https://doi.org/10.31871/IJNTR.8.8.8
International Journal of New Technology and Research (IJNTR)
ISSN: 2454-4116, Volume-8, Issue-8, August 2022 Pages 12-18

Overhead Utility Systems

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***Abstract*— Electricity distribution through utility companies is one of the most important sectors of power distribution, because besides providing power to homes, businesses, across states and countries; it is also very delicate, and if not implemented/maintained properly, can be very dangerous to the rest of the society at large. The distribution of electricity can be done in a variety of ways. Most popularly used in today's day and age is the distribution of electricity through overhead power lines. According to the Edison Electric Institute, "70 percent of wires in the U.S. are . . . on overhead poles" simply because they have relatively cheaper installation and repair costs, compared to other options, for example underground distribution (Wissel). In this report, we shall go into an in depth analysis of the construction of overhead power lines, the materials used, the costs associated, as well as their advantages and disadvantages.**

***Index Terms*— Electricity distribution, power lines.**

INTRODUCTION

An overhead power line is a structure used in electric power transmission and distribution to transmit electrical energy along large distances. It consists of one or more conductors (commonly multiples of three) suspended by towers or poles. Since most of the insulation is provided by air, overhead power lines are generally the lowest-cost method of power transmission for large quantities of electric energy (Wikipedia). A power transmission network typically connects power plants to multiple substations near a populated area.

A dissertation by the Electrical, Electronics Engineering department at the Chisholm Institute of TAFE gives us insightful information about the behind the scenes in constructing overhead lines. These include:

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, helicopters may place aluminum towers. Concrete poles have also been used. Poles made of reinforced plastics are also available, but their high cost restricts application.

Classification

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

1) Low voltage: less than 1000 volts, used for connect between a residential or small commercial customer and the utility.

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

3) High Voltage (Sub transmission 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.

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

5) 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.

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 switch gear to operate at the chosen voltage
- environmental aspects of the system installation

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 un-insulated, design of these lines requires minimum clearances to be observed to maintain safety.

Conductors

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. Overhead conductors are not covered by insulation. The conductor material is nearly always an aluminum alloy, made into several strands and possibly reinforced with steel strands. Copper was sometimes used for overhead transmission but aluminum is lower in weight for equivalent performance, and much lower in cost.

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

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the skin effect, which causes most of the current to flow close to the surface of the wire.

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 minimize 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 wingspan 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.

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 (i.e 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.

Area Under Overhead Lines

The 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.

Things That Can Safely Make Contact with Overhead Lines

-Aluminum paint rollers
-Backhoes
-Concrete pumpers
-Cranes
-Long handled cement finishing float
-Metal building material
-Metal ladders
-Raised dump truck beds
-Scaffolds

Distribution systems

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.

Types of Distribution Feeder System

1) 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.

2) Parallel feeder: A greater level of reliability at a higher cost is achieved with a parallel feeder. 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.

3) 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 (i.e. an alternative path is available if the primary one fails) to each load substation.

4) 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 (“Design overhead distribution systems”).

Sources Of Hazards

According to the Kenya Bureau of Standards, the following are potential causes of hazards:

Electrical charges may appear on a de-energized transmission line due to one or a combination of the following factors:

1. a) Charges induced by electric or magnetic field coupling, or both, with energized adjacent lines especially under fault conditions and lightning strikes
2. b) De-energized lines accidentally energized
3. c) Static charge induced on de-energized lines due to atmospheric conditions

In addition to electrical hazards, there is the hazard posed by violent mechanical movements of cables during fault current exposure. Adequate grounding shall be established at construction work areas. The methods required and equipment used should be based on exposure to maximum system electrical hazards and soil conditions at the site.

All equipment, conductors, anchors, and structures within the work area shall be bonded together and grounded. The recommended method of personnel protection is the establishment of equipotential work zones to limit touch and step voltage to a safe level. An acceptable equipotential zone may be accomplished by the proper use of low- resistance shunts, jumpering, and grounding equipment. Grounding equipment includes personal grounds, master grounds, structure base grounds, running grounds, traveller grounds, ground grids, and ground rods (Kenya).

Reliability/Service Life

An online dissertation by Kevin .J. Mara gives us an insight into the average reliability and service life time frame for overhead power lines.

. Reliability

Overhead lines have more frequent but shorter outages e.g North Carolina study reported 92 minutes for overhead versus 145 minutes for underground

. Service Life

On average, overhead lines have a service life of 30 years for poles, 50 years for conductor (Mara).

Materials/Installation Methods

According to the Electrical Engineering portal, the materials and installation methods involved in overhead construction lines include:

Materials/Tools

The basic materials used in installing/constructing overhead lines include:

1) Conductor blocks: These are made in multiple configurations namely: i) single conductor ii) multiple conductor iii) helicopter iv) multiversal type (can be converted from bundle to single and vice versa). Conductor blocks should be large enough to properly accommodate the conductor and be lined with resilient liner such as neoprene and polyurethane and constructed of lightweight, high strength materials

2) Overhead ground wire blocks
3) Catch-off clocks
4) Sagging blocks
5) Pulling lines
6) Pulling grips
7) Catch-off grips
8) Swivels
9) Running boards
10) Conductor lifting hooks
11) Hold-down blocks

Methods of Installation

1) **Slack stringing**: can only be utilized if it is not necessary to keep the conductor off of the ground, and if no energized lines lie beneath the line being strung. In this method the pulling lines are pulled out on the ground, threaded through the stringing blocks, and the conductor is pulled in with less tension than is required to keep it off the ground. This is not considered to be an acceptable method when demands involve maximum utilization of transmission requirements.

Slack stringing

Tesmec Transmission Line Stringing Equipment

2) **Semi-tension stringing**: is merely and upgrade of slack stringing, but does not necessarily keep the conductor completely clear of the ground, or the lines used to pull.

3) **Full tension stringing**: overhead ground wire in which sufficient pulling capabilities on one end and ground wire on one end and tension capabilities on the other, keep the wires clear of any obstacles during the movement of the conductor from the reel to its final sag position. This ensures that these current-carrying cables are "*clipped*" into the support clamps in the best possible condition, which is the ultimate goal of the work itself

4) **Stringing with helicopters**: which is much more expensive per hour of work, can be much less expensive when extremely arduous terrain exists along the right-of-way and when proper pre-planning is utilized. Although pulling conductors themselves with a helicopter can be done, it is limited and normally not practical. Maximum efficiency can be achieved when structures are set and pilot lines are pulled with the helicopter, and then the conductor stringing is done in a conventional manner (Edvard).

Stringing with helicopters

A helicopter starts the process of stringing a high-voltage transmission line

Process

The set of steps involved in preparing the area and installing overhead power lines varies by company. According to a publication by Northeast Utilities, the steps involved in overhead transmission line construction include:

Right-Of-Way Clearing

Initially, the right-of-way is cleared of trees and brush to provide the necessary access for construction equipment and a safe work area for crews. Clearing the right-of-way ensures an environment that safely and reliably supports the construction and ongoing operation of the transmission lines. No herbicides are used for clearing during construction. Although the right-of-way will appear very different after clearing, brush grows back quickly. To meet electric industry vegetation clearance standards, non-compatible species of trees must be permanently removed. These are trees that could become tall enough to grow or fall into the high voltage transmission lines.

Work Area Preparation

Construction vehicles must be able to access the location of each structure that will support the transmission lines. Gravel roads approximately 15-20 feet wide are needed for the large equipment used during construction. Large level work areas (generally 100 feet by 100 feet), called crane pads, are needed to stabilize equipment, such as drill rigs and cranes. Timber mats may be used in or around wetlands to protect these environmentally sensitive areas. Silt fencing and other environmental controls are also used to stabilize the soil and protect wetlands during construction. With the consent of property owners, gates are placed across new access roads where these intersect with town or state roads. These gates help deter unauthorized access to the right-of-way. By landowner request, gates are also installed where access roads cross-agricultural land containing livestock. Access road/work area development averages two to three days on each property.

Transmission Line Relocation

Distribution lines are the lower-voltage power lines that bring electricity to customers' homes. Sometimes these lines are on transmission rights-of-way. During construction, the utility company carefully coordinates the removal of existing lines with the installation of new lines. Where relocations are required, new distribution poles and wires are first installed in an alternate section of the right-of-way. Once complete, the existing distribution line is de-energized so that power can be transferred to the newly built line. The de-energized lines are then removed so that transmission line construction can continue. The old poles are taken to an off-site location and disposed of properly.

Existing Transmission Structure Removal

The sequence of construction is planned to allow workers to safely construct the new lines while customers continue to receive electrical power. Existing structures that require removal are de-energized and the overhead wires removed. The wood poles or steel structures are taken off-site and disposed of properly. Concrete foundations are removed below grade and the area is filled.

Structure Foundation Installation

The next step in the construction process is drilling foundations for the new transmission structures. This involves drilling large holes, which are then typically filled with concrete for the steel structure foundation. Drilling operations occur for a few days at each new structure location using rigs such as that pictured. Once drilling is complete, a steel rebar cage is placed in each hole and concrete is poured to create a secure foundation for the new steel structure. Concrete trucks are used to deliver the concrete mix for the foundations. Some structures (such as wood pole or H-frames structures) can be placed on a direct-buried foundation where the hole is filled with processed rock, rather than concrete.

New Structure Installation

Once the foundation is cured, transmission structure installation can begin. The new steel poles often come in sections that are assembled on or near the foundation. Cranes and/or bucket trucks are used to lift the poles and set them into position on the foundations. The structure components are delivered to the right-of-way well in advance of this installation process. Generally, it takes one to three days to assemble and erect each new structure. After installation, the structure is grounded.

Wire Stringing

With the new steel structures in place, the next step is to install the wire ("conductor"). The wire-stringing operation requires equipment at each end of the section being strung. Wire is pulled between these "pulling sites" through stringing blocks (pulleys) at each structure. These pulling sites are set up at various intervals along the right-of-way, typically one to three miles apart. Specific pulling sites are determined close to the time the stringing activity takes place. The utility company notifies property owners about the sites chosen at that time. Once the wire is strung, the stringing blocks are removed and the wire clipped into its final hardware attachment. Helicopters may be used during wire stringing operations.

Restoration

When construction is complete, disturbed areas will be restored. Native shrubs and ground cover are allowed to regrow. Environmental controls are removed, though some may remain until the area is stabilized.

In areas that were previously landscaped, the utility company works with property owners to restore the area to its pre-construction condition. Before construction is complete, a project representative will visit affected property owners to develop property-specific restoration plans. These plans will require the final approval of both the property owner and the utility company ("Guide to Overhead Transmission Line Construction").

Cost

According to a 1996 case study by the Connecticut Siting Council, the typical costs(includes initial and life cycle cost) involves:

Initial costs
1) Civil work: 49.4% ($1,234,000)
2) Contingency: 12.7% ($318,000)
3) AFUDC: 2.6% ($64,000)
4) Administration and Engineering: 13.6% (340,000)
5) Conductor: 5.1% ($127,000)
6) Other materials: 16.6% ($416,000)
Total first cost = $2,501,000

Life cycle costs
1) Fixed cost: 61.4% ($3,522,000)
2) O & M cost: 1.7% ($100,000)
3) Loss cost: 36.8% ($2,112,000)
Total life cycle cost: $5,734,000

Although these costs seem high (a little under $8,500,000), in comparison to underground installation costs it is still relatively cheap. As seen in the study, the first costs for underground are $12,926,000 and life cycle costs are $ 19, 016,000 summing up to over $31,000,000. As we see in this study the underground costs are about 15 times higher than overhead. On average underground is five to fifteen times more expensive that overhead costs.

Advantages and Disadvantages of Overhead versus Underground Distribution

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 reliability of underground distribution is greater than for overhead systems because of the lower number of fault interruptions. However, when these interruptions do occur in underground systems, they are generally of much longer duration than those associated with overhead lines.

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, replacing it with larger conductors and/or increasing the voltage insulation/operating level can readily increase the capacity of an overhead feeder. This flexibility is one big advantage of overhead systems.

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, e.g. 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.

Applications

Besides the obvious provision of power to homes and businesses, overhead power lines provide the following services:

1) 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.

2) Antenna: 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 an-

tenna. (“Design overhead distribution systems”).

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