between the pole next to and the pole carrying the transformer would have a grounded conductor (giving each transformer two grounding points for safety reasons).

History

At the end of the 19th century, Nikola Tesla demonstrated that only a single wire was necessary for power systems, with no need for a wired return conductor (using the Earth instead).

Lloyd Mandeno fully developed SWER in New Zealand around 1925 for rural electrification. Although he termed it “Earth Working Single Wire Line” it was often called “Mandeno’s Clothesline”. More than 200,000 kilometres have now been installed in Australia and New Zealand.

It is considered safe, reliable and low cost, provided that safety features and earthing are correctly installed.

The Australian standards are widely used and cited. It has been applied in Saskatchewan of Canada, Brazil, Africa, portions of the United States' Upper Midwest, and SWER interties have been proposed for Alaska and prototyped.

Characteristics

Safety

SWER violates common wisdom about electrical safety, because it lacks a traditional metallic return to a neutral shared by the generator.

SWER’s safety is instead assured because transformers isolate the ground from both the generator and user.

However, certain groups claim that stray voltages from SWER can injure livestock.

Grounding is critical because of the significant currents on the order of 8 amperes that flow through the ground near the earth points, so a good-quality earth connection is needed to prevent risk of electric shock due to earth potential rise near this point.

Separate grounds for power and safety are also used.

Duplication of the ground points assures that the system is still safe if either of the grounds is damaged.

A good earth connection is normally a 6 m stake of copper-clad steel driven vertically into the ground, and bonded to the transformer earth and tank.

A good ground resistance is 5–10 ohms.

SWER systems are designed to limit the voltage in the earth to 20 volts per meter to avoid shocking people and animals that might be in the area.

Other standard features include automatic reclosing circuit breakers (reclosers).

Most faults (over-current) are transient.

Since the network is rural, most of these faults will be cleared by the recloser.

Each service site needs a rewirable drop out fuse for protection and switching of the transformer.

The transformer secondary should also be protected by a standard high-rupture capacity (HRC) fuse or low voltage circuit breaker.

A surge arrestor (spark gap) on the high voltage side is common, especially in lightning-prone areas.

Bare-wire or ground-return telecommunications can be compromised by the ground-return current if the grounding area is closer than 100 m or sinks more than 10 A of current.

Modern radio, optic fibre channels and cell phone systems are unaffected.

Cost advantage

SWER's main advantage is its low cost.

It is often used in sparsely populated areas where the cost of building an isolated distribution line cannot be justified.

Capital costs are roughly 50% of an equivalent two-wire single-phase line.

They can be 70% less than 3-wire three-phase systems.

Maintenance costs are roughly 50% of an equivalent line.

SWER also reduces the largest cost of a distribution network, the number of poles.

Conventional 2-wire or 3-wire distribution lines have a higher power transfer capacity, but can require seven poles per kilometre, with spans of 100 m to 150 m. SWER's high line voltage and low current permits the use of low-cost galvanized steel wire.

Steel's greater strength permits spans of 400 m or more, reducing the number of poles to 2.5 per kilometre.

Reinforced concrete poles have been traditionally used in SWER lines because of their low cost, low maintenance, and resistance to water damage, termites and fungus.

Local labor can produce them in most areas, further lowering costs.

If the cable contains optic fibre, or carries telephone service, this can further amortize the capital costs.

Reliability strengths

SWER can be used in a grid or loop, but is usually arranged in a linear or radial layout to save costs. In the customary linear form, a single-point failure in a SWER line causes all customers further down the line to lose power.

However, since it has fewer components in the field, SWER has less to fail. For example, since there is only one line, winds can't cause lines to clash, removing a source of damage, as well as a source of rural brush fires.

Since the line can't clash in the wind, and the bulk of the transmission line has low resistance attachments to earth, excessive ground currents from shorts and geomagnetic storms are far more rare than in conventional metallic-return systems.

So, SWER has fewer ground-fault circuit-breaker openings to interrupt service.

Power quality weakness

SWER lines tend to be long, with high impedance, so the voltage drop along the line is often a problem, causing poor regulation.

Variations in demand cause variation in the delivered voltage.

To combat this, some installations have automatic variable transformers at the customer site to keep the received voltage within legal specifications.

When used with distributed generation, SWER is substantially more efficient than when it is operated as a single-ended system.

For example, some rural installations can offset line losses and charging currents with local solar power, wind power, small hydro or other local generation.

This can be an excellent value for the electrical distributor, because it reduces the need for more lines.[

After some years of experience, the inventor advocated a capacitor in series with the ground of the main isolation transformer to counteract the inductive reactance of the transformers, wire and earth return path.

The plan was to improve the power factor, reduce losses and improve voltage performance due to reactive power flow.

Though theoretically sound, this is not standard practice.

Networks and circuits

As demand grows, a well-designed SWER line can be substantially upgraded without new poles.
The first step may be to replace the steel wire with more expensive copper-clad or aluminium-clad steel wire.
It may be possible to increase the voltage.
Some distant SWER lines now operate at voltages as high as 35 kV.
Normally this requires changing the insulators and transformers, but no new poles are needed.
If more capacity is needed, a second SWER line can be run on the same poles to provide two SWER lines 180 degrees out of phase.
This requires more insulators and wire, but doubles the power without doubling the poles.
Many standard SWER poles have several bolt holes to support this upgrade.
This configuration causes most ground currents to cancel, reducing shock hazards and interference with communication wirelines.
Two phase service is also possible with a two-wire upgrade:
Though less reliable, it is more efficient.
As more power is needed the lines can be upgraded to match the load, from single wire SWER to two wire, single phase and finally to three wire, three phase.
This ensures a more efficient use of capital and makes the initial installation more affordable.
Customer equipment installed before these upgrades will all be single phase, and can be reused after the upgrade.
If moderate amounts of three-phase are needed, it can be economically synthesized from two-phase with on-site equipment.

Regulatory issues

Many national electrical regulations (notably the U.S.) require a metallic return line from the load to the generator.
In these jurisdictions, each SWER line must be approved by exception.

Use in interties

In 1981 a high-power 8.5 mile prototype SWER intertie was successfully installed from a coal plant in Bethel to Napakiak in Alaska, United States.
It operates at 80 kV, and has special lightweight fiberglass poles forming an A-frame.
The poles can be carried on lightweight snow machines, and most poles can be installed with hand tools on permafrost without extensive digging.
Erection of “anchoring” poles still required heavy machinery, but the cost savings were dramatic.
The phase conductor also carries a bundle of optical fibres within the steel armour wire, so the system supplies telecommunications as well as power.
Researchers at the University of Alaska Fairbanks, United States estimate that a network of such interties, combined with coastal wind turbines, could substantially reduce Alaska’s dependence on increasingly expensive diesel fuel for power generation.
Alaska’s state economic energy screening survey advocated further study of this option to use more of the state’s underutilized power sources.

Use by developing nations

At present, certain developing nations have adopted SWER-systems as their mains electricity systems. Notably Laos and South Africa.

Use for HVDC systems

Many HVDC systems using submarine power cables are (or were until their expansion to bipolar schemes) single wire earth return systems.

To avoid electrochemical corrosion, the ground electrodes of such systems are situated apart from the converter stations and not near the transmission cable.

The electrodes can be situated in the sea or on land.

Bare copper wires can be used for cathodes, and graphite rods buried in the ground, or titanium grids in the sea are used for anodes.

To avoid electrochemical corrosion (and passivation of titanium surfaces) the current density at the surface of the electrodes may be only small and therefore large electrodes are required.

The advantage of such schemes is eliminating the cost of a second conductor, since saltwater is an excellent conductor.

Some ecologists claim bad influences of electrochemical reactions, but they do not occur on very large underwater electrodes.

Revision Exercise 3

1. Where would you expect three phase and single phase systems to be used? Why?

2. How is supply provided to very large customers?

Supply Quality

It is the aim of a well-designed electricity system to provide voltage to customers that is stable, stays within limits and is free from random momentary variations and other disturbing waveforms. The term ‘supply quality’ or ‘quality of supply’ has come to be a collective term which includes electrical power parameters such as:

- voltage variation outside of standards
- voltage sags and swells
- repeated fluctuations
- impulses (spikes)
- momentary interruptions (sudden dips)
- frequency variations and waveform distortion (harmonics).

As well as the problems caused by such variations with computing equipment, variable speed drive controllers and other sensitive electronic controls, there can also be interruptions to customers resulting in loss of production or amenity.

There is also a need to ensure the robustness of a supply, which includes its ability to continue to meet power demands under excessive loads, operation of system protection equipment, etc. The result is that greater care has to be given to what, in the past, may have been considered ‘risk factors’ that the customer was once expected to simply put up with as a part of his electricity supply.

Some of the more established factors considered in supply quality are now listed and discussed.

Voltage and frequency Stability

Standards and legislation in the various countries set out the values and acceptable tolerances on voltage and frequency values allowable from a distributor.

If frequency varies even by small amounts from the nominal 50 hertz (cycles per second) this will cause problems for generation equipment and to customers.

Once system frequency falls as low as only 49.5 Hz the system usually is on the verge of collapse.

From a customer’s perspective, voltages which are too high will severely reduce the life of incandescent lamps and possibly damage sensitive equipment, whilst voltage values which are too low will significantly increase the current drawn (relative to the rated current and voltage) for any motor driven loads, resulting in possible thermal damage to motors and reduce the starting/pull-out torques of motors.

For these reasons considerable care needs to be taken to ensure that voltage values are held stable during the daily cycle of load changes.

The maximum variation in voltage (ie difference between highest and lowest voltage) is referred to as ‘voltage spread’, ‘variation’ or ‘bandwidth’.

This is usually expressed as a percentage of the nominal voltage.

In Australia, standards set the maximum voltage regulation for 230 volt systems to be 230 volts plus 10% or minus 14%, ie a maximum of 253 volts and a minimum of 198 volts for all except emergency conditions.

Voltage Fluctuations

Rapidly varying loads, ie those where the current drawn from the power system goes up and down in magnitude frequently, cause voltage drops in the system which is also rapidly varying and consequently other customers are subjected to them.

This is an additional problem on top of the slow variations in voltage throughout the day discussed above.

Loads of this nature include electric motors which start up, run and shut down (or go from light to full load and back again) frequently, eg rolling mills, metal shredders, as well as arc welders and the like.

The voltage drop can be seen by customers as a dip in the output of lights; if it occurs frequently it causes a flickering of the lights which can be extremely annoying.

The more rapid the flicker, the worse the visual distress that is caused.
There are standards which limit the amount and frequency of such voltage fluctuations on the system.

Momentary Interruptions
Another problem somewhat akin to voltage fluctuations is momentary interruptions to supply.
These can occur for a number of reasons, usually when transient faults on the system may cause a large but very brief voltage dip on the system, or when the primary supply may fail and the system will switch across to a standby supply, eg on a ‘ring’ system.
The effect is sometimes low or no supply from less than a second to maybe several seconds.
Normally this will be of minor inconvenience, often hardly noticed by most customers.
It does cause problems for voltage sensitive equipment such as computers, digital clocks which often have to be reset and to ‘undervoltage’ relays on large electric motors, which often will trip the motor out (on the mistaken assumption that the voltage will stay low and the motor overheat).
In the past momentary interruptions rarely caused problems but with increasing numbers of voltage sensitive devices, especially electronic and digital ones, it is becoming a major issue for electricity distributors.

Revision Exercise 4

1. What are the main areas of concern under the broad definition of ‘supply quality’?

2. What problems can be caused by the following power supply variations?

   a) Excessive voltage

   b) Too low a voltage

3. Why are momentary dips on the system more of a problem now than they used to be?

Power Factor Considerations

As most electrical loads are inductive, and distribution lines, when loaded, are also inductive, a heavily loaded distribution system usually appears to be an inductive impedance and operates at a ‘lagging’ power factor.

This means that the current sine wave lags somewhat behind the voltage sine wave.

Depending on the line construction and its length, a lightly-loaded or open circuit overhead line may appear to be a capacitive load.

This means the current now leads the voltage and reduces voltage drop, but causes other complications including sometimes voltages which are too high at the receiving end.

The component (ie proportion) of the current in phase with the voltage sine wave represents the actual energy supplied by the system.

The rest of the current doesn’t supply useful energy to the customer and causes unwanted voltage drops and losses in the distribution system.

As the customers typically pay for energy in kilowatt-hours, to make best use of the current carrying capacity of a line we endeavour to minimise the reactive current component carried in the system. (This is determined by the amount of inductance and capacitance in the system.)

This can be achieved in a number of ways, the most popular of which is capacitor power factor correction at substations throughout the system.

This consists of adding shunt (ie from each phase to ground) capacitors, which increases the capacitance at selected points to directly counteract the inductance in the system, or the customers’ loads.

Waveform Distortion and Harmonics

Ideally, a power system should have voltages and currents which are pure sine-waves.

The ever increasing use of fluorescent lighting and electronic light dimmers, industrial rectifiers, variable speed motor drive equipment and computers (with switched mode power supplies) results in severe distortion of the sinusoidal waveform of the voltage in the distribution system.

As this electronic equipment is usually connected by the customer the distributor has little control over the extent of the equipment connected but must, on the other hand, ensure the supply complies with the relevant requirements.

The analysis of the effect of waveform distortion is usually done by considering the magnitude of the various harmonic components of the voltage which are present to create this distort it in

Instruments are available to measure the relative magnitudes of the harmonics present.

Harmonics are classified as ‘odd’ or ‘even’, depending on the numeric factor by which their frequency varies from the fundamental frequency (of 50 hertz).

Harmonics are also classified into groups designated as ‘positive’, ‘negative’ and ‘zero’ sequence values or components.

Frequency (Hertz)	***Harmonic Identification***	***Odd / Even***	***Sequence***
50	Fundamental		Positive
100	2ND	Even	Negative
150	3RD	Odd	Zero
200	4TH	Even	Positive
250	5TH	Odd	Negative
300	6TH	Even	Zero
350	7TH	Odd	Positive
400	8TH	Even	Negative
450	9TH	Odd	Zero
500	etc	Even	

Note: The fundamental can be thought of as an odd harmonic. A DC component, if present, is essentially a “zero” harmonic (at 0 hz) and is zero sequence, flowing down all phases to ground. This would fit into the overall pattern.

Table 1. Sequencing and Frequencies of Fundamental and harmonic Currents (based on 50 Hz system)

Whenever a neutral/earth connection is made, any ‘zero’ sequence components of current (resulting from corresponding voltages in the system) will flow to the ‘ground’.

If these values of current are significant (i.e. greater than 15% of the values of line currents) there can be a measurable voltage drop created in the neutral/earth connection.

The effect of this voltage drop is to ‘move’ the neutral (star point) voltage, and this can result in excessively high or low voltage values being applied to any connected equipment.

Other problems which result from harmonic distortion are manifest at or near the ‘earth stake’ location, where it is possible for dangerously high voltage values to result on the surface of the soil, or heating of the soil can occur, due to high earth current density.

Harmonics, especially the ‘negative sequence’ ones, cause overheating problems in electric motors and harmonics of all types interfere with electronic and computer-based equipment.

Revision exercise 5

1. Describe what power factor means and how it can be controlled.

2. List the main problems caused by harmonics in a power system.

Voltage Regulation

Voltage variation is the variation in the magnitude of the voltage value between its highest and lowest levels that occurs as the connected load changes between maximum and minimum. Voltage regulation, in an item of plant such as a transformer, or down a feeder, is the drop in voltage which occurs from the supply end to the connected load.

Both are usually expressed as a ratio or percentage of the load voltage. For an overhead line it can be defined mathematically as

$$\text{Voltage Regulation} = \frac{\overline{E}_S - \overline{E}_R}{\overline{E}_R}$$

where: E_S is the voltage at the supply end, and
E_R is the voltage at the load.

The variation of voltage at a consumer's supply point should be kept to a minimum for the following reasons:

1. When incandescent lamps are connected their performance is very sensitive to variations in the supply voltage. A five per cent reduction below rated voltage results in a decrease between fifteen and twenty per cent of the light output; a five percent increase above rated voltage shortens the 'life' of the lamp by up to 40%.

2. Variations from rated voltage reduce the effectiveness of induction motors and transformers. When operating above rated voltage, the iron in the magnetic circuit of the motor/transformer will be closer to saturation or over saturated resulting in a larger magnetising current and greater heating of the motor/transformer. If the voltage is below the rated value, the starting torque and pull-out torque are considerably reduced and heavier currents have to be drawn which can overheat motors.

3. Depending on the internal circuitry, electronic control equipment, computers and television equipment may not function adequately with wide variations in supply voltage.

There is also an effect on the distribution system as operating above rated voltage causes excessive heating in distribution transformers and results in waveform distortion due to saturation of the iron, causing the introduction of third harmonic values of voltage.

These also can cause heating of earth stakes and local earth potential rise problems, if they are very high.

This variation in the voltage at the connected load between its highest to its lowest value is often referred to as 'bandwidth'.

Limits and standards

There are accepted standards which dictate maximum voltage variations in a public electricity supply system. The international standard recently adopted in Australia is based on 230 volts rather than 240 volts, to enable standardisation of appliances, motors and the like. It specifies 230 volts plus 10% minus 14% as the maximum permissible regulation.

The voltages will however apply to 'utilisation voltages' rather than the voltage at 'customer's terminals' as does the existing standard.

Its important at this stage to fully understand the terminology used and these are explained in the following section.

Terminology

Distribution system

This essentially, is the feeders and substations and their ancillary equipment - poles, switches, circuit breakers, fuses plus the support equipment such as supervisory control and protection systems which makes up the public supply network.

The ‘public’ network is one which is ‘shared’, ie supplies at least two or more customers over the one set of assets.

A ‘private’ system is one which feeds just the one customer, even when the customer is very large and may have a private network which contains many local substations and feeders.

The distribution system also means that part of the public network which operates at voltages below that defined as ‘transmission’ and typically takes voltages at medium to high levels and reduces these down for use by customers.

The role and design of other ancillary equipment is covered in other courses and will not be discussed further in this module; however it is equally important to the function of the distribution system as are the feeders discussed here.

Customer’s terminals

This is the connection point between the public distribution system and the take-off to supply individual customers.

Typically for residential customers, it is the ‘barge board’ on the front of the house. For a farm it is typically the first low voltage pole just inside the property of the customer, where that take-off supplies just the one customer only.

Customer voltage

This is the voltage at the ‘customer’s terminals’, as defined above.

As discussed previously, the current Australian standards for maximum variation in voltage refer to the voltage at the customers’ terminals.

Base voltage

This is the nominal voltage of the distribution system.

For low voltage systems in Australia, this is almost universally 240 volts single phase/415 volts three phase.

There is a separate base voltage for each voltage layer in the distribution system, eg 11 kV, 66 kV, 132 kV etc.

Utilisation voltage

This is the voltage at the ‘point of utilisation’ i.e. the power point inside the customer’s premises. It is a more realistic representation of voltage conditions that appliances will be subject to in their typical use than is ‘customer voltage’.

Under heavy loading conditions, it will be lower than the voltage at the customer’s terminals, due to the voltage drop in the customer’s wiring which runs between the customer terminals and the actual power point.

The proposed 230 volts standard will recognise this by using utilisation voltage in its definition of limits rather than customer voltage.

Revision exercise 6

1. What is the definition of:

   Customers' terminals

   Base voltage

   Customer voltage

   Utilisation voltage

2. With regard to voltage variation, what is the current 400/230 volt supply standard in Australia?

3. With regard to voltage variation, what is the current low voltage supply standard in China?

Causes of voltage variation

Voltage variations on the distribution system may result from one or more of the following causes:

1. The voltage at the source (from the transmission system or generator) may not be controlled, or is controlled only within certain limits.

2. The voltage at the secondary of a transformer varies as the load changes. With a large load current the voltage drop due to the transformer windings needs to be subtracted from the (open circuit) voltage of the secondary terminals (This is the voltage regulation of the transformer). As the load current decreases the terminal voltage increases, being at its greatest when there is no load current from the transformer.

3. The voltage drop in the distribution lines when delivering current, due to the inherent resistance and reactance of the overhead lines.

Variation of resistance of conductors

The value of resistance for conductors is usually stated for an ambient temperature of 20°C, however it is not unusual for an overhead line to have conductors at temperatures up to 65°C or more in summer time with large current loads. Due to this rise in conductor temperature it is possible to have the resistance of the conductor increase by up to 20% or more. The method of calculating this increase is as follows:

Starting from a value of (d.c.) resistance at 20°C, the (d.c.) resistance of the conductor at any other temperature 8°C can be calculated from:

$$R_\theta = R_{20}[1 + \alpha_{2O}(\theta - 20)]$$

where: R_θ = d.c. resistance at 8°C
R_{20} = d.c. resistance at 20°C
α_{20} = temperature coefficient of resistance at 20°C.

For copper, $\alpha_{20} = 0.00393$ per deg C

For aluminium, $\alpha_{20} = 0.00403$ per deg C.

This value then needs to be corrected to allow for the effect of a.c. voltages being applied to the conductors and the resultant slight variations in current density in the conductor, the effect of steel cores (if present) and any insulation (as in Aerial Bundled Cable or ABC). The ‘correcting value’ (R’) is found by measurement (empirically) and added to the previously calculated value of R_θ, so that the effective a.c. resistance $R_{\theta 2}$ is given by:

$$R_{\theta 2} = R_\theta + R'$$

Typically this adds about 10 to 15% to the DC resistance.

Inductance of overhead conductors

Inductance of feeders is caused by the magnetic fields around the currents (‘magnetic flux’) interacting with the conductors and inducing a reverse voltage or ‘back emf’ which opposes the current flow. This is manifest as a voltage drop in the conductors. The inductance of a non-magnetic conductor at 50 hertz, relative to another similar conductor can be calculated from the equation:

$$X_L = 0.0156 + 0.1447 \log_{10} \frac{d}{r} \text{ milli-Henries per km}$$

where: d = distance between conductors in metres
r = radius of the conductor in metres

In practice it is easier and more convenient to use pre-calculated tables for determining line reactance in ohms rather than individual calculations, or use computers and software packages such as spreadsheets.

Because conductor spacings for overhead lines are necessarily large, there is not a great deal of variation in overhead line reactance values for various conductors.

Schedules showing some selected values are given in Table 1 (straight aluminium or copper conductors) and Table 2 (steel-cored aluminium conductors).

Inductive Reactance ohms/km at 50 Hz and 1 metre spacings			
Conductor	***Reactance***	***Conductor***	***Reactance***
7 / 1.25	0.414	7 / 4.50	0.334
7 / 1.75	0.393	7 / 4.75	0.330
7 / 2.00	0.384	19 / 1.75	0.359
7 / 2.25	0.377	19 / 2.00	0.350
7 / 2.50	0.371	19 / 2.75	0.330
7 / 2.75	0.365	19 / 3.00	0.325
7 / 3.00	0.359	19 / 3.25	0.320
7 / 3.50	0.350	19 / 3.75	0.311
7 / 3.75	0.345	19 / 4.75	0.296

Table 2. Non-Ferrous Conductors

Inductive Reactance ohms/km at 50 Hz and 1 metre spacing			
Conductor	***Reactance***	***Conductor***	***Reactance***
6 / 1 / 1.25	0.372	30 / 7 / 2.50	0.315
6 / 1 / 3.00	0.362	30 / 7 / 3.00	0.304
6 / 1 / 3.75	0.346	30 / 7 / 3.50	0.294

Table 3. Steel-cored aluminium conductors (ACSR/GZ and ACSR/AZ)

	Separation mm									
	0	**25**	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**
250	–0.087	–0.081	–0.076	–0.071	–0.066	–0.062	–0.058	–0.054	–0.050	–-0.047
500	–0.044	–0.040	–0.038	–0.035	–0.032	–0.030	–0.027	–0.025	–0.022	–0.020
750	–-0.018	–0.016	–0.014	–0.012	–0.010	–0.008	–0.007	–0.005	–0.003	–0.002
1000	0	0.002	0.003	0.005	0.006	0.007	0.009	0.010	0.011	0.013

Table 4. Correction factors

Note the use of 1 metre as a standard spacing in the tables. In Table 3, correction values are shown which can be applied if the conductor spacing is not 1 metre.

For example if the spacing was 525 mm, looking across the second row labelled ‘500’ to the column ‘25’, we see that the correction factor is –0.040.

You can see that the reactance per unit length of an overhead line does not vary greatly with the spacing regardless of the conductor size.

For instance, with a 19/2.75 (being a 112.9 square millimetre conductor) the reactance varies only between 0.286 ohms per km (0.330 - 0.044 = 0.286) at 0.5 metre spacing and 0.343 ohms per km (0.330 + 0.013 = 0.343) at 1.25 metre spacing.

From a practical aspect, therefore, there is no appreciable error resulting if we assume a constant reactance value for any particular conductor size on the assumption that spacings for the line voltage will stay within a specific range.

The graph in Figure 5 illustrates the relationship between resistance, reactance and impedance for conductors with various values of cross sectional area.

From this we can see why there is little advantage to be gained by using conductors larger than 112.9 square millimetres (19/2.75) to reduce voltage drop because of the impact of the line reactance.

Underground cables also have inductance but as the conductors are much closer together than their overhead counterparts (because they are wrapped in insulation) their inductance is also somewhat lower.

This means a smaller voltage drop for the same load and hence underground cables can transmit power further than a same-sized overhead line.

ABC overhead conductors, because they are insulated, are also spaced closer together than bare conductors and likewise have a somewhat lower inductance, similar to that of underground cables.

Covered conductors, with spacing between that of bare-wire overhead and underground cables, have a slightly lower inductance than bare-wire overhead but not as low as underground.

Transformers at all voltages have inductance, which is caused by some of the magnetic field produced by the primary coils not linking completely with the secondary coil.

This stray field, called ‘leakage flux’, has its own inductance which causes a voltage drop in the transformer.

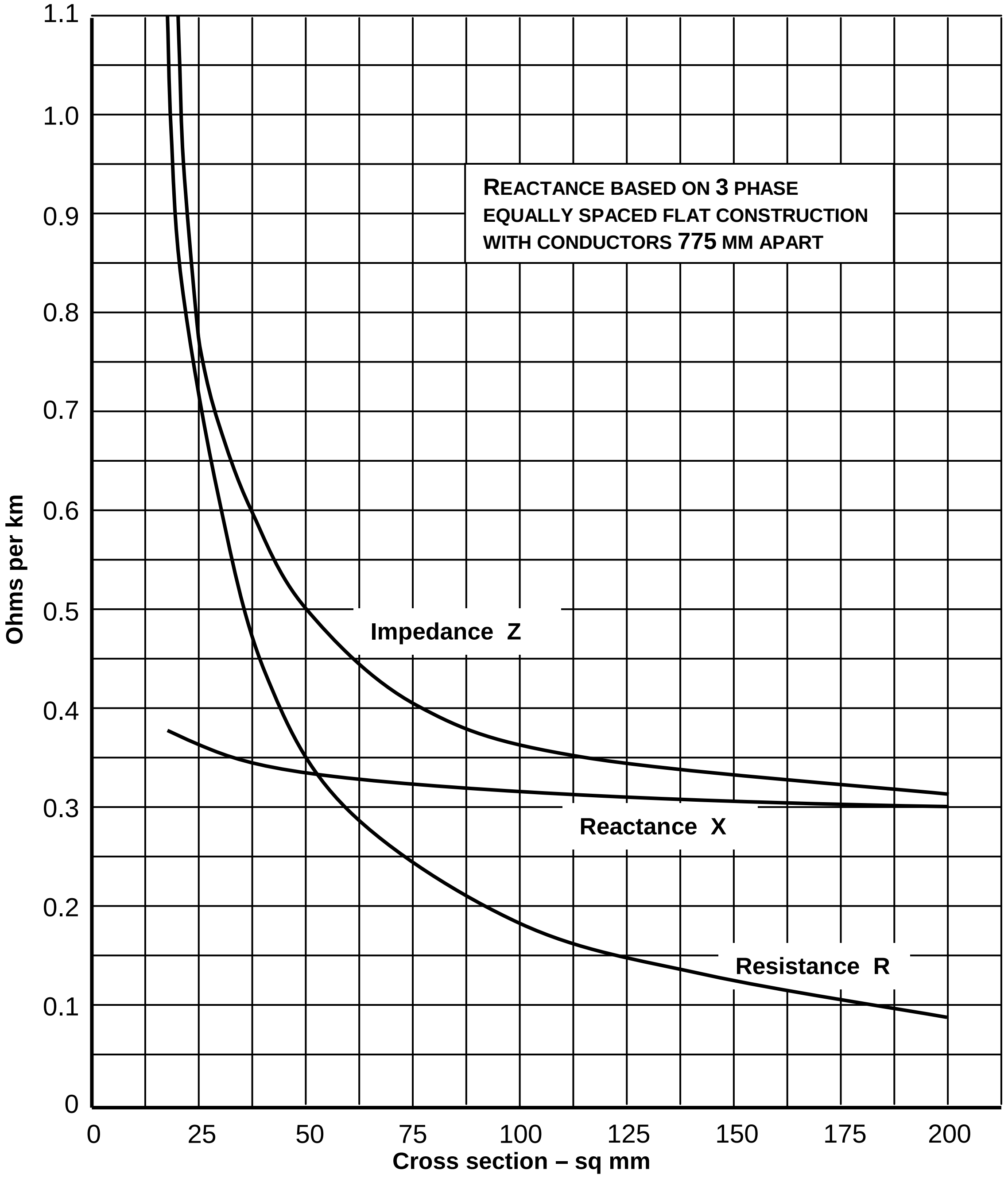


Figure 5. Relationship between resistance, reactance and impedance for conductors of differing cross-sectional areas

Shunt capacitance

Underground cables and long lines at high voltages also have shunt capacitance between conductors and between conductors and ground.

This is because conductors running parallel to one another behave a little like the plates on a capacitor.

Capacitance helps to counteract the effect of inductance in feeders, reducing the voltage drop at full load. it may cause problems at light load, causing the voltage to rise along the line to unacceptably high levels.

Capacitance is rarely an issue for distribution lines and typically is only considered for long transmission lines at voltages of 132kV and above.

Revision exercise 7

1. What three factors combine to determine the value of the impedance of distribution/transmission lines?

2. What are the factors that influence the inductance of overhead lines? Why is inductance a problem?

Equipment used in the control of voltage

Introduction

There are three general methods used to control the voltage at the end of a distribution feeder. They are by using:

- control equipment to vary the voltage at the supply end of the feeder
- control equipment at the load end which can vary the voltage
- controlling the current in the line by changing the power factor.

At the transmission source, voltage is controlled by the voltage regulators on the generators.

Voltage control equipment connected at either the supply end or the load end of the feeder would include off-load tap changing transformers, on-load tap-changing transformers, booster transformers, moving coil regulators, induction regulators.

Current controlling devices intended to control the power factor are either static or rotary capacitors.

Rotary capacitors are rarely if ever used in modem power systems and will not be discussed.

Voltage changing equipment

Tap-changing transformers are constructed so that the output voltage can be adjusted by means of a switch to increase or decrease the voltage.

Details of how this is done are given in the subject Power Transformers.

The switches can be designed to either carry no current at the time the voltage value is changed (off-load tap-changer) or to carry the full rated current (on-load tap-changer).

Usually the voltage is changed in increments of the rated voltage – typically 2.5% for distribution (22/11 kV to 400 volt) transformers but finer, say 1.25 – 1.5% for transformers in transmission substations- with a full range of adjustment up to ±10% of the rated output voltage.

This means that for an 11 kV line the voltage at the supply end can be between 9.9 kV and 12.1kV.

On-load tap-changers ensure there is no interruption to the electricity supply during the change of voltage value, and as a consequence are preferred, even though they are much more expensive.

When off-load tap-changers are installed the electricity supply must be disconnected for the duration of time required to change the voltage setting.

Typically, zone and transmission substation transformers are fitted with on-load tap changers because of the very high numbers of customers which would be affected if they had to be disconnected each time a tap change had to be made.

The essential elements of the load and the compensating circuits used for the automatic control of an on-load tap- changer are shown in Figure 6.

Essentially it consists of a voltage sensing relay, which will actuate the tap-changer motor to move the tap position automatically up or down as the voltage varies away from the set desired voltage level.

This set level is usually referred to as the ‘float voltage’ of the transformer or substation.

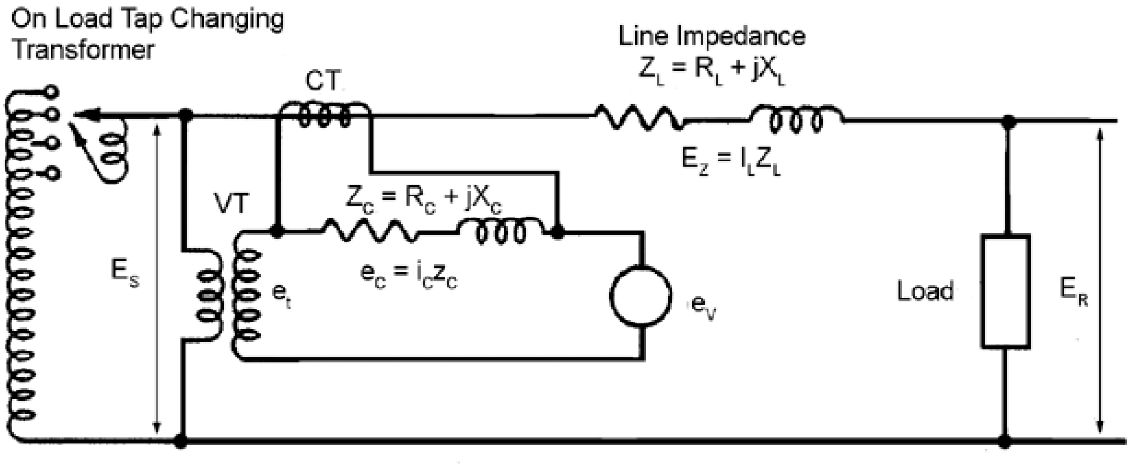
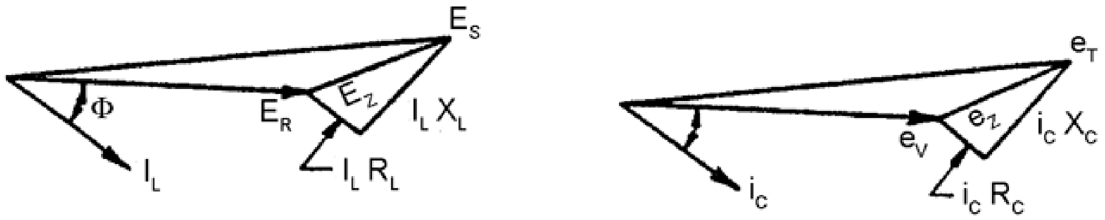


Figure 6(a). Load and Control Circuits



Main Circuit		***Control Circuit***	
E_S	Sending end voltage	e_T	Voltage transformer output voltage
E_Z	Line voltage drop	e_C	Compensator voltage drop
E_R	Receiving end voltage	e_V	Regulating relay voltage
R_L	Line resistance	R_C	Compensator resistance
X_L	Line reactance	X_C	Compensator reactance
I_L	Load current	i_C	C.T. secondary current

Figure 6(b). Phasor diagrams of load and control circuits

The voltage relay senses both transformer output voltage, plus a compensating voltage which reflects the drop expected in the feeder, as below.

To understand how the system works, firstly consider the simplest case, where the transformer output voltage drives the relay.

The output of the transformer is measured by the voltage transformer. If the output voltage falls outside the set level (‘float voltage’) due to say increasing load, the voltage regulating relay will activate the tap-changer and change one tap position on the transformer, to raise the voltage and bring the output voltage back to its desired level. Conversely, as load falls off, the output voltage will start to rise and the voltage regulating relay will cause the transformer to change one tap back to lower the voltage and again bring it back to the desired level.

We can also compensate for the drop in the feeders going out from the substation by circulating the output of the current transformer through adjustable resistance and reactance values (which are set to reflect the resistance and reactance values of the feeder) in the voltage sensing circuit. The drop in the model impedance Z_C in the voltage regulating relay should be able to reflect the drop in voltage in the feeder, if properly set up.

The voltage sensing relay would now cause the transformer to change taps in response to variations in the voltage at the load at the end of the feeder, rather than just at the terminals of the transformers at the substation.

When the load is increasing, this would mean taps would change earlier than by sensing transformer output voltage alone and the transformer output voltage would be higher, but at the load end of the feeder the voltage would be kept at the desired level.

This can be seen in the phasor diagram in Figure 6.

The voltage transformer output e_t is a reflection of E_S, the zone transformer terminal voltage.

By subtracting from the voltage phasor e_t a voltage phasor e_z which is proportional to the line voltage drop E_Z, the resultant voltage e_v (which controls the driving mechanism of the tap-changer) will represent the load voltage E_R for all conditions.

This compensation for the voltage drop in the line is called 'line drop compensation' ('LDC'). It is usually set as a percent boost in voltage at a certain value of transformer load.

In summary, if the LDC is zero, the transformer voltage regulation relay will change taps purely on transformer terminal voltage.

When the LDC is set at some positive value, the transformer voltage regulation relay will change taps based on the transformer terminal voltage less the line drop voltage value.

Types of voltage regulators

Regulators

The simplest and most commonly used method of boosting voltage on distribution lines by far, where capacity is not an issue, but where voltage variation is excessive (eg rural feeders) is via an auto transformer, usually simply (but not accurately) referred to as a 'voltage regulator' (because as we will discuss below, there are many types of regulators).

An auto transformer has one common coil instead of separate primary and secondary coils as with traditional transformers.

Output voltage can be boosted by having more turns on the output tap or reduced ('bucked') by having less turns on the output tap position, as shown in Figure 7.

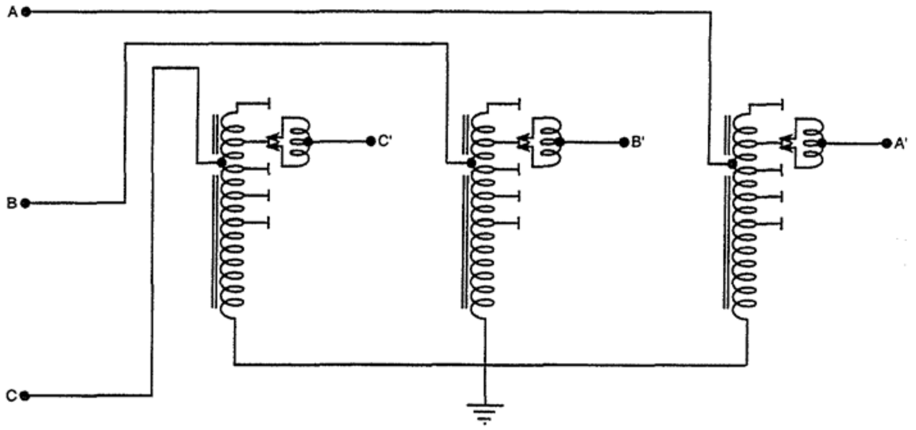


Figure 7. Voltage Regulator (Auto-transformer)

Taps are automatically changed by an on-load tap changer described above.
Another device for controlling voltage which may be used by itself or in conjunction with a transformer is a regulator, of which there are two types:

- induction regulators
- moving coil regulators.

An induction regulator consists of a stator and rotor, and is constructed in a similar manner to a wound rotor induction motor with flexible connections coming from the rotor which does not rotate. The angular position of the (stationary) shaft relative to the stator casing is controllable by means of a manually or motor driven geared wheel.
One winding (the stator) is shunt connected across the lines which need their voltage to be controlled, whilst the other winding (the rotor) is connected in series with the load or overhead line.
Depending on the relative angular positions of the stator and the rotor, the shunt winding induces a voltage (v1) into the series winding, where the induced voltage may be in phase with the system voltage or may be up to 1800 out of phase.
The result is that the output voltage can be varied in magnitude between the range:

$(V + v_1)$ to $(V – v_1)$

where: V is the input voltage
v_1 is the injected series voltage

The normal three phase arrangement has the disadvantage that it introduces a phase shift between the input and output voltages at all values except full boost and full buck.
This is of no consequence when used on an individual supply, but precludes its use on interconnected networks.

A moving coil regulator is constructed with two pairs of closely coupled shunt and series coils A_1 - S_1 and A_2 – S_2 respectively as shown in Figure 8.

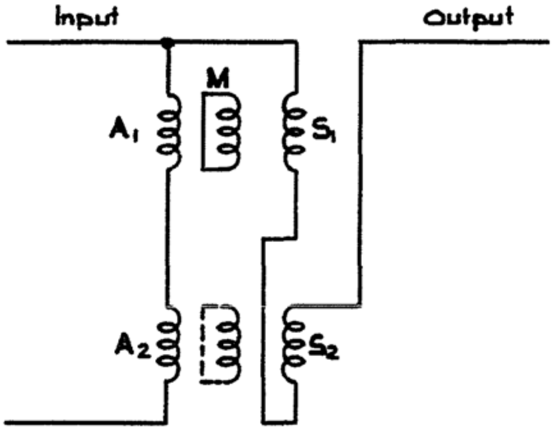


Figure 8. Circuitry of a moving-coil regulator

The four coils are mounted on a common magnetic circuit, and a moving coil M is placed over the top of them.

The moving coil M is short circuited onto itself, and at its limits of travel surrounds one or other of the pairs of fixed coils.

The shunt coils A_1 and A_2 are connected with their voltage polarity additive and the series coils S_1 and S_2 have their voltages in opposition.

The mutual inductance of the short circuited coil M when in the top position, reduces the voltage across A_1 to a minimum and increases that across A_2 to a maximum.

In this case, the voltage induced into S_1 is a minimum and that in S_2 is a maximum.

The range of control on the output voltage depends on the ratios of S_2:A_2 and S_1:A_1.

Boosters

Another less common technique for making small adjustments to line voltages uses line booster transformers.

There are two type of arrangements:

- in phase booster transformers
- quadrature booster transformers.

An in phase regulating booster transformer is used to inject a variable voltage into a line circuit for voltage regulating purposes.

This equipment would be used where it is desirable to obtain additional voltage control on the lines when loaded, and there is no wish to purchase a new transformer.

A typical winding arrangement for an in phase booster is shown in Figure 9.

The active conductors of the three phase system are indicated by AA’, BB’, CC’ respectively, and the relevant voltage levels are shown on the phasor diagram.

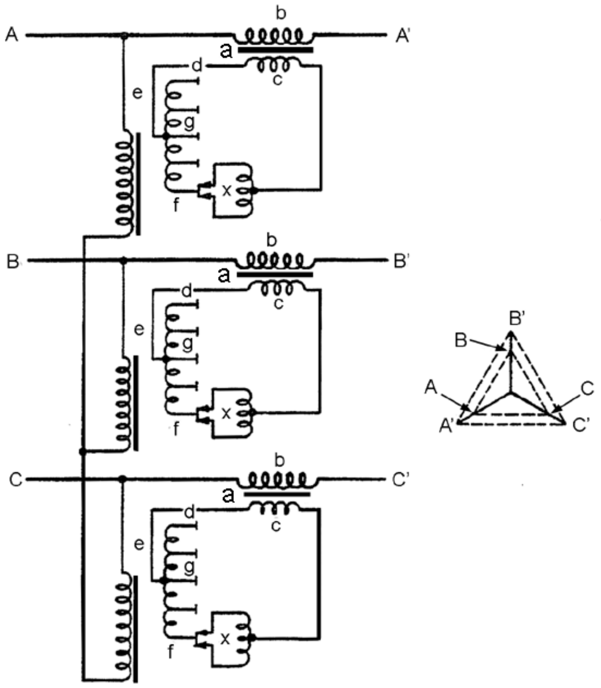


Figure 9. Winding arrangement of a separate in-phase voltage regulating booster transformer

Three series transformers ‘a’ have their secondary windings ‘b’ connected into the lines A-A’, B-B’, C-C’.

The primary windings of these transformers ‘c’ are excited from the variable outputs of the three phase transformer ‘e’ whose primary windings are connected across the line ABC in star configuration.

Variation of the tap-changer ‘x’ between the terminals ‘d to f’ will change the voltage injected into the line A-A’, B-B’, C-C’ through the transformers ‘a’.

Quadrature boosters, or phase angle control units inject a voltage having a major component at 90^0 electrical to the existing line voltage.

This is achieved by combining voltages from different phases instead of the same phase. A general method of interconnection is shown in Figure 10.

They are essentially a variation of the in-phase booster described above.

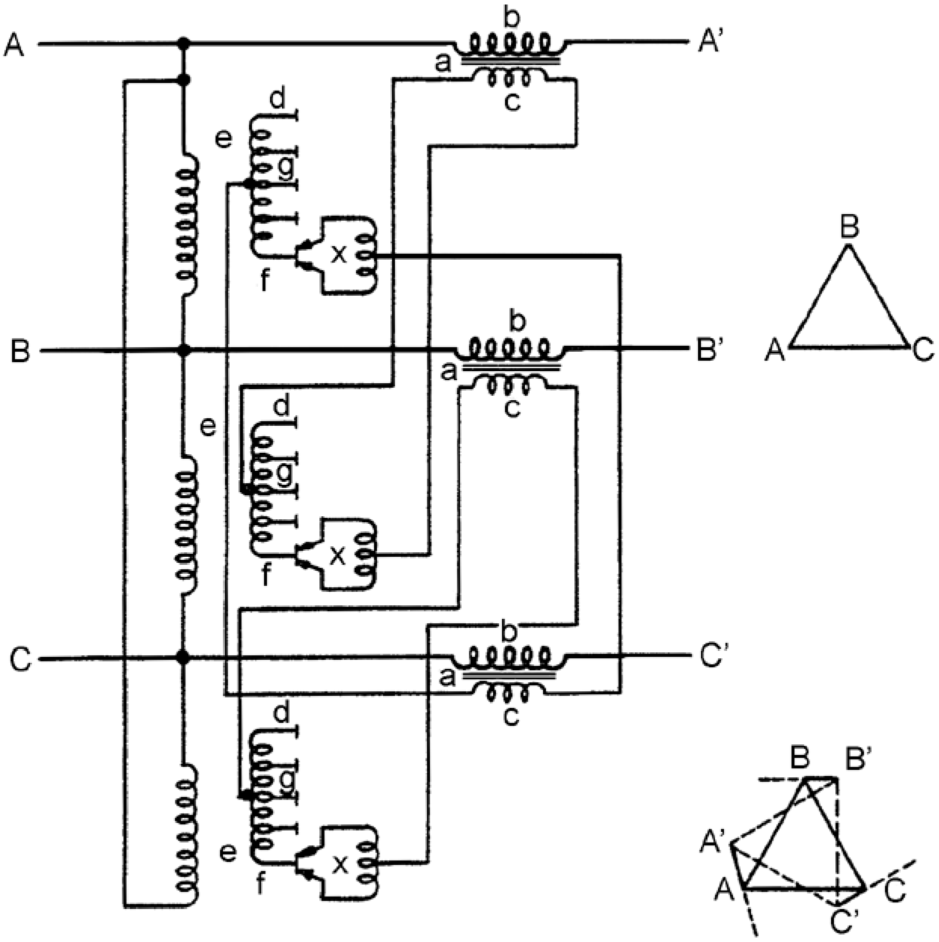


Figure 10. Winding arrangement of phase-angle displacement transformer – quadrature booster

By moving the tap-changer mechanism ‘x’ from terminal ‘g’ to ‘f’ the line voltage will be increased (‘boost’) and when going from ‘g’ to ‘d’ the line voltage will be reduced (‘buck’).

Phase angle control equipment may be required when two circuits of different impedances carrying variable loads are connected at two points on the system.

Starting at the point where the lines have their ends connected together and with the other ends of the lines disconnected, the different line impedances means that there will be a phase difference between the two voltages at the other ends of the lines when they each carry a current. This phase displacement will vary as the loads on the two feeder lines vary. When the two feeder lines are connected into the system the difference in voltages due to the phase displacement at their ends will cause a circulating current to flow.

When a quadrature booster is used at the end of one of these lines it is possible to change the distribution of current in the feeders and minimise any circulating currents.

Power factor correction

While voltage control by means of tap changing transformers is the usual method in distribution systems, power factor correcting capacitors can also have an effect on regulating voltages.

The phasor diagram Figure 11 illustrates the effects on voltage regulation by adding capacitors to a load and so changing the power factor.

The values of voltage supplied without capacitors connected is shown in full lines (E_S) and with capacitors, which reduces the angle of current lag from Φ to Φ_1, in dashed lines (E_{S1}).

Note how E_{S1} is smaller than E_S, ie the voltage regulation is less.

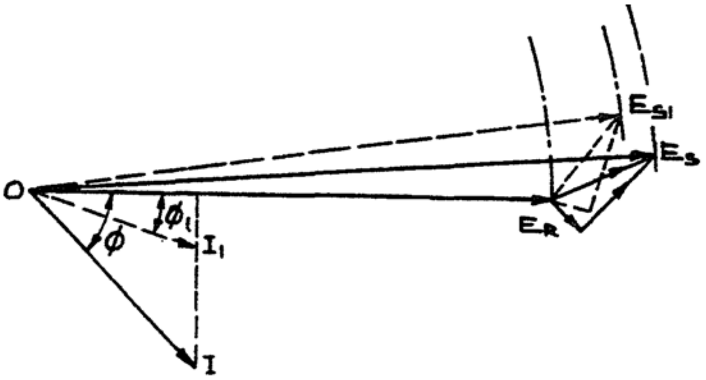


Figure 11. Voltage phasor diagram

For the voltages before the capacitors are connected:

OI = load current at uncorrected phase angle
OE_R = receiving voltage or load voltage
E_RE_S = line voltage drop due to line current I
OE_S = sending end voltage

When the capacitors are connected the ‘in phase’ component of load current I remains the same, but the quadrature component is reduced resulting in a new load current I. Assuming that the load voltage ER remains constant, then:

OI_1 = load current at corrected phase angle
OE_R = receiving voltage or load voltage
E_RE_{S1} = line voltage drop due to line current I_1
OE_{S1} = new sending end voltage

It can be seen that the phasor OE_{S1} is less than OE_S, and so a lower voltage is required at the sending end to keep the load voltage constant. Normal practice is to keep the sending end voltage constant and to switch capacitors in and out at the receiving end to adjust the receiving end voltage.

Revision exercise 8

1. Name the devices which control voltages in transformers.

2. Describe briefly what is meant by 'line drop compensation'. How does it work?

3. List different types of voltage regulators.

4. Explain what is meant by power factor correction and how it assists the distribution system.

Voltage profiles

Voltage profile charts are useful for studying patterns and locating causes or reasons for abnormal voltage conditions.

Put simply, a voltage profile is a chart which shows how the voltage varies as you travel out from the source of supply to the customers.

To obtain the complete variation of voltage, one would need to draw two profiles—one for full load conditions, giving minimum volts at the customer, and one for no-load or light load, giving maximum volts at the customer.

The chart will show all the voltage drops in the various elements which make up the distribution feeder, eg:

a) The supply voltage at the zone substation
b) The voltage drop in the 11/22 kV feeder
c) The voltage drop in the distribution transformer
d) The voltage drop in the low voltage feeder running from the distribution transformer to the take-off point to the customer's terminals
e) The voltage drop in the customer's service line, ie from the take-off point to the 'customer's terminals'.

To make a chart, a common or reference voltage level is selected for the system and the circuit constants of resistance, reactance, etc. are converted to their effective values at this voltage by means of the formula:

$$R_2 = \left(\frac{E_2}{E_1}\right) R_1$$

where: R_2 = resistance value effective at reference voltage E_2
R_1 = resistance value effective at operating voltage E_1

Some practical examples

1. Figure 12 shows a simple distribution system for a single consumer represented by a single line diagram with the voltage profile for full load conditions using a 415 volts base.

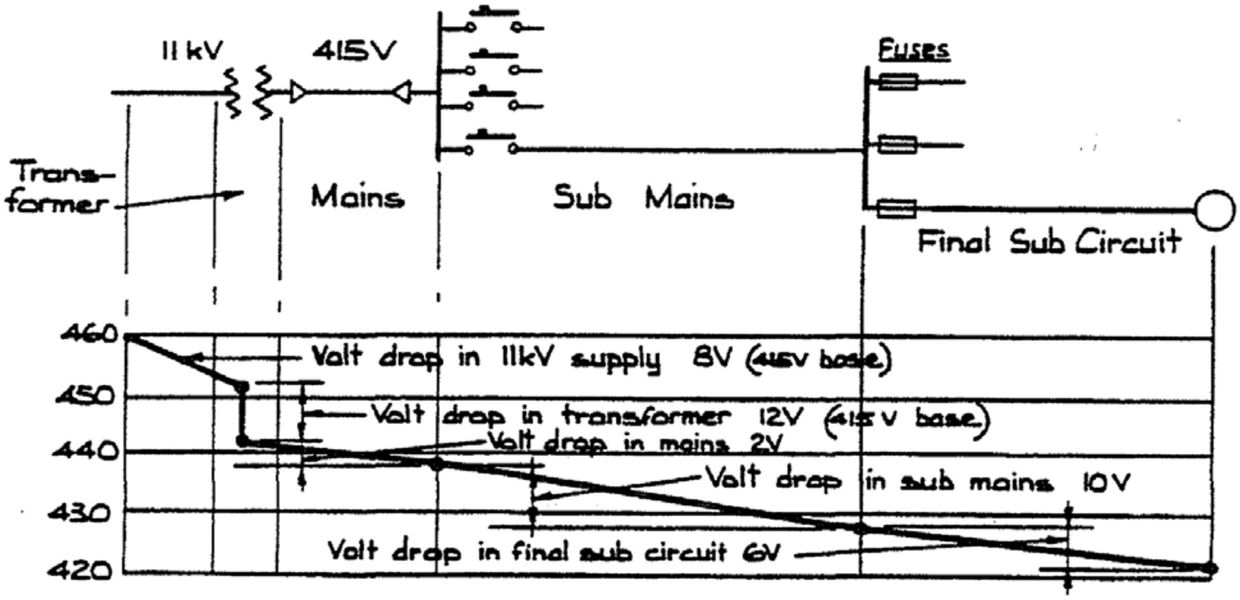


Figure 12. Simplified single line diagram of a distribution system with voltage profile for full-load conditions.

Here, we see the components of the voltage drop as we go outwards from the substation down the feeder to the customer.

2. If we now consider a distribution system for the supply of four consumers a simplified single line diagram could be as shown in Figure 13.

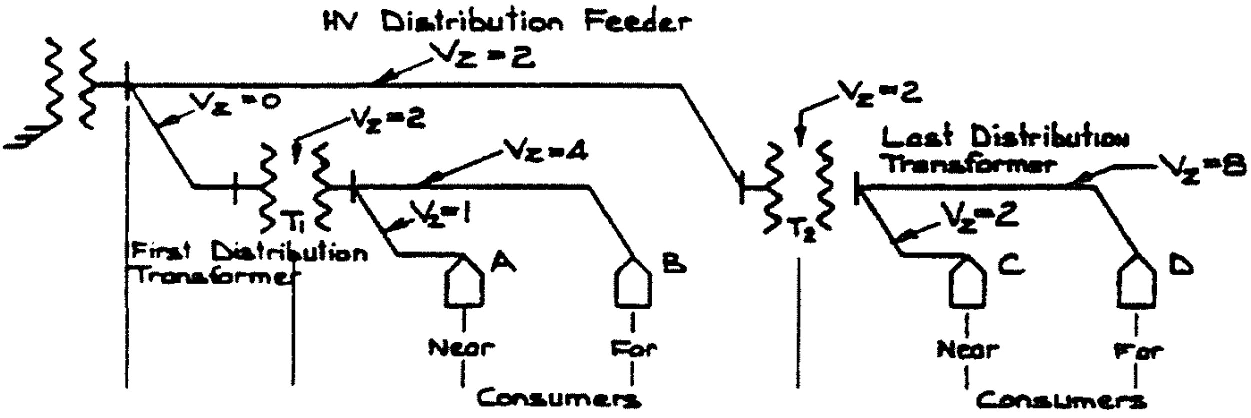


Figure 13. Simplified single line diagram of a distribution system for the supply of four customers.

In this situation we are seeking to keep the voltage to all customers within the range ±6% of the nominal voltage.

Of the four customers, A and B are on distribution transformer T_1 close to the zone substation, whilst C and D are on distribution transformer T_2 remote from the zone substation. Customers A and C are close to their respective transformers and customers B and D are remote from their respective transformers.

The V values indicated on Figure 13 show the percentage impedance voltage drop per unit for each customer's full load current.

For example, if all customers take full load currents the voltage drop on feeder A = 1%, the voltage drop in T_1 = 4% because of the two units of full load current, and the voltage drop in the high voltage feeder = 4% because of the two units of full load current taken by C and D. The light load conditions are taken as being 25% of full load current.

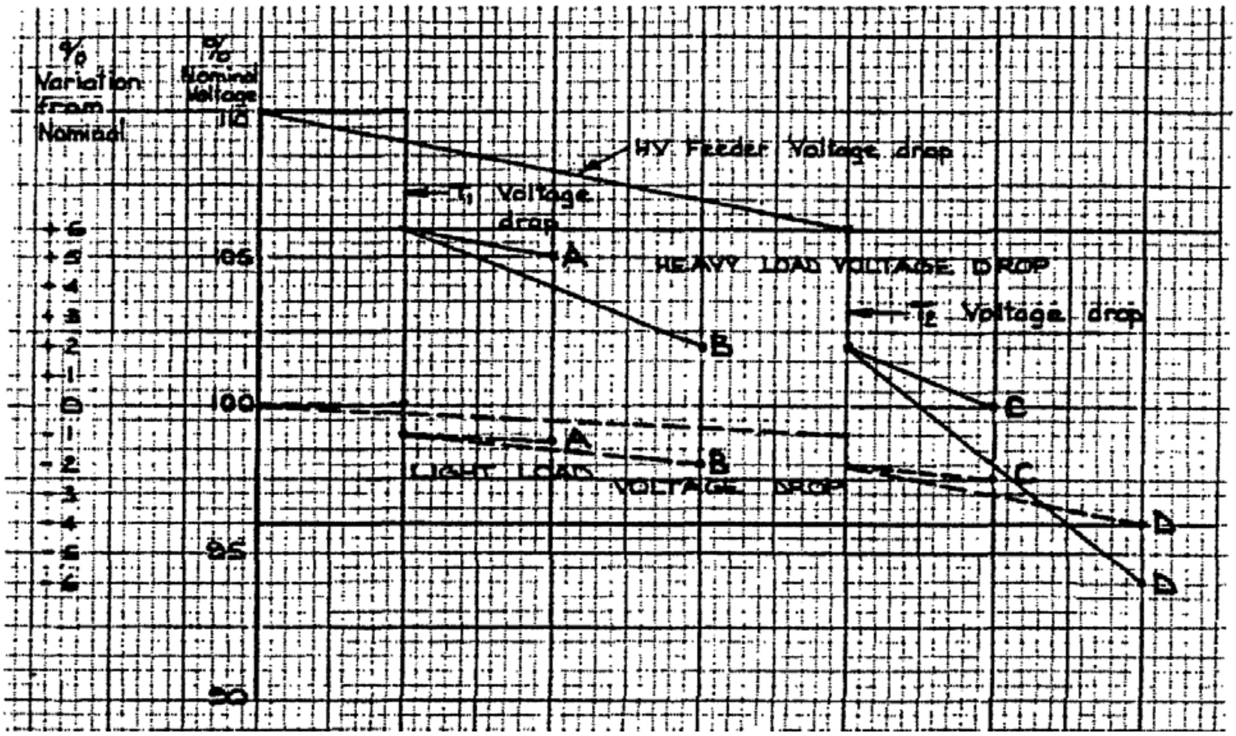


Figure 14. Voltage profile for light and heavy loads - zone transformer with on load tap changer

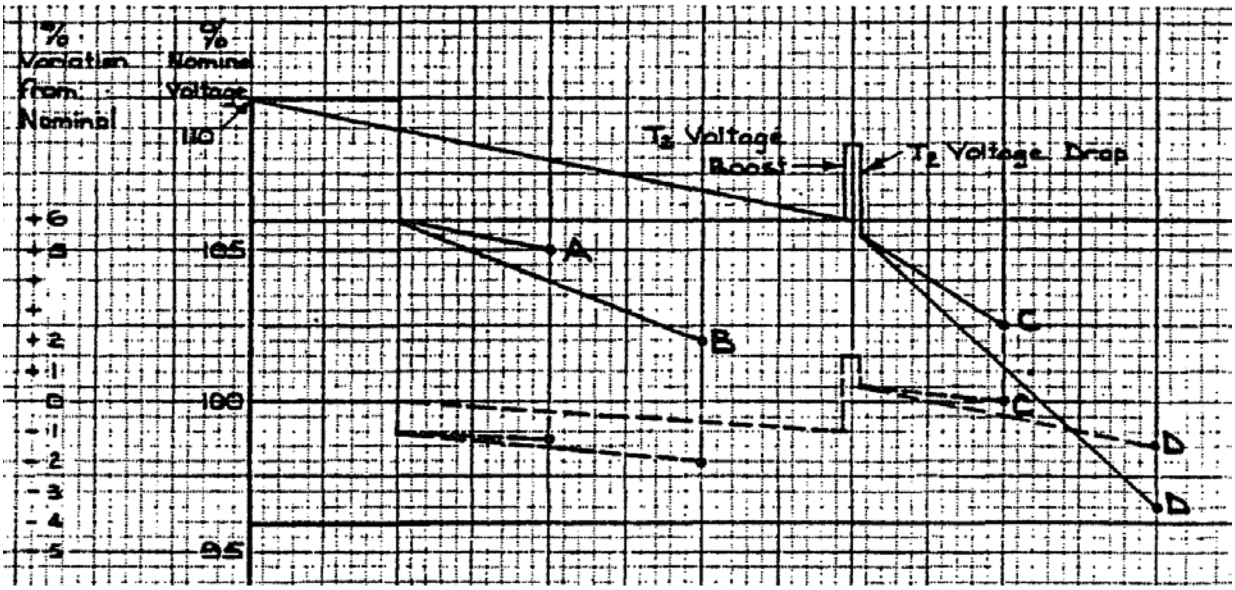


Figure 15. Voltage profile for light and heavy loads - zone transformer with on load tap changer, distribution transformer with off load tap changer

Considering Figure 14, this indicates the voltage variations resulting from where the zone substation tap changer can vary the voltage but the distribution transformers are of fixed ratio. This is the typical arrangement in most power distribution systems.

For a light load the zone transformer tap changer is set at 100%, and for full load the zone transformer might be adjusted to give 10% boost in voltage to compensate for the voltage drop in the feeder, ie the LDC boost is set at 10%.

At full load with 10% voltage boost, the voltage at D is –6% and the voltage at A is +5%. For light load, with the zone transformer at 100%, the voltage at D is –4% and at the voltage at A is –1.5%.

3. Considering Figure 15, this indicates the voltages resulting from a situation where the zone substation tap changer can vary the voltage and the distribution transformer T_2 can provide a 2.5% boost using an off load tap changer. Again, for a light load the zone transformer tap changer is set at 100%, and for full load the zone transformer is adjusted to give 10% boost.

At full load with 10% voltage boost, the voltage at D is –3.5% and the voltage at A is +5%. For light load, with the zone transformer at 100%, the voltage at D is –1.5% and at the voltage at A is –1%.

Diagrams of this type show fairly simply the effects of changing the tap settings on zone and distribution transformers. In contemporary practice, the voltage drop calculations are done quickly and easily on computers.

Revision exercise 9

1. Describe briefly what a ‘voltage profile’ is. Where might you use one?

2. What is meant by the voltage regulation of a feeder? Express this as an equation.

3. Name the causes of voltage regulation in a distribution feeder.

4. What is meant by the inductance of overhead lines? What factors influence the inductance of a line?

5. Name a major advantage that underground cables and ABC systems have in terms of inductance.

Wires and Cables

The qualities desired in electric-service wires, in so far as the construction is concerned, are mechanical strength, tenacity, and ability to resist corrosion or other deterioration. In ordinary practice the breaking strength required for a wire of a given span will depend entirely on the sag, because increasing the sag will reduce the wire tension approximately in proportion to the sag.

Practical considerations, however, indicate a rather indefinite minimum, below which it is undesirable to go. Any surface injury, such as local pitting by arcs and nicks caused by careless handling, or any weakness in the material due to errors in manufacture, will have relatively greater effect on a small wire than on a large one. Moreover, such faults are more serious in solid wires than in stranded cables and in hard-drawn wire than in soft-drawn wire. In stranded cables, an injury to a single strand affects only a fractional part of the entire section; in hard-drawn wire the surface, or skin material, has approximately twice the unit strength of the interior mass, so that an injury will have a relatively greater effect on hard-drawn wire.

Fortunately, however, the process of wire drawing insures a large amount of work per unit of mass, so that the finished product is a very homogeneous and trustworthy material. This quality, combined with the reduction in stress resulting from any increase in sag caused by stretching, explains the comparative immunity from mechanical failures.

Copper

The good qualities of copper wire are a matter of common knowledge, and as stated previously, its manufacture and method of use combine to make it almost unique as a material of construction. It is fairly immune from corrosive action, as ordinarily used in transmission-line work, although it is not absolutely indestructible. The principal sources of injury to copper are due to its softness and low melting point. The former renders it liable to nicks or broken strands in stringing and clamping, and the latter to burning by arcs.

Unless the voltage is such that insulated or weatherproof wire affords some real protection, there is no logical structural reason for using it. Otherwise, it merely serves as an additional load and offers a greater diameter for sleet deposits, besides deteriorating far in advance of the rest of the construction and frequently hanging in unsightly streamers.

Since the sheen of freshly strung copper is greatly lessened after exposure, it becomes problematical whether the attention of the casual observer would in reality be attracted more by the copper or by the size and spacing of insulators which cannot be disguised.

Copper Covered

A comparatively recent development in transmission-line wires is the use of a steel wire covered with copper. This product is produced by drawing out an ingot of steel which has been previously encased in a copper covering.

The thickness of the shell of copper may be varied within wide limits, the usual commercial proportions being an amount of copper that, combined with the lower conductivity of the steel core, produces a wire having either 30 or 40 percent of the conductivity of a copper wire of the combined gage. Thirty percent copper-covered wire is about 5 percent stronger than 40 percent wire of the same gage. The thickness of the shell of copper is quite small, depending in part on the size of the wire.

Such wire should, therefore, be handled at least as carefully as copper wire. Since the thickness of the copper decreases with the size of the wires in the cable, it is preferable, at least for overhead ground wires, to use the 40 percent grade or else to use cables of few strands.

The steel from which the wire is drawn is a high-carbon steel having an ultimate strength of about 90,000 lb. per square inch, and a correspondingly high elastic limit. During the process of copper coating and wire drawing, there is an annealing effect followed by hardening, the net result being to produce a wire having an ultimate strength not greatly below that of the original ingot material. In general, and with the grade of steel commonly used by manufacturing companies, the ultimate strength of copper-covered wire is from 20 percent to 40 percent greater than that of the corresponding sizes of hard-drawn copper.

The principal uses of this material in transmission work are for overhead ground wires, telephone wires, and the power wires of the lighter and lower capacity lines, where little future growth of business may be expected.

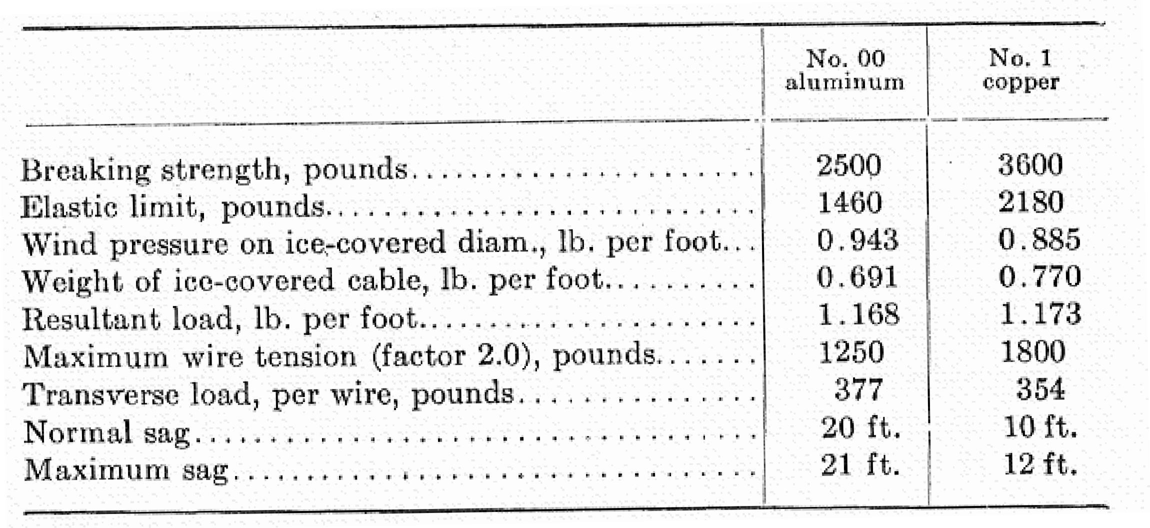
Aluminium

Aluminium wire, as now used for power-line purposes, is usually employed in the form of stranded cables, and when so used is no longer subject to some of the troubles incident to the earlier installations. As a material, it is quite different from copper, although used for similar purposes. Therefore, in making price comparisons, it is necessary to consider not only the price per mile per unit of electrical rating, but also the changes in the general construction of the line.

The conductivity of aluminium is about 60 percent, based on the Matthiesen standard for copper, making aluminium cables about 1.5 times the area and 1.25 times the diameter of copper cables having equal conductivity. As the specific weight of aluminium is about 0.33 that of copper, the weight of aluminium cable will be about 0.5 times that of copper cable having the same conductivity.

The strength of aluminium is about 0.8 that of soft copper and 0.4 the strength of hard copper.

The net result of these differences is best shown by a concrete example. Thus, a No.00 aluminium cable has about the same conductivity as a No.1 stranded hard-drawn copper cable, and their other characteristics for a 400 foot span are as follows:



	No. 00 aluminum	No. 1 copper
Breaking strength, pounds	2500	3600
Elastic limit, pounds	1460	2180
Wind pressure on ice-covered diam., lb. per foot	0.943	0.885
Weight of ice-covered cable, lb. per foot	0.691	0.770
Resultant load, lb. per foot	1.168	1.173
Maximum wire tension (factor 2.0), pounds	1250	1800
Transverse load, per wire, pounds	377	354
Normal sag	20 ft.	10 ft.
Maximum sag	21 ft.	12 ft.

Since the coefficient of expansion of aluminium is considerably higher than that of copper, aluminium cables are more affected by temperature changes. Relatively greater sags will therefore occur in hot weather, while at low temperatures there is a greater increase in tension due to the contraction of the material with its resultant decrease in sag. In addition, the lighter weight of aluminium renders it more liable to local displacement by wind pressure. It is necessary, as a result of these differences in the material, to provide greater pin separation and overhead clearance for aluminium conductors. From a construction viewpoint, however, the lighter weight of aluminium does not possess any particular merit, except possibly greater ease of handling the reels and pulling out wire in stringing.

The saving in dead load on the supports is negligible and is more than offset by the greater sag and separation required. Furthermore, the increased diameter imposes a greater wind load. The choice between aluminium and copper will depend on the relative cost of the two materials and their accompanying construction, together with the allowances which can be made for the scrap values of the two installations.

Steel

Steel cable can be obtained of almost any desired unit breaking strength, the commercial grades ranging from the low grade steel of guy wire, which has an ultimate strength of 60,000 lb. per square inch, to steels of 200,000 lb. or more.

For transmission-line purposes steel cable is used chiefly for overhead ground wires or as power wires for very long spans. The occasional use of steel messengers for telephone or insulated cables does not involve any considerable quantity of such material employed on typical transmission lines.

Steel cables for line work should always be galvanized, and should be larger than is actually required for strength. The galvanizing of cable is by no means as permanent a protection as the hot-dip, unwiped process applied to structural steel; therefore some allowance should be made for future corrosion.

Despite the temptation to use small-gage cables made of the higher grade steels, on account of their greater strength, it is generally preferable to adhere to medium grades such as the Siemens-Martin. Guy-strand steel cable is the lowest commercial grade and its quality is relatively much lower than that of any of the higher grades, Large diameter cables, particularly of high-grade steel, are rather difficult to handle as they are very stiff. It should be noted that all cables of great strength require special clamping attachments for dead ending, the ordinary quota of clips and clamps being inadequate to transmit the tension.

Telephone Wire

Supporting a telephone circuit on long-span transmission-line structures introduces a difficulty, in that the small wires which are sufficient for telephone service do not have the mechanical strength to carry safely in long spans.

It is almost impossible to string any ordinary telephone wires so that they will be reasonably secure on long-span lines. There have arisen, therefore, two general methods of procedure; one is to use larger and stronger wires; and the other to contemplate failure in the telephone circuit as a necessary evil.

Solid steel wire No.6 BWG, sometimes called river crossing wire, has an ultimate strength about equal to that of No.00 stranded hard-drawn copper and can, therefore, be strung equally well in long-span lines.

Catenary

If two ends of an imaginary wire having perfect flexibility and uniformity of material but no ductility were supported at two points in the same horizontal plane the wire would take the shape of a curve known as the catenary. For all practical purposes it may be assumed that actual wires and cables possess the same characteristics. The curve of the wires between the supports is therefore known, if the span and sag are known. However, as the equation of the catenary is rather complicated, while that of the parabola, which closely resembles it, is simple, the latter is usually employed instead; thus,

$$y^2 = ax$$

"a" being an constant found by substituting the known value of sc for the point on the curve at the support, ie.,

$a = \frac{S^2}{4d}$ in which S is the length of the span and d is the sag

Assume a uniform load on each lineal foot of the span, and imagine half of the span removed and the wire held in place by the tension T at the middle of the span. Then considering the moments about the remaining support we have the weight of the half span multiplied by its lever arm which is one-quarter of the span, equals the balancing force T multiplied by its lever arm d.

Since the total weight W = the weight per foot, X the half span or W = $\frac{ws}{2}$ we have

$$\frac{wS}{2} \times \frac{S}{4} = Td$$

Therefore $\frac{wS^2}{8} = Td$

and $T = \frac{wS^2}{8d}$

or, the tension in the wire equals the weight per foot times the span squared divided by eight times the sag.

It is necessary, however, to take into consideration the effect of a change in length of the wire due to temperature and loading, and a simple arrangement of formula in which this is done is given below. The following mathematical treatment is not new, but the writer has found the arrangement convenient:

S = span, in feet.
d = sag, in feet.
W = load per lineal foot in plane of wire.
A = area of wire, in square inches. .
E = modulus of elasticity.
θ = coefficient of expansion.
t = change of temperature, in degrees.
e = elongation or change of length, within elastic limit.
L_o = length, in feet, of imaginary wire (W = 0) at normal temperature.
L_{oc} = length, in feet, of imaginary wire, cold (t°F. below normal temperature).
L_{oh} = length, in feet, of imaginary wire, hot (t°F. above normal temperature).

Index to Subscripts. -
No subscript = normal conditions.
$_c$ = cold: t°F. below normal + dead load.
$_i$ = cold: ice load + dead load.
$_{cw}$ = cold: wind load + dead load.
$_{iw}$ = cold: ice + wind + dead load.
$_h$ = hot: t°F. above normal + dead load.
W_{iw} is the resultant of the vertical dead + ice loads and the horizontal wind load.
W_{cw} is the resultant of the vertical dead load and the horizontal wind load.

Stresses

Substitute normal values in Eqs. 1, 2, 3, and 4. Assume values of T_h, T_{iw}, T_c, T_i, or T_{cw}, such that Eqs. 5 and 6 will give identical values of d_h, d_{iw}, etc. The tension that will give the same sag by Eqs. 5 and 6 (independently) is the tension resulting from that sag and the given loading.

$$T = \frac{WS^2}{8d} \tag{1}$$

$$L = S\left[1 + \frac{8d^2}{3S^2}\right] \tag{2}$$

$$e = \frac{TL}{EA} \tag{3}$$

$$L_o = L - e \tag{4}$$

(t°. above normal, with dead load.)

$$L_{oh} = L_o\,(1 + \theta\, t_h) \qquad e_n = \frac{Loh\ X\ Th}{EA} \qquad L_h = L_{oh} + e_n$$

$$d_h = 0.612\sqrt{S\,(Lh - S} \tag{5}$$

$$d_h = \frac{Wh\ X\ S^2}{8Th} \tag{6}$$

(t°. below normal, with dead + ice + wind loads.)

$$L_{oc} = L_o(1 - \theta t_c) \qquad e_{iw} = \frac{Loc\ X\ Tiw}{EA} \qquad L_{iw} = L_{oc} + e_{iw}$$

$$d_{iw} = 0.612\sqrt{S\,(Liw - S)} \tag{5}$$

$$diw = \frac{Wiw\ X\ S^2}{8Tiw} \tag{6}$$

(t°F. below normal, with dead load.)

$$L_{oc} = L_o(1 - \theta t_c) \qquad e_c = \frac{Loc\ X\ Tc}{EA} \qquad L_c = L_{oc} + e_c$$

$$d_c = 0.612\sqrt{S(Lc - S)} \tag{5}$$

$$d_c = \frac{Wc\ X\ S^2}{8Tc} \tag{6}$$

(t°F. below normal, with dead + ice loads.)

$$L_{oc} = L_o(1 - \theta t_c) \qquad e_i = \frac{Loc\ X\ Ti}{EA} \qquad L_i = L_{oc} + e_i$$

$$d_i = 0.612\sqrt{S(Li - S)} \tag{5}$$

$$d_i = \frac{Wi\ X\ S^2}{8Ti} \tag{6}$$

(t°F. below normal, with dead + wind loads.)

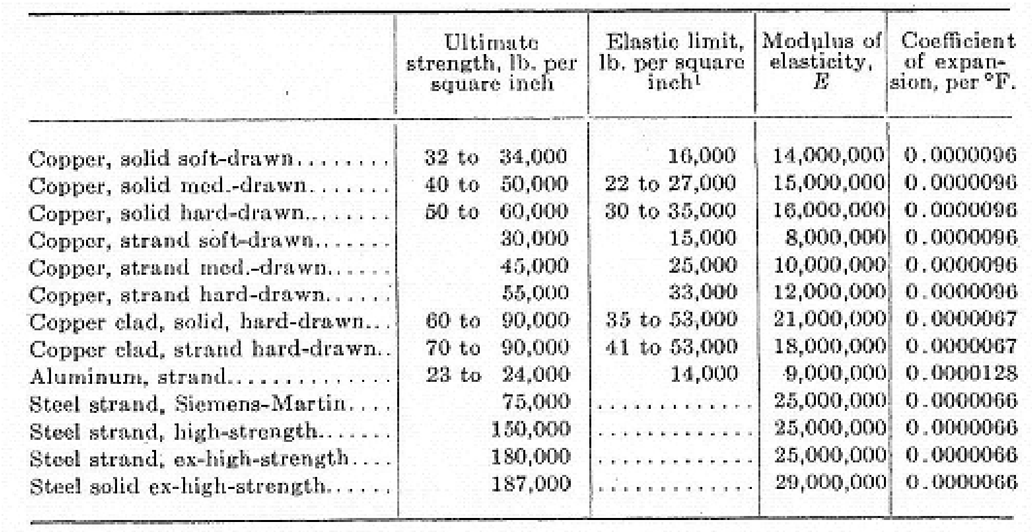
$$L_{oc} = L_o\,(1 - \theta t_c) \qquad e_{cw} = \frac{Loc\ C\ Tcw}{EA} \qquad L_{cw} = L_{oc} + e_{cw}$$

$$d_{cw} = 0.612\sqrt{S(Lcw - S)} \tag{5}$$

$$d_{cw} = \frac{Wcw\ X\ S^2}{8Tcw} \tag{6}$$

In Tables 1 to 8 are given the physical properties and the wind and ice loads for various wire gages.

Table 1 – Properties of Wire Material



	Ultimate strength, lb. per square inch	Elastic limit, lb. per square inch[1]	Modulus of elasticity, E	Coefficient of expansion, per °F.
Copper, solid soft-drawn	32 to 34,000	16,000	14,000,000	0.0000096
Copper, solid med.-drawn	40 to 50,000	22 to 27,000	15,000,000	0.0000096
Copper, solid hard-drawn	50 to 60,000	30 to 35,000	16,000,000	0.0000096
Copper, strand soft-drawn	30,000	15,000	8,000,000	0.0000096
Copper, strand med.-drawn	45,000	25,000	10,000,000	0.0000096
Copper, strand hard-drawn	55,000	33,000	12,000,000	0.0000096
Copper clad, solid, hard-drawn	60 to 90,000	35 to 53,000	21,000,000	0.0000067
Copper clad, strand hard-drawn	70 to 90,000	41 to 53,000	18,000,000	0.0000067
Aluminum, strand	23 to 24,000	14,000	9,000,000	0.0000128
Steel strand, Siemens-Martin	75,000	....	25,000,000	0.0000066
Steel strand, high-strength	150,000	....	25,000,000	0.0000066
Steel strand, ex-high-strength	180,000	....	25,000,000	0.0000066
Steel solid ex-high-strength	187,000	....	29,000,000	0.0000066

It has been urged by some that using the 0.5 inch, ice and 8-lb. wind load with the parabolic formula for computing the stress in the wire docs not give results which accord with experience, since actual spans erected with less than the specified sags have not failed in service.

On the other hand, it is sometimes claimed that allowing maximum stresses near the elastic limit is dangerous. The facts of the matter are:

First, the true catenary formula is scientifically and mathematically correct within the elastic limit.

Second, the parabolic formula, ordinarily used for simplicity, gives results which in the vast majority of cases are closer to the exact values than the actual wire stringing will be to the specified stringing.

Third, the material of a wire catenary is more uniform in section, strength, and other characteristics than that of any other engineering structure; therefore the error of design is correspondingly less.

Fourth, the stretch of a ductile material, such as copper, permits the sag to increase and the stress to decrease and, within limits, does not perceptibly decrease the cross-section at any point. Therefore, a loaded span stretches enough to relieve the stress and docs not fail unless the load is very excessive.

Fifth, the specified maximum loading is an emergency loading and is not a general or frequent occurrence on any span or line.

The facts of the matter are that the spans in service have either not been subjected to loads in excess of those required by the catenary formula to develop their elastic limit, or the wire has stretched and the sag has increased.

Possibly there are two other reasons for seemingly overstressed lines giving satisfactory service.

One is that the poles have bent or the wires slipped through the ties, thus temporarily increasing the sag.

Second, the wires may have become tempered or hardened by tension, possibly by atmospheric changes or other action, and by becoming harder have been able to sustain a greater load.

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[1] **The elastic limit used is in reality the yield point, or point of appreciable extension, as this value seems more applicable to wire stringing than that obtained by accurate laboratory tests.**

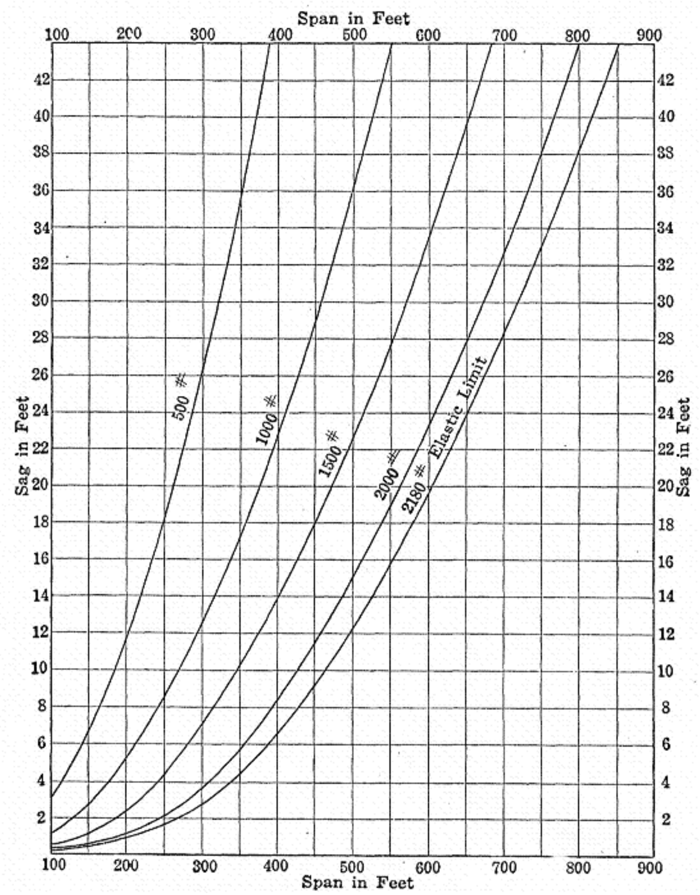


Figure 1 Sags and Tension of No. 1 H.D. Copper

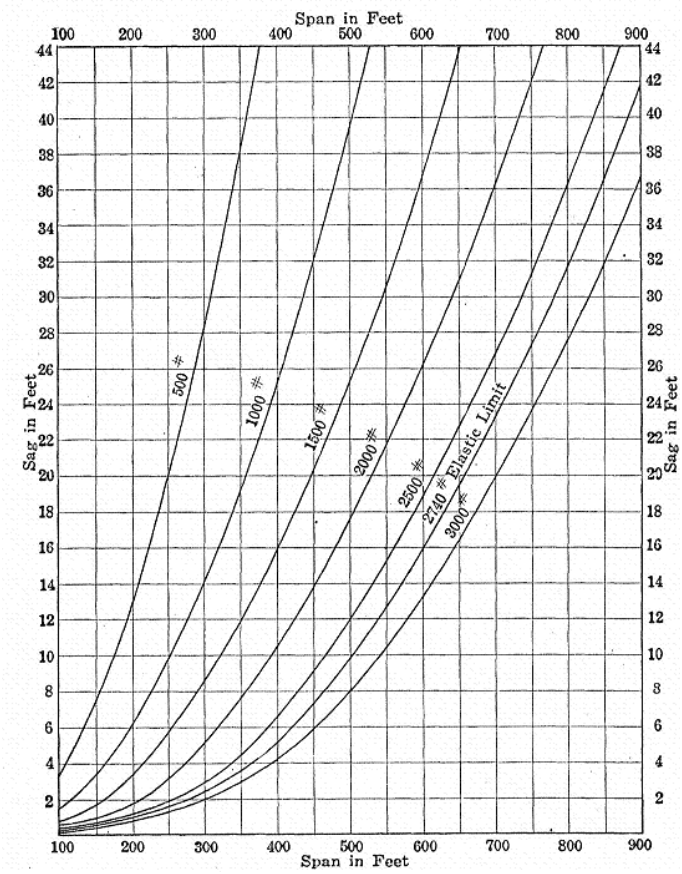


Figure 2 Sags and tensions of No. 0 H.D.Copper

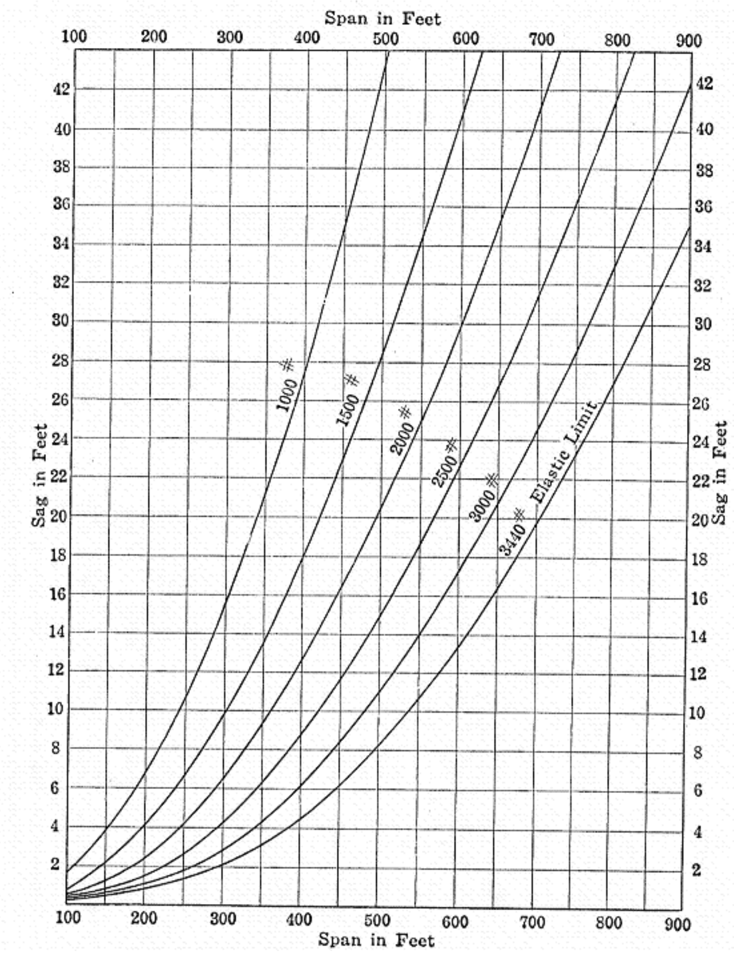
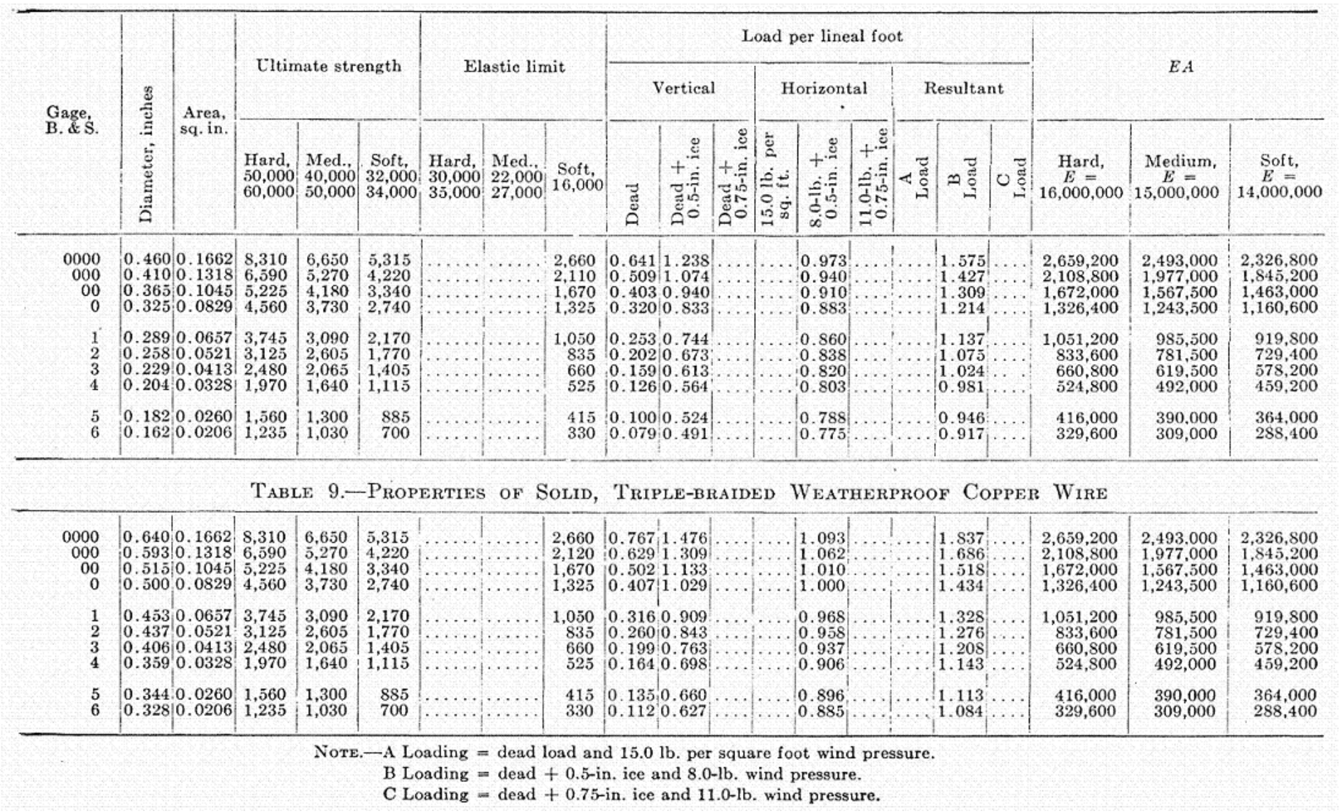


Figure 3 Sags and Tensions on No. 00 H.D. Copper

Table 2 Properties of Bare Stranded Copper Cable

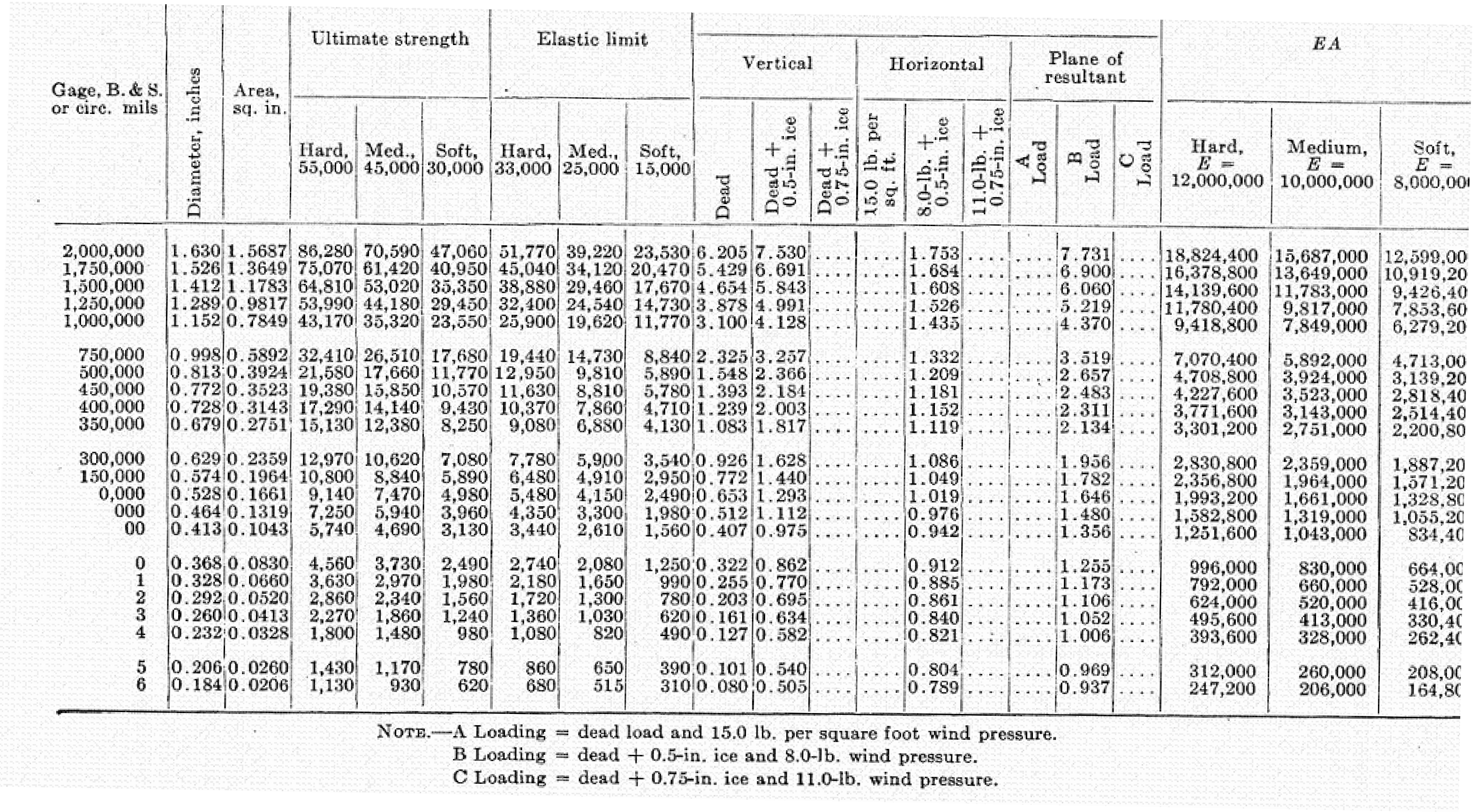


Gage, B. & S.	Diameter, inches	Area, sq. in.	Ultimate strength			Elastic limit			Load per lineal foot									EA		
									Vertical			Horizontal			Resultant					
			Hard, 50,000 60,000	Med., 40,000 50,000	Soft, 32,000 34,000	Hard, 30,000 35,000	Med., 22,000 27,000	Soft, 16,000	Dead	Dead + 0.5-in. ice	Dead + 0.75-in. ice	15.0 lb. per sq. ft.	8.0-lb. + 0.5-in. ice	11.0-lb. + 0.75-in. ice	A Load	B Load	C Load	Hard, E = 16,000,000	Medium, E = 15,000,000	Soft, E = 14,000,000
0000	0.460	0.1662	8,310	6,650	5,315	.....	.....	2,660	0.641	1.238	....	....	0.973	....	....	1.575	....	2,659,200	2,493,000	2,326,800
000	0.410	0.1318	6,590	5,270	4,220	.....	.....	2,110	0.509	1.074	....	....	0.940	....	....	1.427	....	2,108,800	1,977,000	1,845,200
00	0.365	0.1045	5,225	4,180	3,340	.....	.....	1,670	0.403	0.940	....	....	0.910	....	....	1.309	....	1,672,000	1,567,500	1,463,000
0	0.325	0.0829	4,560	3,730	2,740	.....	.....	1,325	0.320	0.833	....	....	0.883	....	....	1.214	....	1,326,400	1,243,500	1,160,600
1	0.289	0.0657	3,745	3,090	2,170	.....	.....	1,050	0.253	0.744	....	....	0.860	....	....	1.137	....	1,051,200	985,500	919,800
2	0.258	0.0521	3,125	2,605	1,770	.....	.....	835	0.202	0.673	....	....	0.838	....	....	1.075	....	833,600	781,500	729,400
3	0.229	0.0413	2,480	2,065	1,405	.....	.....	660	0.159	0.613	....	....	0.820	....	....	1.024	....	660,800	619,500	578,200
4	0.204	0.0328	1,970	1,640	1,115	.....	.....	525	0.126	0.564	....	....	0.803	....	....	0.981	....	524,800	492,000	459,200
5	0.182	0.0260	1,560	1,300	885	.....	.....	415	0.100	0.524	....	....	0.788	....	....	0.946	....	416,000	390,000	364,000
6	0.162	0.0206	1,235	1,030	700	.....	.....	330	0.079	0.491	....	....	0.775	....	....	0.917	....	329,600	309,000	288,400

TABLE 9.—PROPERTIES OF SOLID, TRIPLE-BRAIDED WEATHERPROOF COPPER WIRE

0000	0.640	0.1662	8,310	6,650	5,315	.....	.....	2,660	0.767	1.476	....	....	1.093	....	....	1.837	....	2,659,200	2,493,000	2,326,800
000	0.593	0.1318	6,590	5,270	4,220	.....	.....	2,120	0.629	1.309	....	....	1.062	....	....	1.686	....	2,108,800	1,977,000	1,845,200
00	0.515	0.1045	5,225	4,180	3,340	.....	.....	1,670	0.502	1.133	....	....	1.010	....	....	1.518	....	1,672,000	1,567,500	1,463,000
0	0.500	0.0829	4,560	3,730	2,740	.....	.....	1,325	0.407	1.029	....	....	1.000	....	....	1.434	....	1,326,400	1,243,500	1,160,600
1	0.453	0.0657	3,745	3,090	2,170	.....	.....	1,050	0.316	0.909	....	....	0.968	....	....	1.328	....	1,051,200	985,500	919,800
2	0.437	0.0521	3,125	2,605	1,770	.....	.....	835	0.260	0.843	....	....	0.958	....	....	1.276	....	833,600	781,500	729,400
3	0.406	0.0413	2,480	2,065	1,405	.....	.....	660	0.199	0.763	....	....	0.937	....	....	1.208	....	660,800	619,500	578,200
4	0.359	0.0328	1,970	1,640	1,115	.....	.....	525	0.164	0.698	....	....	0.906	....	....	1.143	....	524,800	492,000	459,200
5	0.344	0.0260	1,560	1,300	885	.....	.....	415	0.135	0.660	....	....	0.896	....	....	1.113	....	416,000	390,000	364,000
6	0.328	0.0206	1,235	1,030	700	.....	.....	330	0.112	0.627	....	....	0.885	....	....	1.084	....	329,600	309,000	288,400

NOTE.—A Loading = dead load and 15.0 lb. per square foot wind pressure.
B Loading = dead + 0.5-in. ice and 8.0-lb. wind pressure.
C Loading = dead + 0.75-in. ice and 11.0-lb. wind pressure.

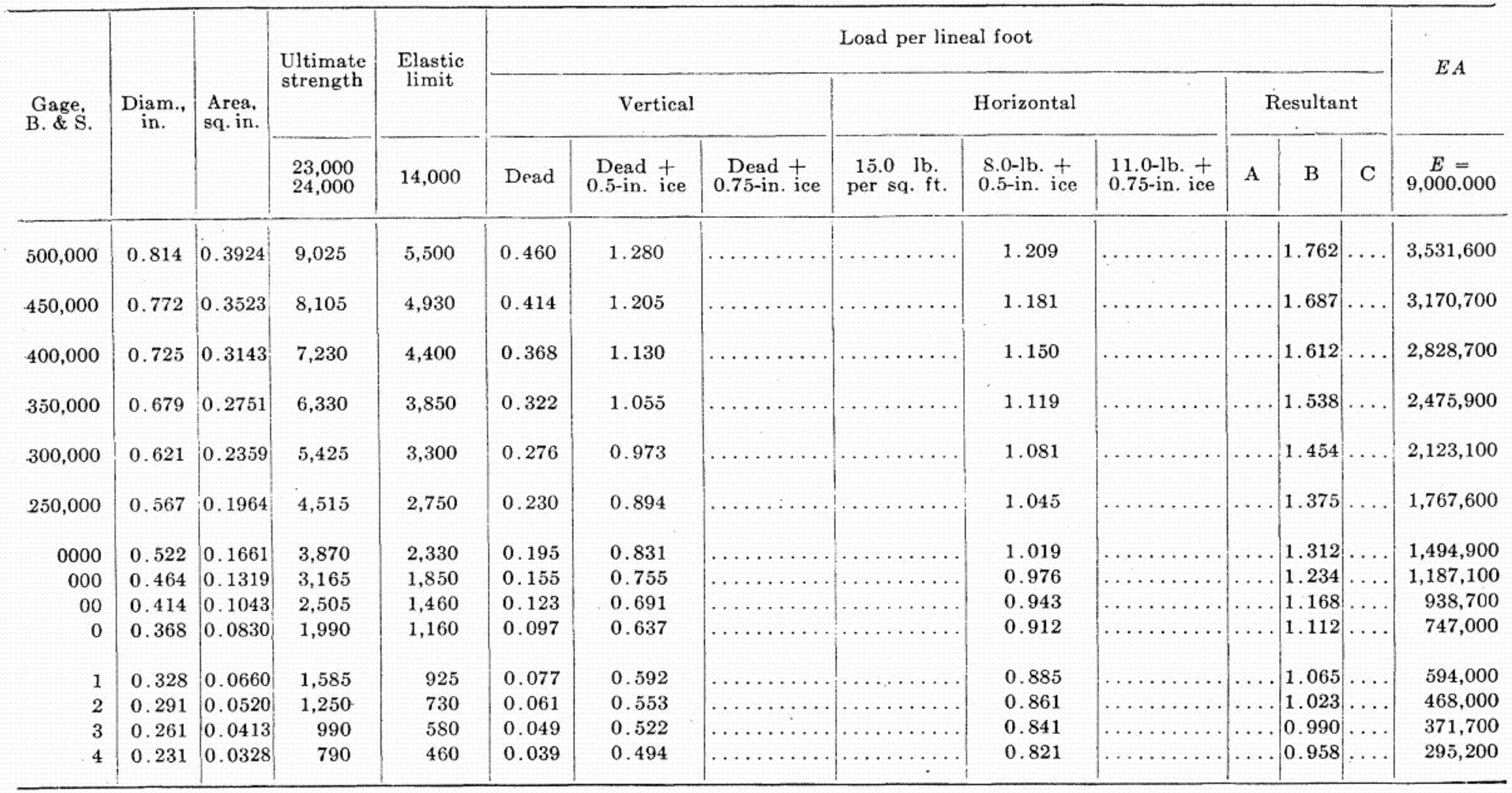


Gage, B. & S. or circ. mils	Diameter, inches	Area, sq. in.	Ultimate strength			Elastic limit			Vertical			Horizontal			Plane of resultant			EA		
			Hard, 55,000	Med., 45,000	Soft, 30,000	Hard, 33,000	Med., 25,000	Soft, 15,000	Dead	Dead + 0.5-in. ice	Dead + 0.75-in. ice	15.0 lb. per sq. ft.	8.0-lb. + 0.5-in. ice	11.0-lb. + 0.75-in. ice	A Load	B Load	C Load	Hard, E = 12,000,000	Medium, E = 10,000,000	Soft, E = 8,000,00
2,000,000	1.630	1.5687	86,280	70,590	47,060	51,770	39,220	23,530	6.205	7.530	....	....	1.753	....	....	7.731	....	18,824,400	15,687,000	12,599,00
1,750,000	1.526	1.3649	75,070	61,420	40,950	45,040	34,120	20,470	5.429	6.691	....	....	1.684	....	....	6.900	....	16,378,800	13,649,000	10,919,20
1,500,000	1.412	1.1783	64,810	53,020	35,350	38,880	29,460	17,670	4.654	5.843	....	....	1.608	....	....	6.060	....	14,139,600	11,783,000	9,426,40
1,250,000	1.289	0.9817	53,990	44,180	29,450	32,400	24,540	14,730	3.878	4.991	....	....	1.526	....	....	5.219	....	11,780,400	9,817,000	7,853,60
1,000,000	1.152	0.7849	43,170	35,320	23,550	25,900	19,620	11,770	3.100	4.128	....	....	1.435	....	....	4.370	....	9,418,800	7,849,000	6,279,20
750,000	0.998	0.5892	32,410	26,510	17,680	19,440	14,730	8,840	2.325	3.257	....	....	1.332	....	....	3.519	....	7,070,400	5,892,000	4,713,00
500,000	0.813	0.3924	21,580	17,660	11,770	12,950	9,810	5,890	1.548	2.366	....	....	1.209	....	....	2.657	....	4,708,800	3,924,000	3,139,20
450,000	0.772	0.3523	19,380	15,850	10,570	11,630	8,810	5,780	1.393	2.184	....	....	1.181	....	....	2.483	....	4,227,600	3,523,000	2,818,40
400,000	0.728	0.3143	17,290	14,140	9,430	10,370	7,860	4,710	1.239	2.003	....	....	1.152	....	....	2.311	....	3,771,600	3,143,000	2,514,40
350,000	0.679	0.2751	15,130	12,380	8,250	9,080	6,880	4,130	1.083	1.817	....	....	1.119	....	....	2.134	....	3,301,200	2,751,000	2,200,80
300,000	0.629	0.2359	12,970	10,620	7,080	7,780	5,900	3,540	0.926	1.628	....	....	1.086	....	....	1.956	....	2,830,800	2,359,000	1,887,20
150,000	0.574	0.1964	10,800	8,840	5,890	6,480	4,910	2,950	0.772	1.440	....	....	1.049	....	....	1.782	....	2,356,800	1,964,000	1,571,20
0,000	0.528	0.1661	9,140	7,470	4,980	5,480	4,150	2,490	0.653	1.293	....	....	1.019	....	....	1.646	....	1,993,200	1,661,000	1,328,80
000	0.464	0.1319	7,250	5,940	3,960	4,350	3,300	1,980	0.512	1.112	....	....	0.976	....	....	1.480	....	1,582,800	1,319,000	1,055,20
00	0.413	0.1043	5,740	4,690	3,130	3,440	2,610	1,560	0.407	0.975	....	....	0.942	....	....	1.356	....	1,251,600	1,043,000	834,40
0	0.368	0.0830	4,560	3,730	2,490	2,740	2,080	1,250	0.322	0.862	....	....	0.912	....	....	1.255	....	996,000	830,000	664,0
1	0.328	0.0660	3,630	2,970	1,980	2,180	1,650	990	0.255	0.770	....	....	0.885	....	....	1.173	....	792,000	660,000	528,0
2	0.292	0.0520	2,860	2,340	1,560	1,720	1,300	780	0.203	0.695	....	....	0.861	....	....	1.106	....	624,000	520,000	416,0
3	0.260	0.0413	2,270	1,860	1,240	1,360	1,030	620	0.161	0.634	....	....	0.840	....	....	1.052	....	495,600	413,000	330,4
4	0.232	0.0328	1,800	1,480	980	1,080	820	490	0.127	0.582	....	....	0.821	....	....	1.006	....	393,600	328,000	262,4
5	0.206	0.0260	1,430	1,170	780	860	650	390	0.101	0.540	....	....	0.804	....	....	0.969	....	312,000	260,000	208,0
6	0.184	0.0206	1,130	930	620	680	515	310	0.080	0.505	....	....	0.789	....	....	0.937	....	247,200	206,000	164,8

NOTE.—A Loading = dead load and 15.0 lb. per square foot wind pressure.
B Loading = dead + 0.5-in. ice and 8.0-lb. wind pressure.
C Loading = dead + 0.75-in. ice and 11.0-lb. wind pressure.

Table3 properties of solid copper

Table 4 Properties of Stranded Aluminium Cable



Gage, B. & S.	Diam., in.	Area, sq. in.	Ultimate strength	Elastic limit	Load per lineal foot									EA
					Vertical			Horizontal			Resultant			
			23,000 24,000	14,000	Dead	Dead + 0.5-in. ice	Dead + 0.75-in. ice	15.0 lb. per sq. ft.	8.0-lb. + 0.5-in. ice	11.0-lb. + 0.75-in. ice	A	B	C	E = 9,000,000
500,000	0.814	0.3924	9,025	5,500	0.460	1.280	....	....	1.209	....	....	1.762	....	3,531,600
450,000	0.772	0.3523	8,105	4,930	0.414	1.205	....	....	1.181	....	....	1.687	....	3,170,700
400,000	0.725	0.3143	7,230	4,400	0.368	1.130	....	....	1.150	....	....	1.612	....	2,828,700
350,000	0.679	0.2751	6,330	3,850	0.322	1.055	....	....	1.119	....	....	1.538	....	2,475,900
300,000	0.621	0.2359	5,425	3,300	0.276	0.973	....	....	1.081	....	....	1.454	....	2,123,100
250,000	0.567	0.1964	4,515	2,750	0.230	0.894	....	....	1.045	....	....	1.375	....	1,767,600
0000	0.522	0.1661	3,870	2,330	0.195	0.831	....	....	1.019	....	....	1.312	....	1,494,900
000	0.464	0.1319	3,165	1,850	0.155	0.755	....	....	0.976	....	....	1.234	....	1,187,100
00	0.414	0.1043	2,505	1,460	0.123	0.691	....	....	0.943	....	....	1.168	....	938,700
0	0.368	0.0830	1,990	1,160	0.097	0.637	....	....	0.912	....	....	1.112	....	747,000
1	0.328	0.0660	1,585	925	0.077	0.592	....	....	0.885	....	....	1.065	....	594,000
2	0.291	0.0520	1,250	730	0.061	0.553	....	....	0.861	....	....	1.023	....	468,000
3	0.261	0.0413	990	580	0.049	0.522	....	....	0.841	....	....	0.990	....	371,700
4	0.231	0.0328	790	460	0.039	0.494	....	....	0.821	....	....	0.958	....	295,200

NOTE.—A Loading = dead load and 15.0 lb. per square foot wind pressure.
B Loading = dead + 0.5-in. ice and 8.0-lb. wind pressure.
C Loading = dead + 0.75-in. ice and 11.0-lb. wind pressure.

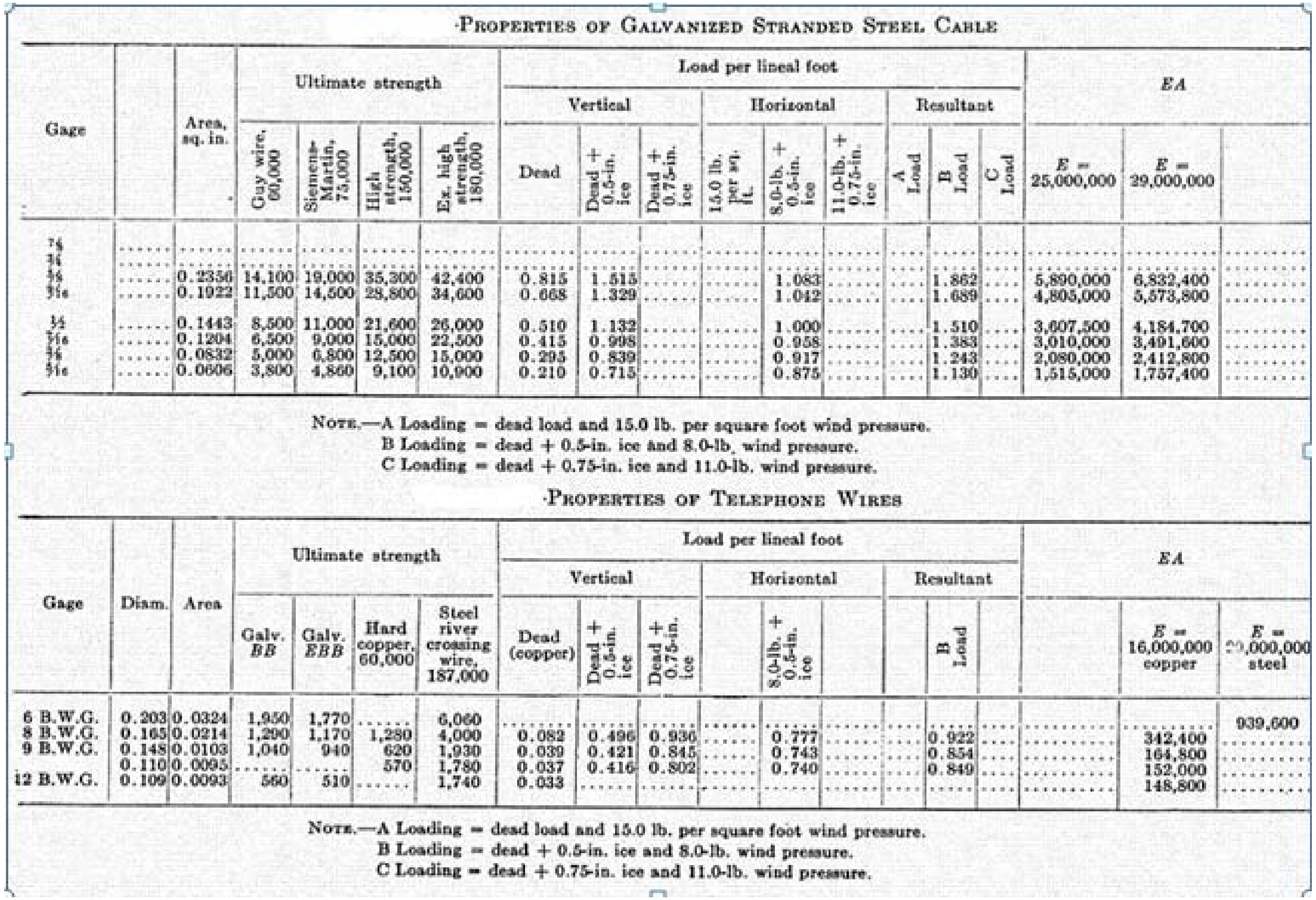


Table 5

Properties of Galvanized Stranded Steel Cable

Gage		Area, sq. in.	Ultimate strength				Load per lineal foot									EA		
							Vertical			Horizontal			Resultant					
			Guy wire, 60,000	Siemens-Martin, 75,000	High strength, 150,000	Ex. high strength, 180,000	Dead	Dead + 0.5-in. ice	Dead + 0.75-in. ice	15.0 lb. per sq. ft.	8.0-lb. + 0.5-in. ice	11.0-lb. + 0.75-in. ice	A Load	B Load	C Load	E = 25,000,000	E = 29,000,000	
7/8	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
3/4	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
5/8	......	0.2356	14,100	19,000	35,300	42,400	0.815	1.515	......	......	1.083	......	......	1.862	......	5,890,000	6,832,400	......
9/16	......	0.1922	11,500	14,500	28,800	34,600	0.668	1.329	......	......	1.042	......	......	1.689	......	4,805,000	5,573,800	......
1/2	......	0.1443	8,500	11,000	21,600	26,000	0.510	1.132	......	......	1.000	......	......	1.510	......	3,607,500	4,184,700	......
7/16	......	0.1204	6,500	9,000	15,000	22,500	0.415	0.998	......	......	0.958	......	......	1.383	......	3,010,000	3,491,600	......
3/8	......	0.0832	5,000	6,800	12,500	15,000	0.295	0.839	......	......	0.917	......	......	1.243	......	2,080,000	2,412,800	......
5/16	......	0.0606	3,800	4,860	9,100	10,900	0.210	0.715	......	......	0.875	......	......	1.130	......	1,515,000	1,757,400	......

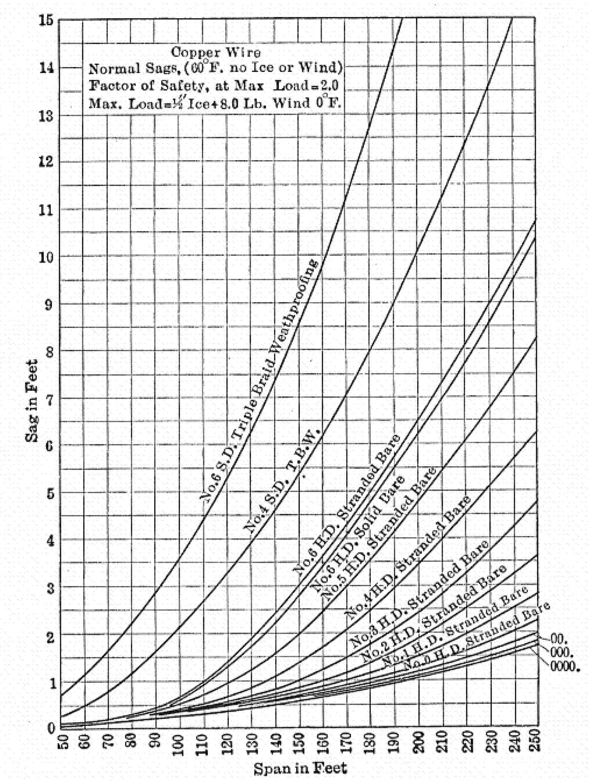
NOTE.—A Loading = dead load and 15.0 lb. per square foot wind pressure.
B Loading = dead + 0.5-in. ice and 8.0-lb. wind pressure.
C Loading = dead + 0.75-in. ice and 11.0-lb. wind pressure.

Table 6

Properties of Telephone Wires

Gage	Diam.	Area	Ultimate strength				Load per lineal foot									EA		
							Vertical			Horizontal			Resultant					
			Galv. *BB*	Galv. *EBB*	Hard copper, 60,000	Steel river crossing wire, 187,000	Dead (copper)	Dead + 0.5-in. ice	Dead + 0.75-in. ice		8.0-lb. + 0.5-in. ice			B Load			E = 16,000,000 copper	E = [illegible],000,000 steel
6 B.W.G.	0.203	0.0324	1,950	1,770	......	6,060	......	......	......	......	......	......	......	......	......	......	......	939,600
8 B.W.G.	0.165	0.0214	1,290	1,170	1,280	4,000	0.082	0.496	0.936	......	0.777	......	......	0.922	......	......	342,400	......
9 B.W.G.	0.148	0.0103	1,040	940	620	1,930	0.039	0.421	0.845	......	0.743	......	......	0.854	......	......	164,800	......
	0.110	0.0095	......	......	570	1,780	0.037	0.416	0.802	......	0.740	......	......	0.849	......	......	152,000	......
12 B.W.G.	0.109	0.0093	560	510	......	1,740	0.033	......	......	......	......	......	......	......	......	......	148,800	......

NOTE.—A Loading = dead load and 15.0 lb. per square foot wind pressure.
B Loading = dead + 0.5-in. ice and 8.0-lb. wind pressure.
C Loading = dead + 0.75-in. ice and 11.0-lb. wind pressure.



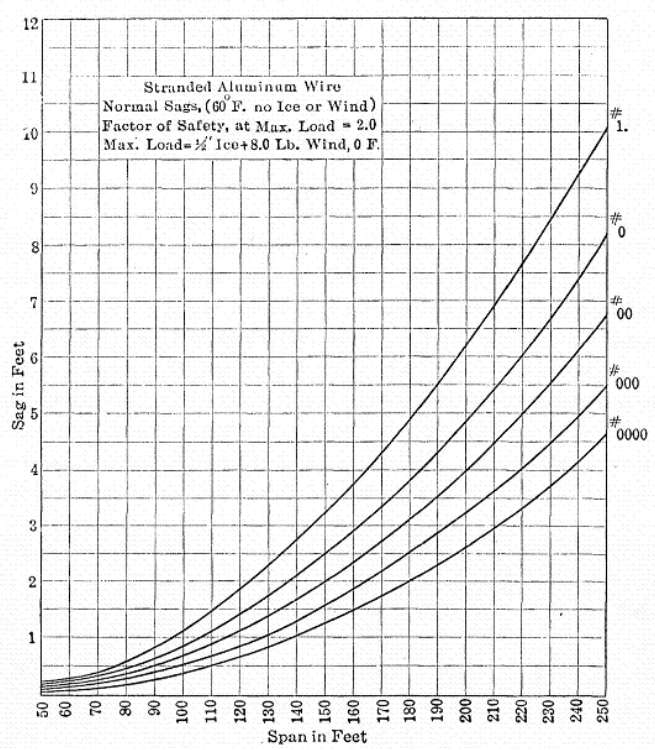
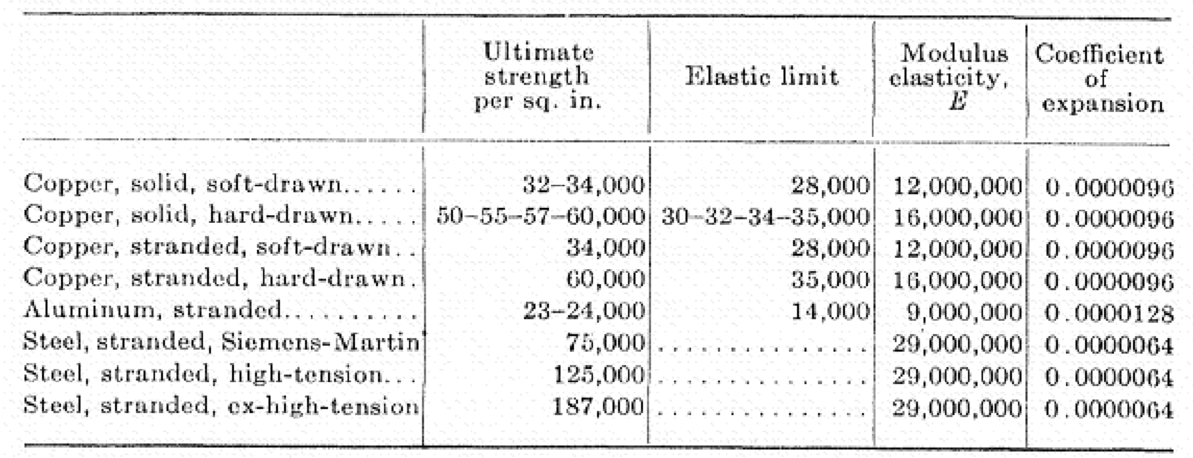


Figure 4 Normal Sags, copper wires and cables

Figure 5 Normal Sags, Aluminium Cables

Table 7 Properties of Wire Material



	Ultimate strength per sq. in.	Elastic limit	Modulus elasticity, *E*	Coefficient of expansion
Copper, solid, soft-drawn......	32–34,000	28,000	12,000,000	0.0000096
Copper, solid, hard-drawn.....	50–55–57–60,000	30–32–34–35,000	16,000,000	0.0000096
Copper, stranded, soft-drawn..	34,000	28,000	12,000,000	0.0000096
Copper, stranded, hard-drawn.	60,000	35,000	16,000,000	0.0000096
Aluminum, stranded..........	23–24,000	14,000	9,000,000	0.0000128
Steel, stranded, Siemens-Martin	75,000	....	29,000,000	0.0000064
Steel, stranded, high-tension...	125,000	....	29,000,000	0.0000064
Steel, stranded, ex-high-tension	187,000	....	29,000,000	0.0000064