Unit-II Design of distributed networks

Distribution substation

- A distribution substation transfers power from the transmission system to the distribution system of an area. The input for a distribution substation is typically at least two transmission or sub transmission lines.
- Distribution voltages are typically medium voltage, between 2.4 and 33 kV depending on the size of the area served and the practices of the local utility. Besides changing the voltage, the job of the distribution substation is to isolate faults in either the transmission or distribution systems.
- Distribution substations may also be the points of voltage regulation, although on long distribution circuits (several km/miles), voltage regulation equipment may also be installed along the line.
- Complicated distribution substations can be found in the downtown areas of large cities, with high-voltage switching, and switching and backup systems on the low-voltage side.

Design

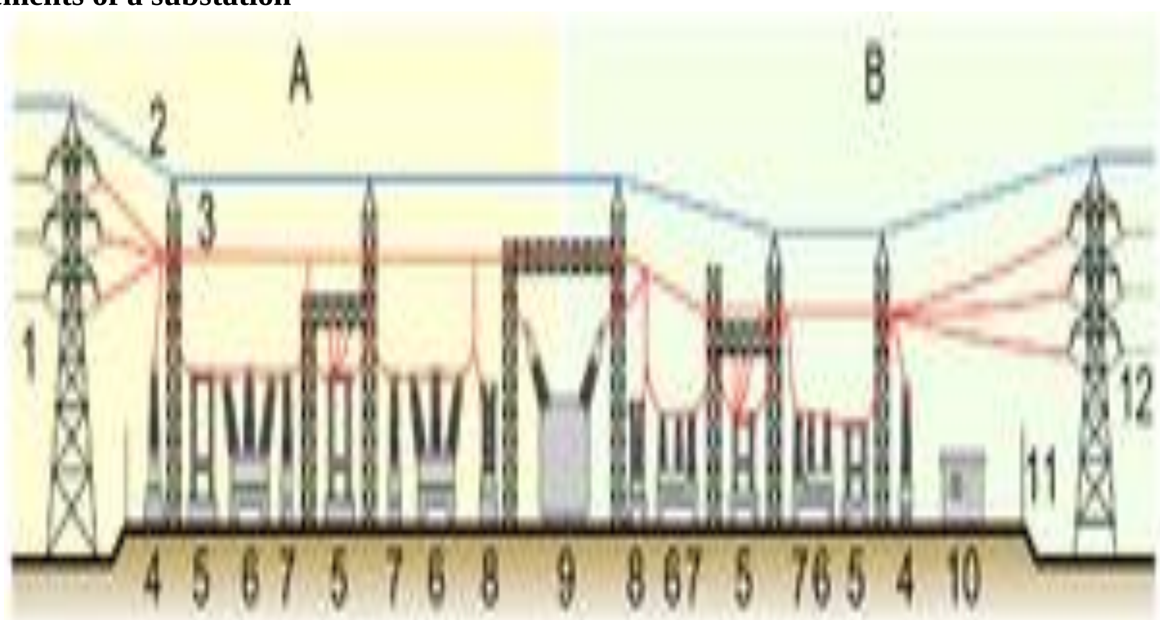
The main considerations taking into account during the design process are:

1. Reliability
2. Cost (sufficient reliability without excessive cost)
3. Expansion of the station, if required.

Selection of the location of a substation must consider many factors:

1. Sufficient land area
2. Necessary clearances for electrical safety
3. Access to maintain large apparatus such as transformers.
4. The site must have room for expansion due to load growth or planned transmission additions.
5. Environmental effects such as drainage, noise and road traffic effects.
6. Grounding must be taking into account to protect passers-by during a short circuit in the transmission system
7. The substation site must be reasonably central to the distribution area to be served

Elements of a substation



A: Primary power lines' side B: Secondary power lines' side
1.Primary power lines 2.Ground wire 3.Overhead lines
4. Transformer for measurement of electric voltage 5.Disconnect switch 6.Circuit breaker
7. Current transformer 8.Lightning arrester 9.Main transformer 10.Control building
11. Security fence 12.Secondary power lines

Substations generally have switching, protection and control equipment, and transformers. In a large substation, circuit breakers are used to interrupt any short circuits or overload currents that may occur on the network. Smaller distribution stations may use recloser circuit breakers or fuses for protection of distribution circuits. Substations themselves do not usually have generators, although a power plant may have a substation nearby. Other devices such as capacitors and voltage regulators may also be located at a substation.

Substations may be on the surface in fenced enclosures, underground, or located in special-purpose buildings. High-rise buildings may have several indoor substations. Indoor substations are usually found in urban areas to reduce the noise from the transformers, for reasons of appearance, or to protect switchgear from extreme climate or pollution conditions.

Where a substation has a metallic fence, it must be properly grounded to protect people from high voltages that may occur during a fault in the network. Earth faults at a substation can cause a ground potential rise. Currents flowing in the Earth's surface during a fault can cause metal objects to have a significantly different voltage than the ground under a person's feet; this touch potential presents a hazard of electrocution. The main issues facing a power engineer are reliability and cost. A good design attempts to strike a balance between these two, to achieve reliability without excessive cost. The design should also allow expansion of the station, when required.

Design Diagrams

The first step in planning a substation layout is the preparation of a one-line diagram, which shows in simplified form the switching and protection arrangement required, as well as the incoming supply lines and outgoing feeders or transmission lines. It is a usual practice by many electrical utilities to prepare one-line diagrams with principal elements (lines, switches, circuit breakers and transformers) arranged on the page similarly to the way the apparatus would be laid out in the actual station.

In a common design, incoming lines have a disconnect switch and a circuit breaker. In some cases, the lines will not have both, with either a switch or a circuit breaker being all that is considered necessary. A disconnect switch is used to provide isolation, since it cannot interrupt load current. A circuit breaker is used as a protection device to interrupt fault currents automatically, and may be used to switch loads on and off, or to cut off a line when power is flowing in the 'wrong' direction. When a large fault current flows through the circuit breaker, this is detected through the use of current transformers. The magnitude of the current transformer outputs may be used to trip the circuit breaker resulting in a disconnection of the load supplied by the circuit break from the feeding point. This seeks to isolate the fault point from the rest of the system, and allow the rest of the system to continue operating with minimal impact. Both switches and circuit breakers may be operated locally (within the substation) or remotely from a supervisory control center.

With Overhead Transmission Lines (OHTLs), the propagation of lightning and switching surges can cause insulation failures into substation equipment. Line entrance surge arrestors are used to protect substation equipment accordingly. Insulation Coordination studies are carried out extensively to ensure equipment failure (and associated outages) is minimal.

Once past the switching components, the lines of a given voltage connect to one or more buses. These are sets of busbars, usually in multiples of three, since three-phase electrical power distribution is largely universal around the world.

The arrangement of switches, circuit breakers and buses used affects the cost and reliability of the substation. For important substations a ring bus, double bus, or so-called "breaker and a half" setup can be used, so that the failure of any one circuit breaker does not interrupt power to other circuits, and so that parts of the substation may be de-energized for maintenance and repairs. Substations feeding only a single industrial load may have minimal switching provisions, especially for small installations.

Once having established buses for the various voltage levels, transformers may be connected between the voltage levels. These will again have a circuit breaker, much like transmission lines, in case a transformer has a *fault* (commonly called a "short circuit").

Along with this, a substation always has control circuitry needed to command the various circuit breakers to open in case of the failure of some component.

Design Considerations in Distribution Feeders & Distributors

Good voltage regulation of a distribution network is probably the most important factor responsible for delivering good service to the consumers. For this purpose, design of feeders and distributors requires careful consideration.

Feeders

A feeder is designed from the point of view of its current carrying capacity while the voltage drop consideration is relatively unimportant. It is because voltage drop in a feeder can be compensated by means of voltage regulating equipment at the substation.

Distributors

A distributor is designed from the point of view of the voltage drop in it. It is because a distributor supplies power to the consumers and there is a statutory limit of voltage variations at the consumer's terminals (± 6% of rated value). The size and length of the distributor should be such that voltage at the consumer's terminals is within the permissible limits.

Primary feeders or Primary distribution feeders

The primary distribution system is that part of the electric distribution system between the distribution substation and distribution transformers. It is made up of circuits called primary feeders or distribution feeders. These feeders include the primary feeder main or main feeder, usually a three-phase, four-wire circuit, and branches or laterals, which can be either three-phase or single-phase circuits.

These are tapped from the primary feeder main, as shown in the simplified distribution feeder diagram of Figure. A typical power distribution feeder provides power for both primary and secondary circuits.

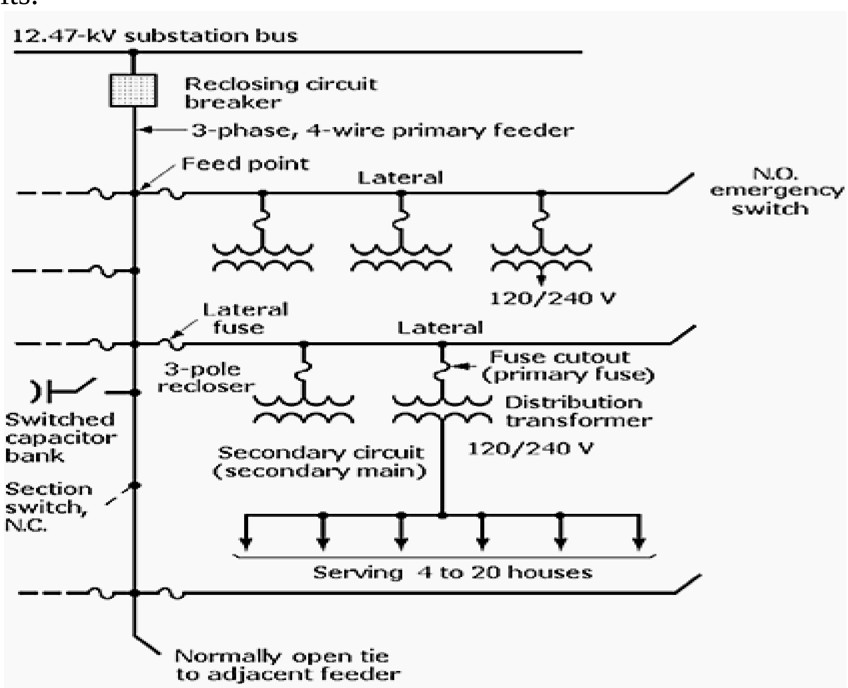


Figure – Simplified diagram of a power distribution feeder

In primary system circuits, three-phase, four-wire, multigrounded common-neutral systems, such as 12.47Y/7.2 kV, 24.9Y/14.4 kV, and 34.5Y/19.92 kV, are used almost exclusively. The fourth wire of these Y-connected systems is the neutral, grounded at many locations for both primary and secondary circuits.

Single-phase loads are served by distribution transformers with primary windings that are connected between a phase conductor and the neutral.

Three-phase loads can be supplied by three-phase distribution transformers or by single-phase transformers connected to form a three-phase bank. Primary systems typically operate in the 15kV range, but higher voltages are gaining acceptance.

The primary feeder main is usually sectionalized by reclosing devices positioned at various locations along the feeder. This arrangement minimizes the extent of primary circuitry that is taken out of service if a fault occurs. Thus the reclosing of these devices confines the outage to the smallest number of customers possible. This can be achieved by coordinating all the fuses and reclosers on the primary feeder main.

From the Figure, distribution substation voltage is 12.47 kV line-to-line and 7.2 kV line-to-neutral (this is conventionally written as 12,470Y/7200 V). However, the trend is toward higher primary four-wire distribution voltages in the 25kV to 35kV range. Single-phase feeders such as those serving residential areas are connected line-to-neutral on the four-wire systems.

The use of underground primary feeders that are radial three-conductor cables is increasing. They are serving urban areas where load demand is heavy, particularly during the hot summer months, and newer suburban residential developments. Both cost factors and the importance of reliability to the customers being served influence the design of primary systems.

There are various factors affecting selection of primary feeder rating;

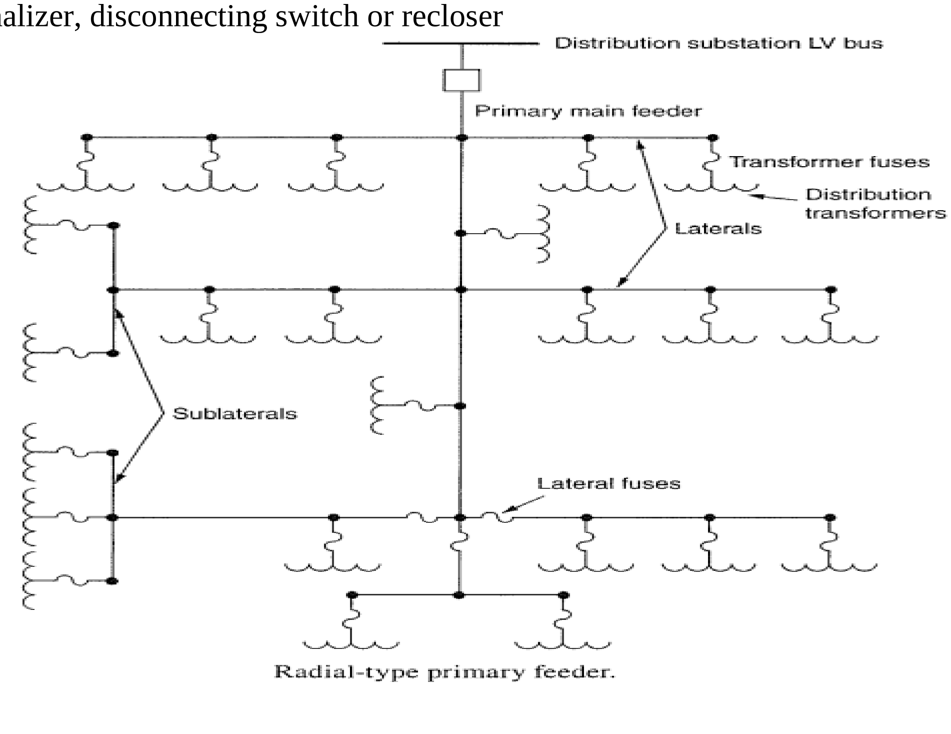
- The nature of the load connected
- The load density
- The growth rate of the load
- Cost
- Capacity of substation
- Regulating equipment
- Continuously power factor the service

Primary feeders are mainly two types. They are

- Radial type primary feeder
- Loop type primary feeder

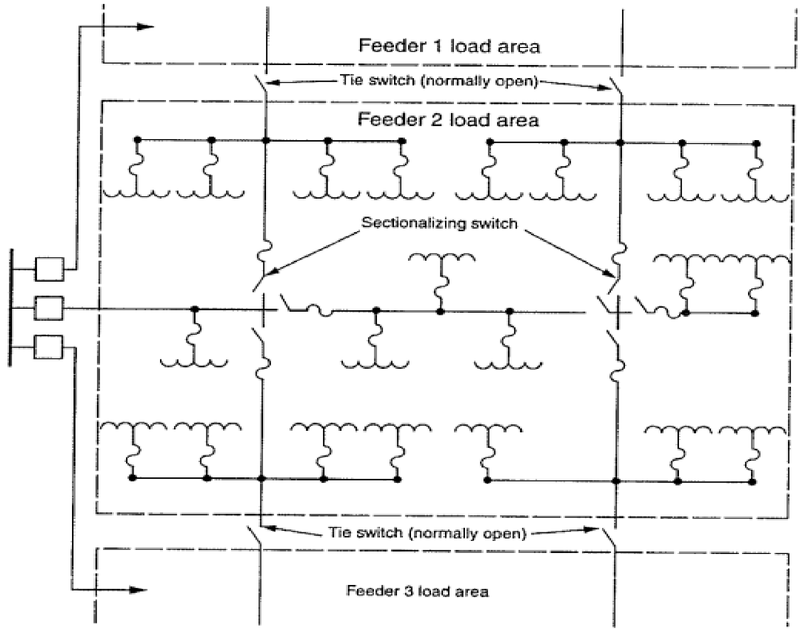
Radial type primary feeder

The simplest, lowest cost and the most common form of primary feeder is the redial type. The main primary feeder branches into various laterals which in turn separated into several sub-lateral to cover all distribution transformers. In general the main feeder is three phase, four wire system and the sub-lateral is single/ or three phase circuit. The current magnitude is the greatest in the feeder conductors leave the substation and continuously lessens out at the end of the feeder as the laterals and sub-laterals are tapped off the feeder. As the current lessen the size of the conductor is also lessen. The reliability of the service continuity of the redial system is the lowest. Any fault at any location on the main feeder cause a power outage for every consumer on the feeder unless the fault can be isolated from the source by a disconnecting devices such as fuse, sectionalizer, disconnecting switch or recloser



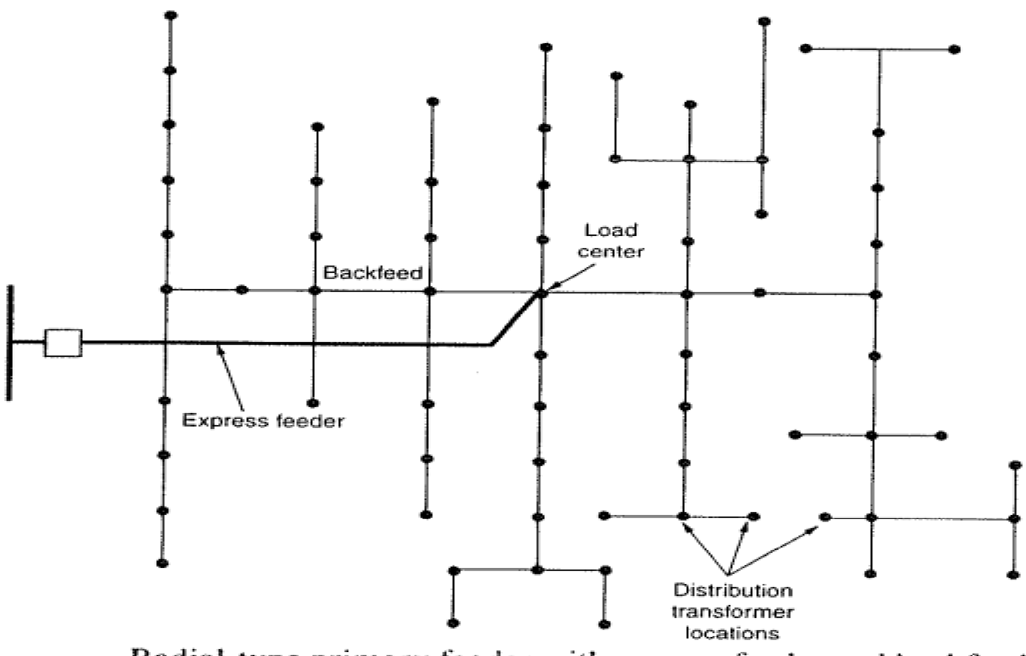
Radial-type primary feeder.

Below figure shows a modified redial type primary feeder with tie and sectionalizing switches to provide fast restoration of the service to customers by switching unfaulted section of the feeder. The fault can be isolated by opening the associated disconnection device s on each side of the faulted section.

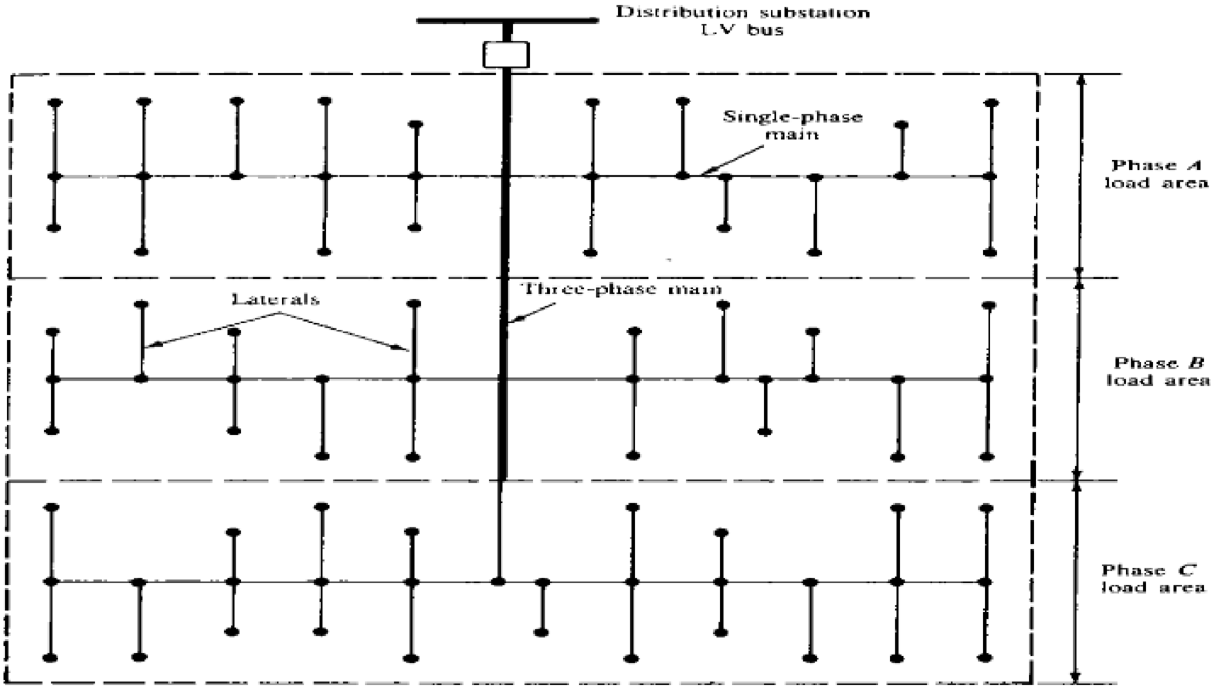


Radial-type primary feeder with tie and sectionalizing switches. (Data abstracted from Rome Cable Company, URD Technical Manual, 4th ed.)

Below figure shows another type of the modified primary feeder with express feeder and backfeed. The section between the substation low voltage bus and the load center of the service area is called an express feeder. No sub feeders or laterals are allowed to tap off the express feeder. However a sub feeder is allowed to provide a backfeed toward the substation from the load center.

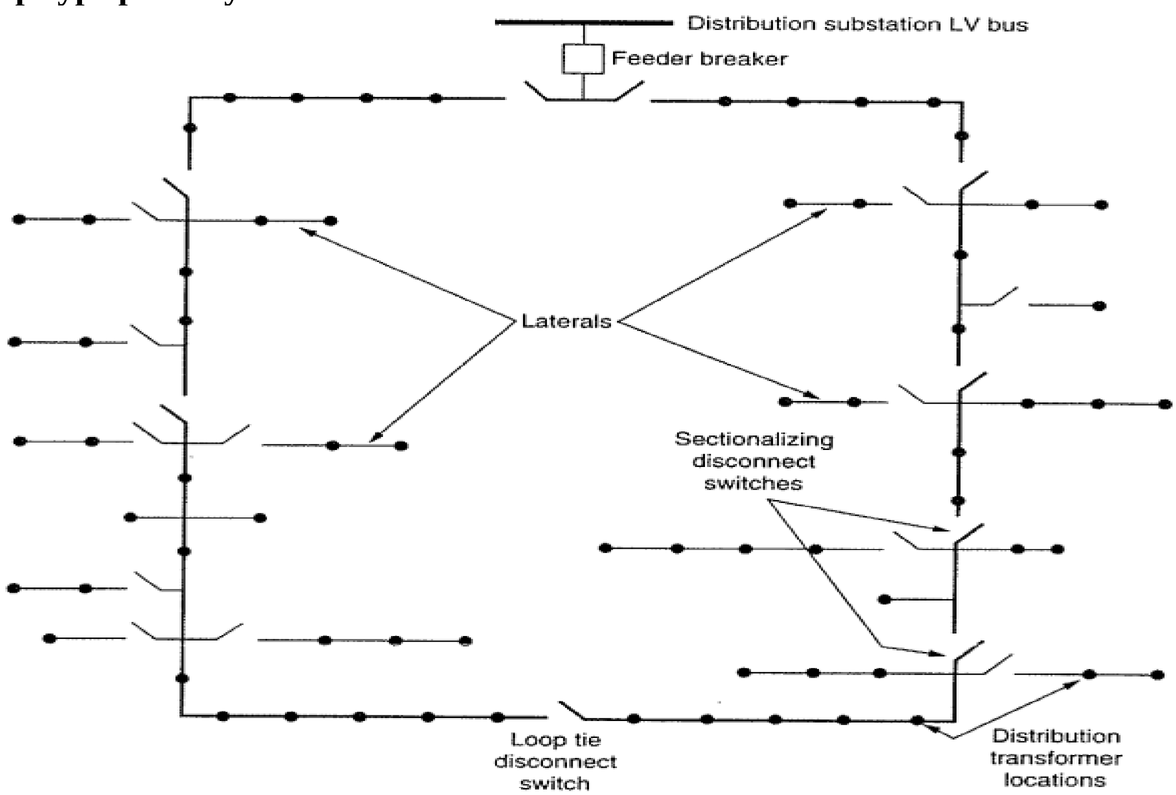


Radial-type primary feeder with express feeder and backfeed.



Radial type phase area feeder

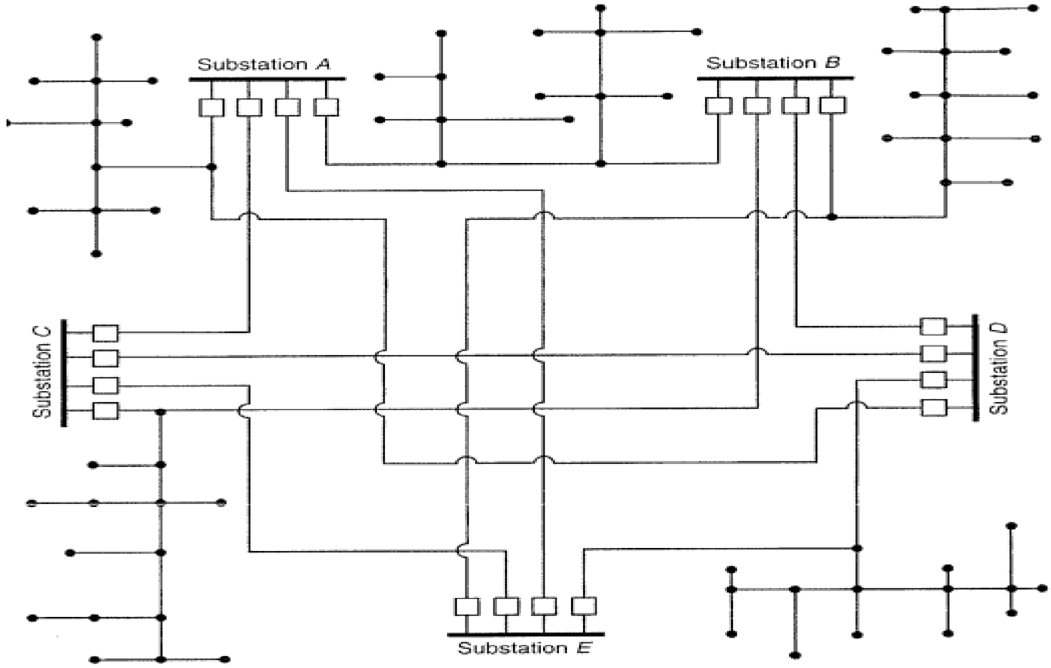
Loop-type primary feeder



Loop-type primary feeder.

Figure represent a loop type primary feeder which loop through the feeder load area and return beck to the bus. Sometime the loop tie disconnect switch is replaced by a loop tie breaker according to loads conditions. The size of the feeder conductor is kept the same throughout the loop, it is selected to carry its rated load plus the load of the other half of the loop. This arrangement provides two parallel paths from the substation to the load when the loop is operated with normally open tie breaker. The loop type feeder is preferred to provide service for loads where high reliability service is required. In general two separated tie breaker is on each end of the loop is preferred although the cost involved.

Primary Network



Primary network.

As shown in Figure, a primary network is a system of interconnected feeders supplied by a number of substations. The radial primary feeders can be tapped off the interconnecting tie feeders. They can also be served directly from the substations. Each tie feeder has two associated circuit breakers at each end in order to have less load interrupted because of a tie-feeder fault.

The primary network system supplies a load from several directions. Proper location of transformers to heavy-load centers and regulation of the feeders at the substation buses provide for adequate voltage at utilization points. In general, the losses in a primary network are lower than those in a comparable radial system because of load division.

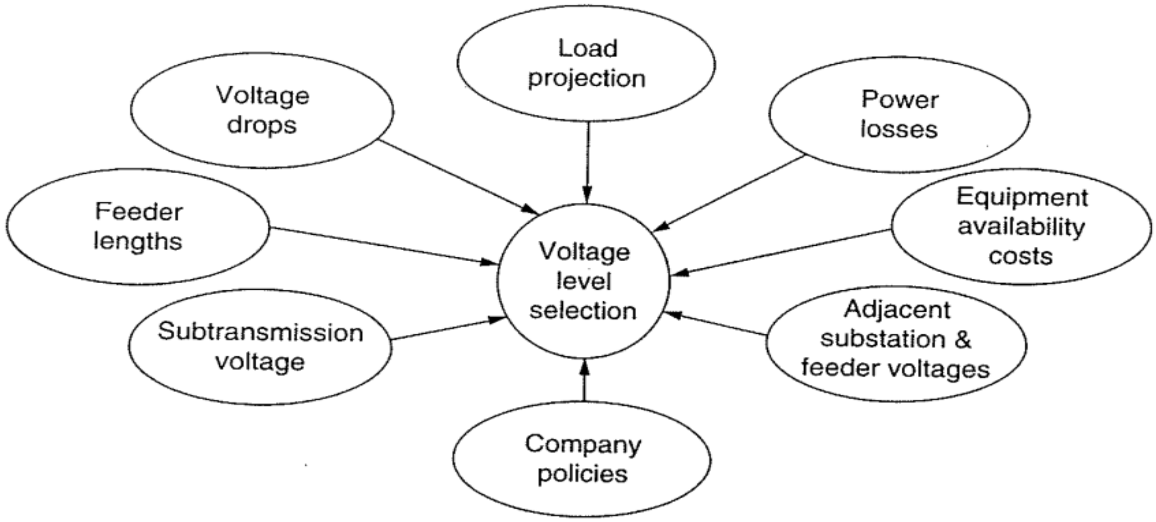
The reliability and the quality of service of the primary network arrangement is much higher than the radial and loop arrangements. However, it is more difficult to design and operate than the radial or loop systems.

Primary feeder voltage levels

The primary-feeder voltage level is the most important factor affecting the system design, cost, and operation. Some of the design and operation aspects affected by the primary-feeder voltage level are:

1. Primary-feeder length
2. Primary-feeder loading
3. Number of distribution substations
4. Rating of distribution substations
5. Number of subtransmission lines
6. Number of customers affected by a specific outage
7. System maintenance practices
8. The extent of tree trimming
9. Joint use of utility poles
10. Type of pole-line design and construction
11. Appearance of the pole line.

Usually, primary feeders located in low-load density areas are restricted in length and loading by permissible voltage drop rather than by thermal restrictions, whereas primary feeders located in high-load density areas, for example, industrial and commercial areas, may be restricted by the thermal limitations.



Factors affecting primary-feeder voltage-level selection decision.

In general, for a given percent voltage drop, the feeder length and loading are direct functions of the feeder voltage level. This relationship is known as the *voltage-square rule*. For example, if the feeder voltage is doubled, for the same percent voltage drop, it can supply the same power four times the distance. However, as Lokay explains it clearly, the feeder with the increased length feeds more load. Therefore, the advantage obtained by the new and higher-voltage level through the voltage-square factor, that is,

$$\text{Voltage-square factor} = \left(\frac{V_{L\text{-}N,\,\text{new}}}{V_{L\text{-}N,\,\text{old}}}\right)^2$$

has to be allocated between the growth in load and in distance. Further, the same percent voltage drop will always result provided that the following relationship exists:

$$\text{Distance ratio} \times \text{load ratio} = \text{voltage-square factor}$$

where

$$\text{Distance ratio} = \frac{\text{new distance}}{\text{old distance}}$$

and

$$\text{Load ratio} = \frac{\text{new feeder loading}}{\text{old feeder loading}}.$$

The relationship between the voltage-square factor rule and the feeder *distance coverage principle*.

There is a relationship between the area served by a substation and the voltage rule. Lokay defines it as the *area-coverage principle*. As illustrated in Figure 5.10, for a constant percent voltage drop and a uniformly distributed load, the feeder service area is proportional to:

$$\left[\left(\frac{V_{L-N,\,\text{new}}}{V_{L-N,\,\text{old}}}\right)^2\right]^{2/3},$$

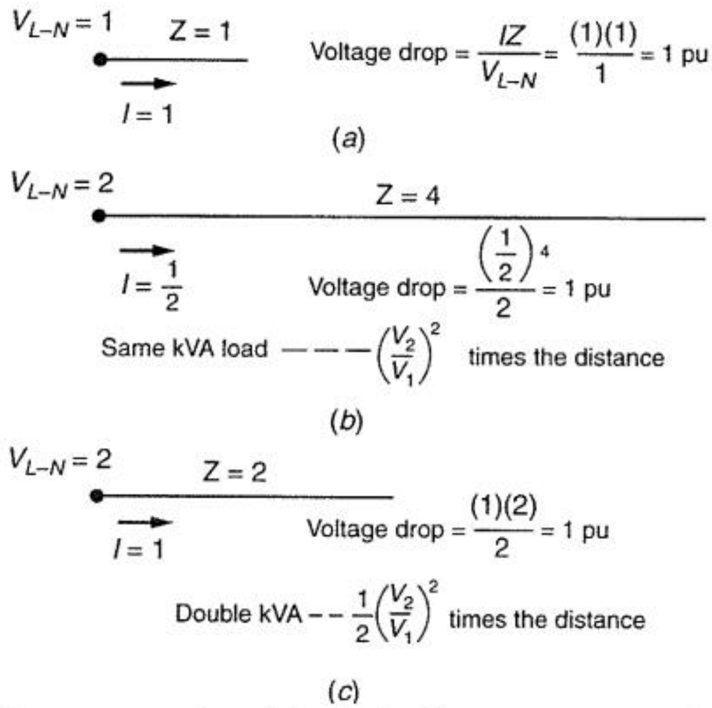
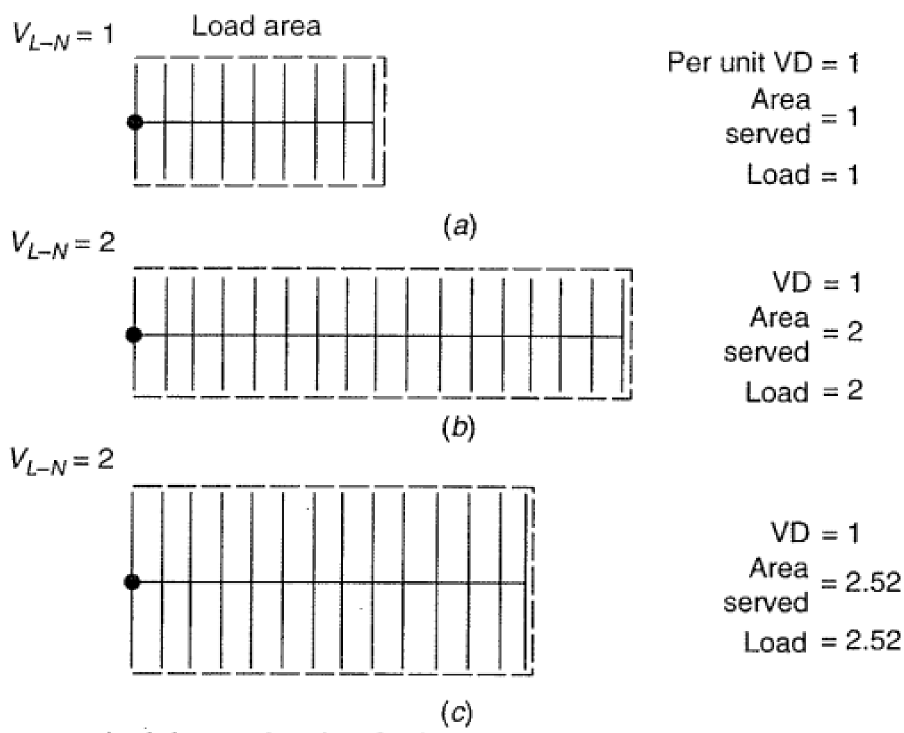


Illustration of the voltage-square rule and the feeder distance coverage principle as a function of feeder voltage level and a single load.



Feeder area coverage principle as related to feeder voltage and a uniformly distributed load.

provided that both dimensions of the feeder service area change by the same proportion. For example, if the new feeder voltage level is increased to twice the previous voltage level, the new load and area that can be served with the same percentage of voltage drop is

$$\left[\left(\frac{V_{L-N,\,\text{new}}}{V_{L-N,\,\text{old}}}\right)^2\right]^{2/3} = (2^2)^{2/3} = 2.52$$

times the original load and area. If the new feeder voltage level is increased to three times the previous voltage level, the new load and area that can be served with the same percentage of voltage drop is

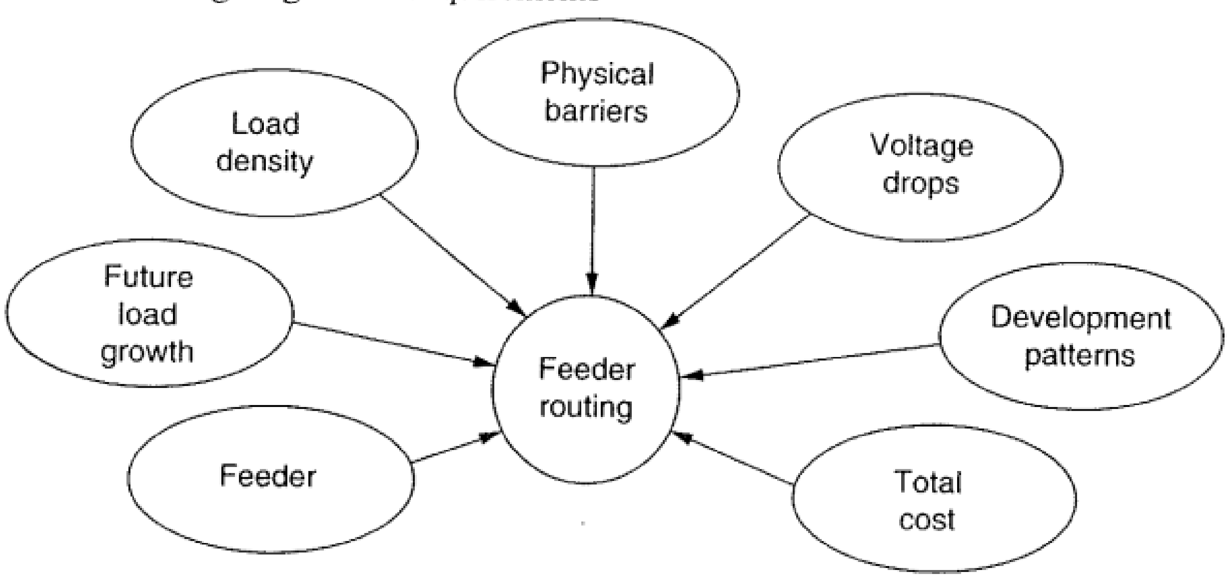
$$\left[\left(\frac{V_{L-N,\,\text{new}}}{V_{L-N,\,\text{old}}}\right)^2\right]^{2/3} = (3^2)^{2/3} = 4.32$$

times the original load and area.

Primary feeder loading

Primary-feeder loading is defined as the loading of a feeder during peak load conditions as measured at the substation. Some of the factors affecting the design loading of a feeder are:

1. The density of the feeder load
2. The nature of the feeder load
3. The growth rate of the feeder load
4. The reserve capacity requirements for emergency
5. The service continuity requirements
6. The service reliability requirements
7. The quality of service
8. The primary-feeder voltage level
9. The type and cost of construction
10. The location and capacity of the distribution substation
11. The voltage regulation requirements



Factors affecting feeder routing decisions.

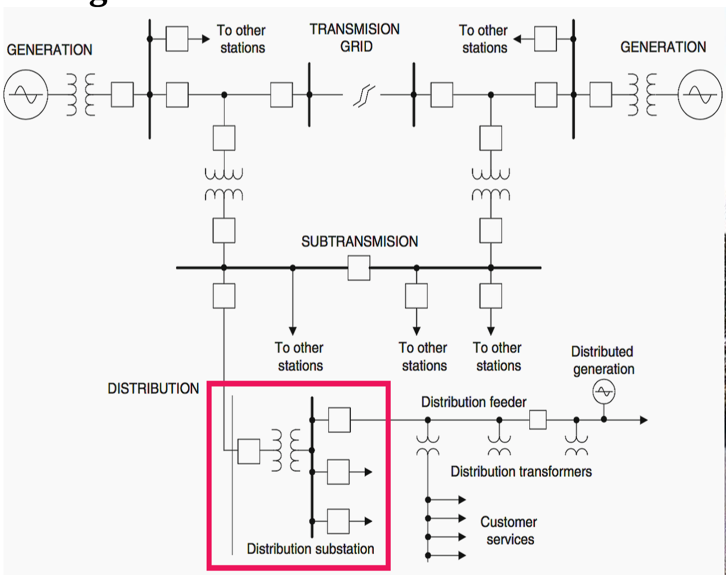
Location of substations

Selection of the location of a substation must consider many factors:

1. Sufficient land area
2. Necessary clearances for electrical safety

3. Access to maintain large apparatus such as transformers.
4. The site must have room for expansion due to load growth or planned transmission additions.
5. Environmental effects such as drainage, noise and road traffic effects.
6. Grounding must be taking into account to protect passers-by during a short circuit in the transmission system
7. The substation site must be reasonably central to the distribution area to be served

Rating of distribution Substations



The additional capacity requirements of a system with increasing load density can be met by:

1. Either holding the service area of a given substation constant and increasing its capacity
2. Or developing new substations and thereby holding the rating of the given substation constant

It is helpful to assume that the system changes (1) at constant load density for short-term distribution planning and (2) at increasing load density for long-term planning. Further, it is also customary and helpful to employ geometric figures to represent substation service areas, as suggested by Van Wormer [3], Denton and Reps [4], and Reps [5]. It simplifies greatly the comparison of alternative plans which may require different sizes of distribution substation, different numbers of primary feeders, and different primary-feeder voltages.

Reps [5] analyzed a square-shaped service area representing a part of, or the entire service area of, a distribution substation. It is assumed that the square area is served by four primary feeders from a central feed point, as shown in Fig. 4-16. Each feeder and its laterals are of three-phase. Dots represent balanced three-phase loads lumped at that location and fed by distribution transformers.

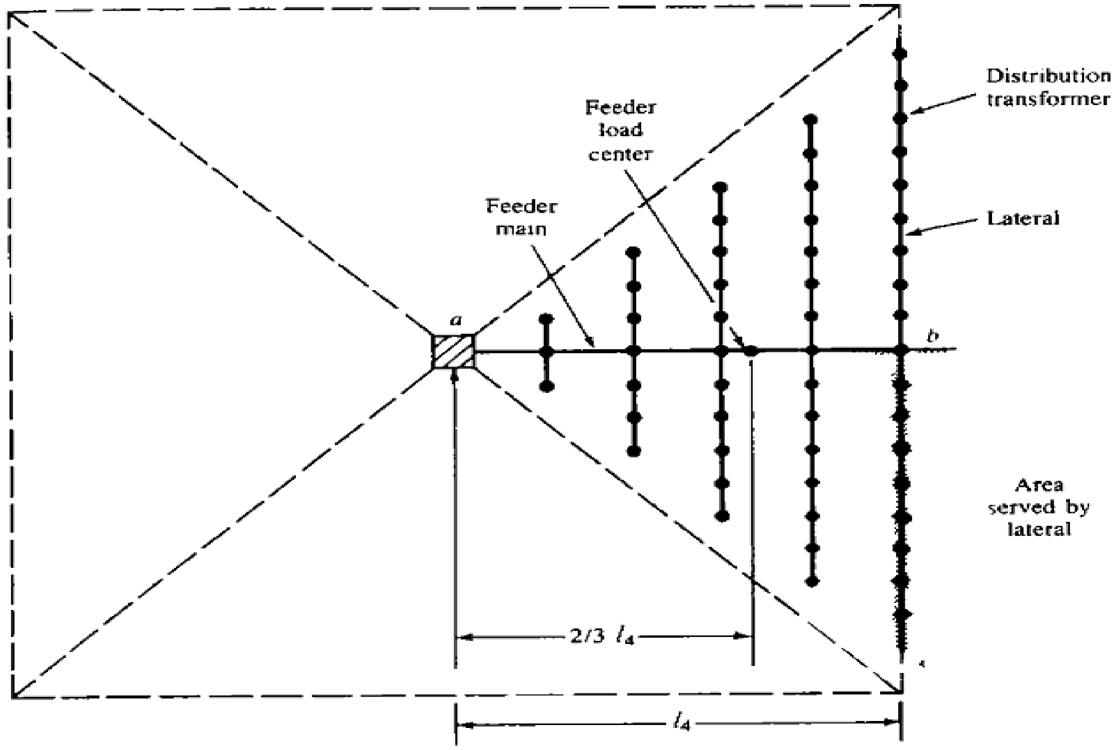


Figure 4-16 Square-shaped distribution substation service area. (*Based on* [5].)

Here, the percent voltage drop from the feed point a to the end of the last lateral at c is

$$\%\,\mathrm{VD}_{ac} = \%\,\mathrm{VD}_{ab} + \%\,\mathrm{VD}_{bc}$$

Reps [5] simplified the above voltage-drop calculation by introducing a constant K which can be defined as *percent voltage drop per kilovoltampere-mile*. Figure 4-17 gives the K constant for various voltages and copper conductor sizes. Figure 4-17 is developed for three-phase overhead lines with an equivalent spacing of 37 in between phase conductors. The following analysis is based on the work done by Denton and Reps [4] and Reps [5].

In Fig. 4-16, each feeder serves a total load of

$$S_4 = A_4 \times D \qquad \mathrm{kVA} \tag{4-1}$$

where S_4 = kilovoltampere load served by one of four feeders emanating from a feed point
A_4 = area served by one of four feeders emanating from a feed point, mi^2
D = load density, $\mathrm{kVA/mi}^2$

Equation (4-1) can be rewritten as

$$S_4 = l_4^2 \times D \qquad \mathrm{kVA} \tag{4-2}$$

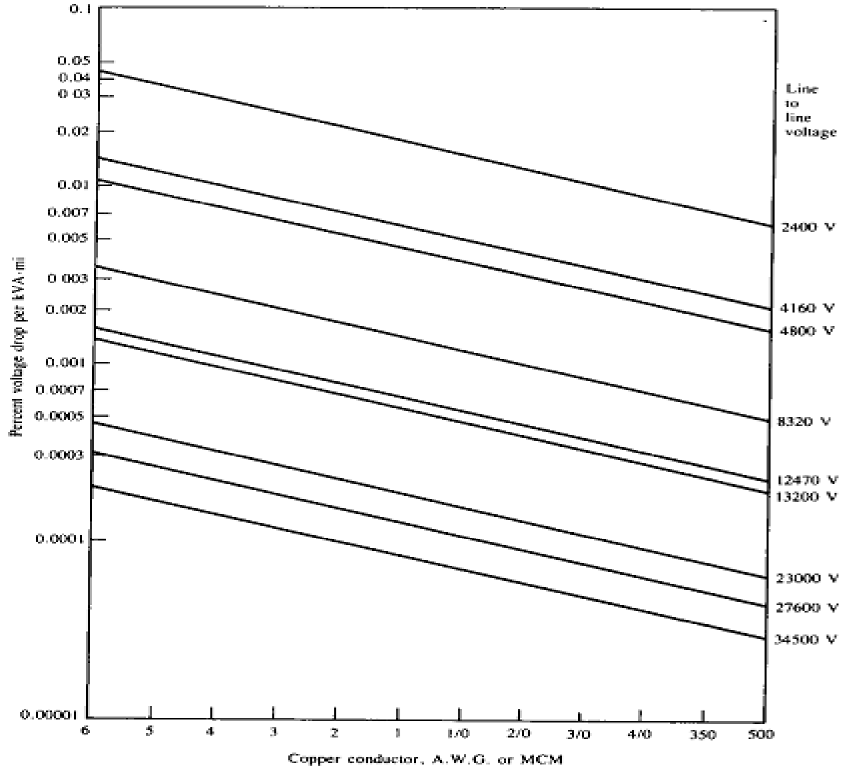


Figure 4-17 The K constant for copper conductors, assuming a lagging-load power factor of 0.9.

since

since

$$A_4 = l_4^2 \tag{4-3}$$

where l_4 is the linear dimension of the primary-feeder service area in miles.

Assuming uniformly distributed load, i.e., equally loaded and spaced distribution transformers, the voltage drop in the primary-feeder main is

$$\% \mathrm{VD}_{4,\,\mathrm{main}} = \tfrac{2}{3} \times l_4 \times K \times S_4 \tag{4-4}$$

or substituting Eq. (4-2) into Eq. (4-4),

$$\% \mathrm{VD}_{4,\,\mathrm{main}} = 0.667 \times K \times D \times l_4^3 \tag{4-5}$$

In Eq. (4-4) and (4-5), it is assumed that the total or lumped-sum load is located at a point on the main feeder at a distance of $\frac{2}{3} \times l_4$ from the feed point a.

Reps [5] extends the discussion to a hexagonally shaped service area supplied by six feeders from the feed point which is located at the center, as shown in Fig. 4-18. Assume that each feeder service area is equal to one-sixth of the hexagonally shaped total area, or

$$A_6 = \frac{l_6}{\sqrt{3}} \times l_6$$

$$= 0.578 \times l_6^2 \qquad (4\text{-}6)$$

where A_6 = area served by one of six feeders emanating from a feed point, mi^2
l_6 = linear dimension of a primary-feeder service area, mi

Here, each feeder serves a total load of

$$S_6 = A_6 \times D \qquad \text{kVA} \qquad (4\text{-}7)$$

or substituting Eq. (4-6) into Eq. (4-7),

$$S_6 = 0.578 \times D \times l_6^2 \qquad (4\text{-}8)$$

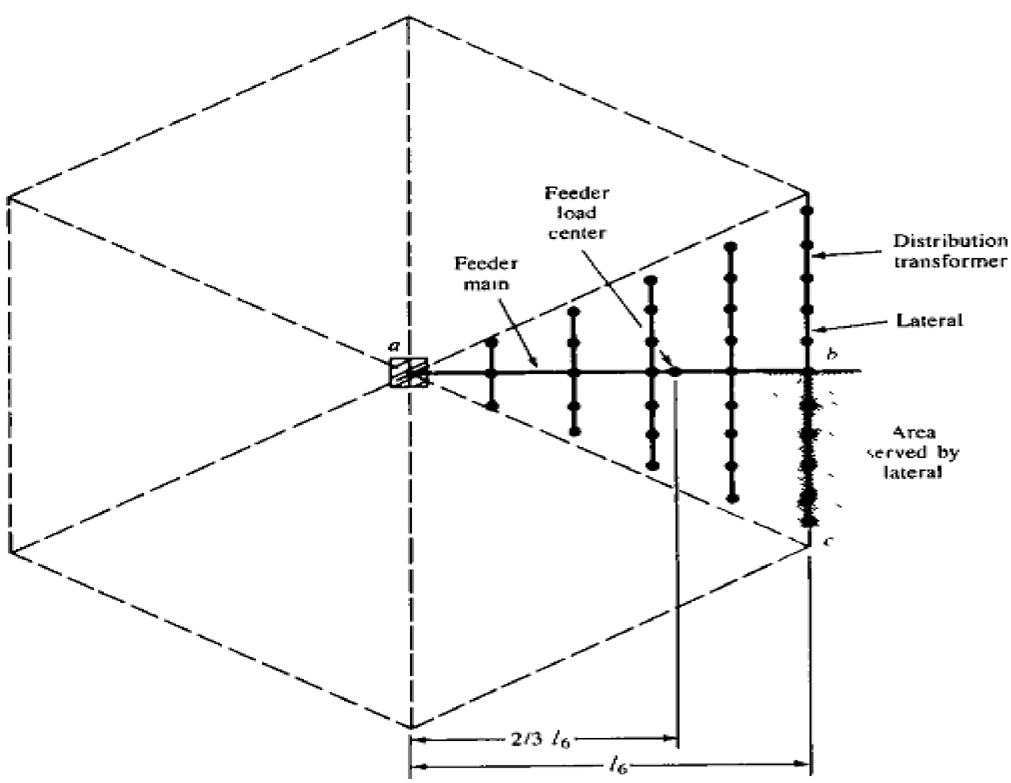


Figure 4-18 Hexagonally shaped distribution substation area. (*Based on* [5].)

As before, it is assumed that the total or lump-sum is located at a point on the main feeder at a distance of $\frac{2}{3} \times l_6$ from the feed point. Therefore, the percent voltage drop in the main feeder is

$$\%\,\text{VD}_{6,\text{main}} = \frac{2}{3} \times l_6 \times K \times S_6 \qquad (4\text{-}9)$$

or substituting Eq. (4-8) into Eq. (4-9),

$$\%\,\text{VD}_{6,\text{main}} = 0.385 \times K \times D \times l_6^3 \qquad (4\text{-}10)$$

Service area with 'n' primary feeders

Denton and Reps [4] and Reps [5] extend the discussion to the general case in which the distribution substation service area is served by n primary feeders emanating from the point, as shown in Fig. 4-19. Assume that the load in the service area is uniformly distributed and each feeder serves an area of triangular shape. The differential load served by the feeder in a differential area of dA is

$$dS = D\,dA \qquad \text{kVA} \tag{4-11}$$

where dS = differential load served by the feeder in the differential area of dA, kVA
D = load density, kVA/mi²
dA = differential service area of the feeder, mi²

In Fig. 4-19, the following relationship exists:

$$\tan\theta = \frac{y}{x + dx} \tag{4-12}$$

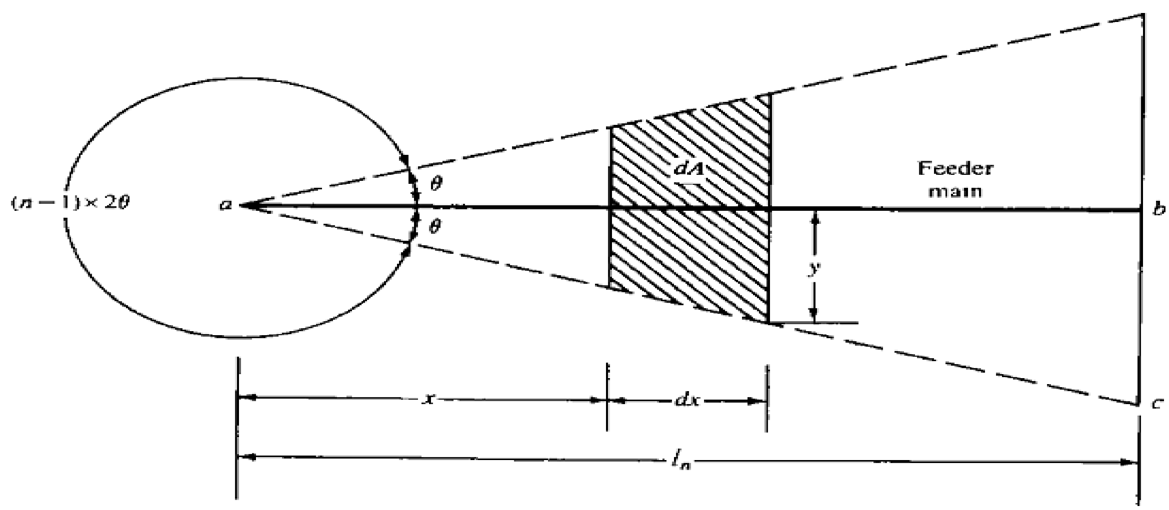


Figure 4-19 Distribution substation service area served by n primary feeders.

or

$$\begin{aligned} y &= (x + dx)\tan\theta \\ &\cong x \cdot \tan\theta \end{aligned} \tag{4-13}$$

Therefore the total service area of the feeder can be calculated as

$$\begin{aligned} A_n &= \int_{x=0}^{l_n} dA \\ &= l_n^2 \times \tan\theta \end{aligned} \tag{4-14}$$

Hence, the total kilovoltampere load served by one of n feeders can be calculated as

$$\begin{aligned} S_n &= \int_{x=0}^{l_n} dS \\ &= D \times l_n^2 \times \tan\theta \end{aligned} \tag{4-15}$$

This total load is located, as a lump-sum load, at a point on the main feeder at a distance of $\frac{2}{3} \times l_4$ from the feed point a. Therefore, the summation of the percent voltage contributions of all such areas is

$$\%\,\text{VD}_n = \tfrac{2}{3} \times l_n \times K \times S_n \tag{4-16}$$

or, substituting Eq. (4-15) into Eq. (4-16),

$$\% \text{VD}_n = \frac{2}{3} \times K \times D \times l_n^3 \times \tan\theta \tag{4-17}$$

or, since

$$n(2\theta) = 360° \tag{4-18}$$

Eq. (4-17) can also be expressed as

$$\% \text{VD}_n = \frac{2}{3} \times K \times D \times l_n^3 \times \tan\frac{360°}{2n} \tag{4-19}$$

Equations (4-18) and (4-19) are only applicable when $n \geq 3$. Table 4-2 gives the results of the application of Eq. (4-17) to square and hexagonal areas.

For $n = 1$ the percent voltage drop in the feeder main is

$$\% \text{VD}_1 = \frac{1}{2} \times K \times D \times l_1^3 \tag{4-20}$$

Table 4-2 Application results of Eq. (4-17)

n	θ	$\tan\theta$	$\% \text{VD}_n$
4	45°	1.0	$\frac{2}{3}K \times D \times l_4^3$
6	30°	$\frac{1}{\sqrt{3}}$	$\frac{1}{\sqrt{3}}\left(\frac{2}{3}K \times D \times l_6^3\right)$

and for $n = 2$ it is

$$\% \text{VD}_2 = \frac{1}{2} \times K \times D \times l_2^3 \tag{4-21}$$

To compute the percent voltage drop in uniformly loaded lateral, lump and locate its total load at a point halfway along its length, and multiply the kilovoltampere-mile product for that line length and loading by the appropriate K constant [5].

Benefits of optimal location of substations

1. Reduce line losses – A close coordination between the substation equipment, distribution feeders and associated equipment is necessary to increase system reliability
2. Deferred capital expenses - Capital expenses will decreases
3. Energy cost reduction
4. Economic benefits
5. Coordination – Number of substations connected. If one substations fails, another substations provides supply
6. Over load reduction
7. Reliability increases because of continuity of supply
8. Effectiveness
9. Efficiency – Losses will decreases so efficiency will increases