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Faculty of Engineering

Department of Electrical and Electronic Engineering

Power Distribution and Transmission System

Graduation Project
EE – 400

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ACKNOWLEDGTMENT

All glory to Almighty ALLAH, the lord of the universe, who is the entire source of all knowledge and wisdom endowed to mankind. All thanks are due to him who gave me the ability and patience throughout my studies and to complete this task.

I would like to acknowledge to my parents especially to my father Chaudhry Ghulam Muhammad who has brought all of his efforts to support me, without knowing the return and who has patiently encouraged me to be the best everywhere.

I would also like to thank my supervisor Prof. Dr. Sc. Parviz Ali Zade for his intellectual support, encouragement and enthusiasm which made it possible to accomplish this project. I appreciate his most gracious encouragement and very valued constructive criticism throughout my education.

My special thanks goes to NEU educational staff especially to Electrical & Electronic Engineering teaching staff for their generosity & special concern of me and all EE students.

ABSTRACT

The aim of this project is to explain the transmission and distribution of electrical energy. This process of transmission and distribution has been explained in detail from the generation point to the ultimate consumption point. The electrical power generated at the generating stations and distributed to the consumers includes many substations interlinked with each other with many grid lines. These substations include generating substations, transmission substation, interconnection substation and distribution substation. These substations serve to change the line voltage by means of step-up and step-down transformers and to regulate it by means of synchronous condensers, static var compensators or transformers with variable taps. These substations also contain circuit breakers, fuses and lightning arrestors to protect expensive apparatus and to provide for quick isolation of faulted lines from the system. In the transmission system line voltage is roughly between 115 KV and 800 KV while in the distribution system line voltage generally lies between 120 V and 69 KV, these distribution systems, in turn, are further divided into medium-voltage distribution systems (2.4 KV to 69 KV) and low-voltage distribution systems (120V to 600 V). The distribution of electrical energy has great importance in our daily life as our most of the home utilities work on electrical power. We have got many ways for both the transmission and distribution of electrical power. The transmission of electrical power is done at different voltage levels, which include low-voltage, medium-voltage, high-voltage and extra high-voltage. These different types of voltage levels are further distributed by different types of delivery system. This distribution may be further divided into primary and secondary distribution.

CONTENTS

INTRODUCTION

The electrical power supply system consists of the network of conductors and associated equipment over which energy is transmitted from the generating station to the consumer, this system is mainly divided into two distinct parts, the transmission system and the distribution system. The transmission system may again be divided into primary and secondary transmission and the distribution system may be divided into primary, secondary and tertiary distribution.

Electrical energy is carried by conductors such as overhead transmission lines and underground cable. Although these conductors appear very ordinary, they possess important electrical properties that greatly affect the transmission of electrical energy. We distinguish four types of power lines, according to their voltage class.

- Low-voltage (LV) lines
- Medium-voltage (MV) lines
- High-voltage (HV) lines
- Extra high voltage (EHV) lines

The delivery of electric energy from the generating plant to the consumer may consist of several more or less distinct parts that are nevertheless somewhat interrelated. The part considered "distribution" i.e., from the bulk supply substation to the meter at the consumer's premises, can be conveniently divided into two main subdivisions:

- Primary distribution, which carries the load at higher than utilization voltages from the substation (or other source) to die point where the voltage is stepped down to the value at which the energy is utilized by the consumer.

Primary distribution systems include three basic types:

- Radial systems, including duplicate and throwover systems
- Loop systems, including both open and closed loops
- Primary network systems

- Secondary distribution, which includes that part of the system operating at utilization voltages, up to the meter at the consumer's premises.

Secondary distribution systems operate at relatively low utilization voltages and, like primary systems, involve considerations of service reliability and voltage regulation. The secondary system may be of four general types:

- An individual transformer for each consumer; i.e., a single service from each
  transformer.
- A common secondary main associated with one transformer from which a
  group of consumers is supplied.
- A continuous secondary main associated with two or more transformers,
  connected to the same primary feeder, from which a group of consumers is
  supplied. This is known as *banking* of transformer secondaries.
- A continuous secondary main or grid fed by a number of transformers,
  connected to two or more primary feeders, from which a large

group of consumers is supplied. This is known as a *low-voltage* or *secondary* network.

Each of these types has its application to which it is particularly suited.

Electrical energy may be distributed over two or more wires. The principal features desired are safety; smooth and even flow of power, as far as is practical and economy. The safety factor usually requires a voltage low enough to be safe when the electric energy is utilized by the ordinary consumer.

A steady, uniform, nonfluctuating flow of power is highly desirable, both for lighting and for the operation of motors for power purposes. Although a direct current system fills these requirements admirably, it is limited in the distance over which it can economically supply power at utilization voltage.

Alternating current systems deliver power in a fluctuating manner following the cyclic variations of the voltage generated. Such fluctuations of power are not objectionable for heating, lighting, and small motors, but are not entirely satisfactory for the operation of some devices such as large motors, which must deliver mechanical power steadily and therefore require a steady input of electric power. This may be done by supplying electricity to the motors by two or three circuits, each supplying a portion of the power, whose fluctuations are purposely made not to occur at the same time, thereby decreasing or damping out the effect of the fluctuations. These two or three separate alternating current circuits (each often referred to as a single-phase circuit) are combined into one polyphase (two- or three-phase) circuit. The voltages for polyphase circuits or systems are supplied from polyphase generators. We can divide our electrical power supply system into following categories.

- Direct Current Systems
- Alternating Current Single-Phase Systems
- Alternating Current Two-Phase Systems
- Alternating Current Three-phase Systems
- Alternating Current Six-Phase Systems

While the energy flow is obviously from the power generating plant to the consumer, it may be more informative for our purposes to reverse the direction of observation and consider events from the consumer back to the generating source.

Energy is consumed by users at a nominal utilization voltage that may range generally from 110 to 125 V, and from 220 to 250 V (for some large commercial and industrial users, the nominal figures are 277 and 480 V). It flows through a metering device that determines the billing for the consumer, but which may also serve to obtain data useful later for planning, design, and operating purposes. The metering equipment usually includes a means of disconnecting the consumer from the incoming supply should this become necessary for any reason. In general in an a.c. system there will be a change in voltage at each point where the subdivision takes place, the change being effected by transformation, usually at a substation, and therefore there may be several working voltages in the same system.

The transmission of electrical energy does not usually raise as much interest as does its generation and utilization: consequently, we sometimes tend to neglect this important subject. This is unfortunate because the human and material resources involved in transmission are much greater than those employed in generation.

Chapter 1: TRANSMISSION OF ELECTRICAL ENERGY

1.1 Principal components of a power transmission system

In order to provide electrical energy to consumers in usable form, a transmission and distribution system must satisfy some basic requirements. Thus, the system must:

1. Provide, at all times, the power that consumers need;
2. Maintain a stable, nominal voltage that does not vary by more than ± 10%;
3. Maintain a stable frequency that does not vary by more than ±0.1 Hz;
4. Supply energy at an acceptable price;
5. Meet standards of safety;
6. Respect the standards of environment.

Figure 1-1 shows an elementary diagram of a transmission and distribution system. It consists of two generating stations G_1 and G_2, a few substations, an interconnecting substation and several commercial, residential and industrial loads. The energy is carried over lines designated *extra high voltage* (EHV), *high* voltage (HV), *medium* voltage (MV) and *low* voltage (LV). This voltage classification is made according to a scale of standardized voltages whose limiting values are given in Table 1A.

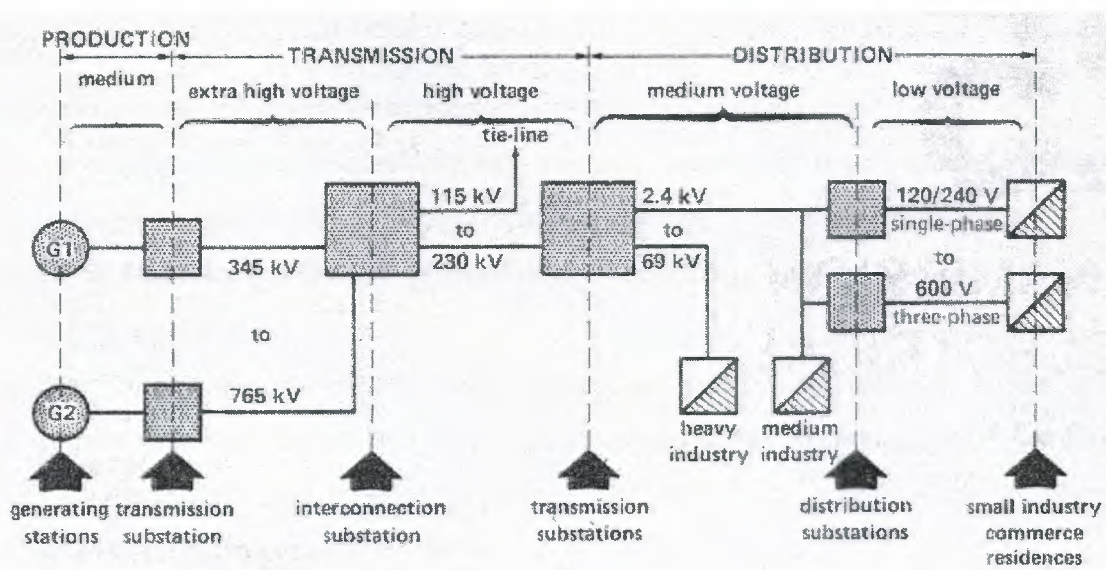


Figure 1-1 Single-line diagram of a generation, transmission and distribution system.

Substations serve to change the line voltage by means of step-up and step-down transformers and to regulate it by means of synchronous condensers, static var compensators, or transformers with variable taps. Substations also contain circuit breakers, fuses and lightning arrestors, to protect expensive apparatus and to provide for quick isolation of faulted lines from the system.

Interconnecting substations serve to tie different power systems together, to enable Power exchanges between them, and to increase the stability of the overall network.

Electrical power utilities divide their power distribution systems into two major categories:

1. Transmission systems in which the line voltage is roughly between 115 kV and 800 kV;
2. Distribution systems in which the voltage generally lies between 120V and 69 kV.

Distribution systems, in turn, are divided into medium-voltage distribution systems (2.4 kV to 69 kV) and low-voltage distribution systems (120 V to 600 V).

1.2 Types of power lines

The design of a power line depends upon

1. The amount of active power it has to transmit;
2. The distance over which the power must be carried;
3. The cost;
4. Esthetic considerations, urban congestion, ease of installation, and expected load growth.

We distinguish four types of power lines, according to their voltage class:

1. Low-voltage (LV) lines are installed inside buildings, factories and houses to supply power to motors, electric stoves, lamps, heaters and air conditioners. The service entrance panel constitutes the source and the lines are made of insulated cable or bus-bars operating at voltages below 600 V.

In some metropolitan areas, the distribution system feeding the factories, homes and commercial buildings consists of a grid of under ground cables operating at 600 V or less. Such a network provides dependable service, because even the outage of one or several cables will not interrupt customer service.

2. Medium-voltage (MV) lines tie the load centers to the main substation of the utility company. The voltage is usually between 2.4 kV and 69 kV. Such medium-voltage radial

distribution systems are preferred in the larger cities. In radial systems, the transmission lines spread out like fingers from one or more substations to feed power to various load centers, such as high-rise buildings, shopping centers and universities.

3. High-voltage (HV) lines connect the main substations to the generating stations. The lines are composed of aerial wire or under ground cable operating at voltages below 230 kV. In this category, we also find lines that transmit energy between two power systems, to increase the stability of the network.

4. Extra high voltage (EHV) lines are used when generating stations are very far from the load centers. We put these lines in a separate class because of their special electrical proper ties. Such lines operate at voltages up to 1000 kV and may be as long as 1000 km.

TABLE 1A

VOLTAGE CLASSES AS APPLIED TO INDUSTRIAL AND COMMERCIAL POWER			
Voltage Class	**Nominal System Voltage**		
	Two-wire	Three-wire	Four-wire
Low voltage	120	120/240 *	-
	single-phase	Single phase	120/208 *
LV		480 V *	277/480 *
		600 V	347/600
Medium voltage		2400	
		4160 *	
		4800	
		6900	
MV		13800 *	7200/12470 *
		23000	7620/13200 *
		34500	7970/13800
		46000	14400/24940 *
		69000 *	19920/34500 *
High voltage		115000 *	
		138000 *	
HV		161000	
		230000 *	
Extra high voltage		345000 *	
		500000 *	
EHV		735000-765000 *	

All voltages are 3-phase unless indicated otherwise.

Voltages designated by the symbol * are preferred voltages.

1.3 Components of a transmission line

A transmission line is composed of conductors, insulators and supporting structures.

1. Conductors. Conductors for high-voltage lines are always bare. We use stranded copper conductors or steel-reinforced aluminum cable (ACSR). ACSR conductors are usually preferred, because they result in a lighter and more economical line. Conductors have to be spliced when a line is very long. Special care must be taken so that the joints have low resistance and great mechanical strength.

2. Insulators. Insulators serve to support and anchor the conductors and to insulate them from ground. Insulators are usually made of porcelain, but glass and other synthetic insulating materials are also used.

From an electric standpoint, insulators must offer a high resistance to surface leakage currents and they must be sufficiently thick to prevent breakdown under the high voltage stresses they have to withstand. To increase the leakage path (and hence the leakage resistance), the insulators are molded with wave-like folds. From a mechanical standpoint, they must be strong enough to resist the pull due to the weight of the conductors.

There are two main types of insulators: *pin-type* insulators and *suspension-type* insulators (Figs. 1-2 and 1-3). The pin-type insulator has several porcelain skirts (folds) and the conductor is fixed at the top. A steel pin screws into the insulator so it can be bolted to a support.

For voltages above 70 kV, we always use suspension-type insulators, strung together by their cap and pin metallic parts. The number of insulators depends upon the voltage: for 110kV, we generally use from 4 to 7; for 230 kV, from 13 to 16 insulators.

3. Supporting structures. The supporting structure must keep the conductors at a safe height from the ground and at an adequate distance from each other. For voltages below 70 kV, we can use single wooden poles equipped with cross-arms, but for higher voltages, a wooden H-frame must be used. The wood is treated with creosote or special metallic salts to prevent it from rotting. For very high voltage lines, we always use steel towers made of galvanized angle-iron pieces that are bolted together.

The spacing between conductors must be sufficient to prevent arc-over under gusty wind conditions. The spacing has to be increased as we increase the distance between towers and as the line voltages becomes higher.

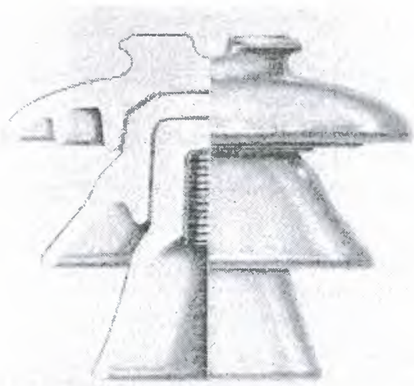


Figure 1.2 Sectional view of a 69 KV pin-type insulator. BIL: 270KV; 60 Hz flashover voltage under wet conditions: 125 KV

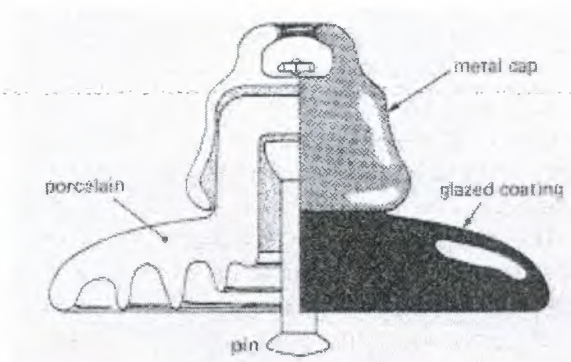


Figure 1.3 Sectional view of a suspension insulator. Diameter: 254 mm; BIL: 125 KV, 60Hz flashover voltage. Under wet conditions: 50 KV

1.4 Construction of a line

Once we know the conductor size, the height of the poles and the distance between the poles (span), we can direct our attention to stringing the conductors. A wire supported between two points (Fig. 1-5) does not remain horizontal, but loops down at the middle. The vertical distance between the straight line joining the points of support and the lowest point of the conductor is called sag. The tighter the wire, the smaller the sag will be.

Before undertaking the actual construction of a line, it is important to calculate the permissible sag and the corresponding mechanical pull. Among other things, the summer to winter temperature range must be taken into account because the length of the conductor varies with the temperature. Thus, if the line is strung in the winter, the sag must not be too great; otherwise the wire will stretch even more during the summer heat, with the result that the clearance to ground may no longer be safe. On the other hand, if the line is installed in the summer, the sag must not be too small otherwise the wire, contracting in winter, may become so dangerously tight as to snap. Wind and sleet add even more to the tractive force, which may also cause the wire to break (Fig. 1-6)

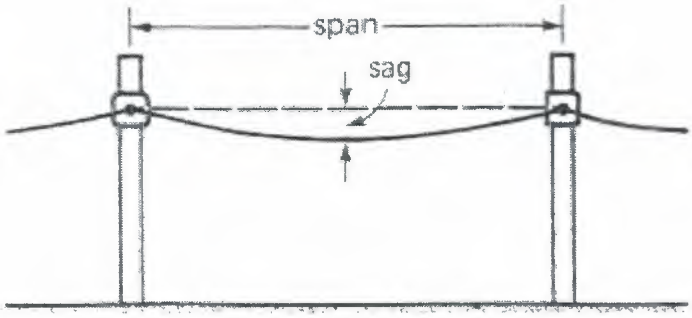


Figure 1-5 Span and sag of a line.

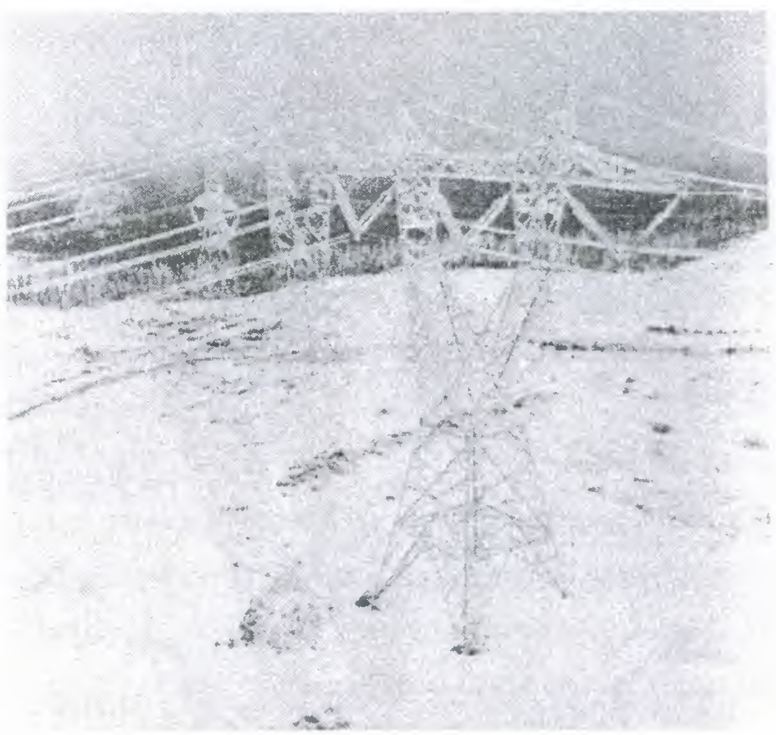


Figure 1.6 During winter, steel towers must carry the combined weight of conductors and accumulated ice.

1.5 Galloping lines

If a coating of sleet is deposited on a line during windy conditions, the line may begin to oscillate. Under certain conditions, the oscillations may become so large that the line is seen to actually "gallop". Galloping lines can produce short-circuits between phases or snap the conductors. To eliminate the problem we sometimes load the line with special mechanical weights, to dampen the oscillations or to prevent them from building up.

1.6 Corona effect - radio interference

The very high voltages in use today produce a continual electrical discharge around the conductors, owing to local ionization of the air. This discharge, or corona effect, produces losses over the entire length of the transmission line. In addition, corona emits high frequency noise which interferes with nearby radio receivers and TV sets. To diminish corona, we must reduce the electric field (V/m) around the conductors, either by increasing their diameter or by arranging them in sets of two, three or more bundled conductors per phase. This *bundling* arrangement also reduces the inductance of the line, enabling it to carry more power. This constitutes an important additional benefit.

1.7 Lightning and transmission lines

When lightning makes a direct hit on a transmission line, it deposits a large electric charge, producing an enormous over voltage between the line and ground. The dielectric strength of air is immediately exceeded and a flashover occurs. The line discharges itself and the over voltage disappears in typically less than 50 us.

Unfortunately, the arc between the line and ground, (initiated by the lightning stroke) produces a highly ionized path which behaves like a conducting short-circuit. Consequently, the normal ac line voltage immediately delivers a large ac current which follows the ionized path. This follow-through current sustains the arc until the circuit-breakers open at the end of the line. The fastest circuit-breakers will trip in about 1 /15th of a second, which is almost 1000 times longer than the duration of the lightning stroke itself.

Direct hits on a transmission line are rare; more often, lightning will strike the overhead ground wire that shields the line. In the latter case, a local charge still accumulates on the line, producing a very high local over voltage. This concentrated charge immediately divides into two waves that swiftly move in opposite directions at close to the speed of light (300 m/us); the height of the impulse wave represents the magnitude of the so-called surge-voltage that exists from point to point, between the line and ground (Fig. 1-7). The peak voltage (corresponding to the crest of the wave) may attain one or two million volts. Wave front ab is concentrated over a distance of about 300 m, while tail be may stretch out over several kilometers.

The wave also represents the point-to-point value of the current flowing in the line. For most aerial lines, the ratio between surge voltage and surge current corresponds to a resistance of about 400 Ω. A surge voltage of 800 000 V at a given point is therefore accompanied by a surge current of 800 000/400 = 2000 A.

As the wave travels along the line, the I^2R and corona losses gradually cause it to flatten out, and the peak of the surge voltage decreases.

Should the wave encounter a line insulator, the latter will be briefly subjected to a violent over voltage. The over voltage period is equal to the time it takes for the wave to sweep past the insulator. The voltage rises from its nominal value to several hundred kilovolts in about 1 us, corresponding to the length of wavefront ab. If the insulator cannot withstand this over voltage, it will flash over, and the resulting follow-through current will cause the circuit-breakers to trip. On the other hand, if the insulator does not fail, the wave will continue to travel along the line until it eventually encounters a substation. It is here that the impulse wave can produce real havoc. The windings of transformers, synchronous condensers, reactors, etc., are seriously damaged when they flash over to ground. Expensive repairs and even more costly shut-downs are incurred while the apparatus is out of service. The over voltage may also damage circuit-breakers, switches, insulators, relays, etc., which make up a substation. To reduce the impulse voltage on station apparatus, lightning arresters are installed on all incoming lines.

Lightning arresters are designed to clip off all voltage peaks that exceed a specified level, say 400 kV. In turn, the apparatus within the substation is designed to withstand an impulse voltage considerably higher than the arrester "clipping voltage", say 550 kV. Consequently, if a 1000 kV surge voltage enters a substation, the station arrester diverts a substantial part of the surge energy to ground. The residual impulse wave which travels beyond the arrester then has a peak of only 400 kV. This impulse can easily be borne by station apparatus built to withstand an impulse of 550 kV.

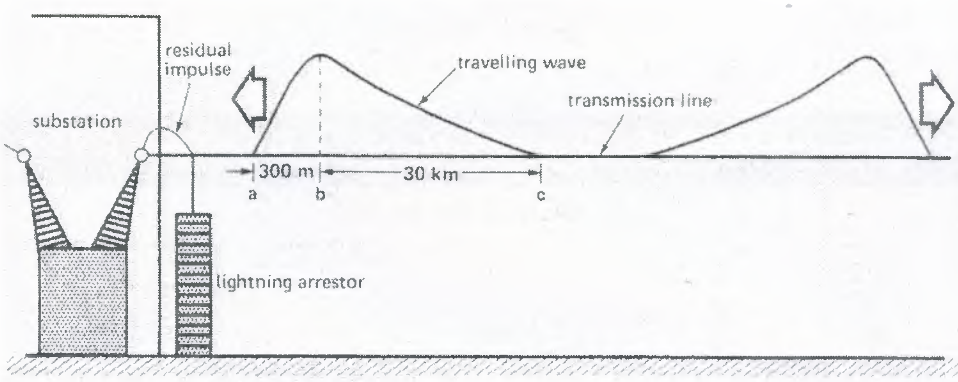


Figure 1-7 Flow of electric charge along a transmission line.

1.8 Basic impulse insulation level (BIL)

How do insulating materials react to impulse voltages? Tests have shown that the withstand capability increases substantially when voltages are applied for very brief periods. To illustrate, suppose we wish to carry out an insulation test on a transformer, by applying a 60 Hz sinusoidal voltage between the windings and ground. As we slowly raise the voltage, a point will be reached where breakdown occurs. Let us assume that the breakdown voltage is 46 kV (RMS) or 65 kV crest.

On the other hand, if we apply a dc impulse of short duration between the windings and ground, we discover that it takes about twice the peak voltage (or 130 kV) before the insulation breaks down.

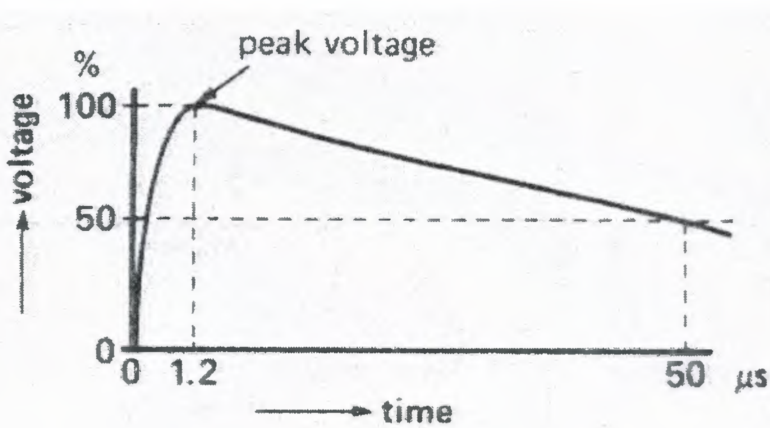


Figure 1-8 Standard shape of impulse voltage used to determine the BIL rating of electrical apparatus.

TABLE 1B

TYPICAL PEAK VOLTAGES FOR 1.2x50 us BIL TESTS		
Values are in Kilovolts		
1550	825	250
1425	750	200
1300	650	150
1175	550	110
1050	450	90
900	350	30

The same is true of suspension insulators, bushings, spark gaps, etc., except that the ratio between impulse voltage and crest ac voltage is closer to 1.5.

In the interest of standardization, and to enable a comparison between the impulse withstand capability of similar devices, standards organizations have precisely defined the shape and crest values of impulse waves. Figure 1-8 shows such a standard impulse wave. It attains its peak after 1.2 us and falls to one-half the peak in 50 us. The peak voltage has a defined set of values that range from 30 kV to 1550 kV (see Table 1B).

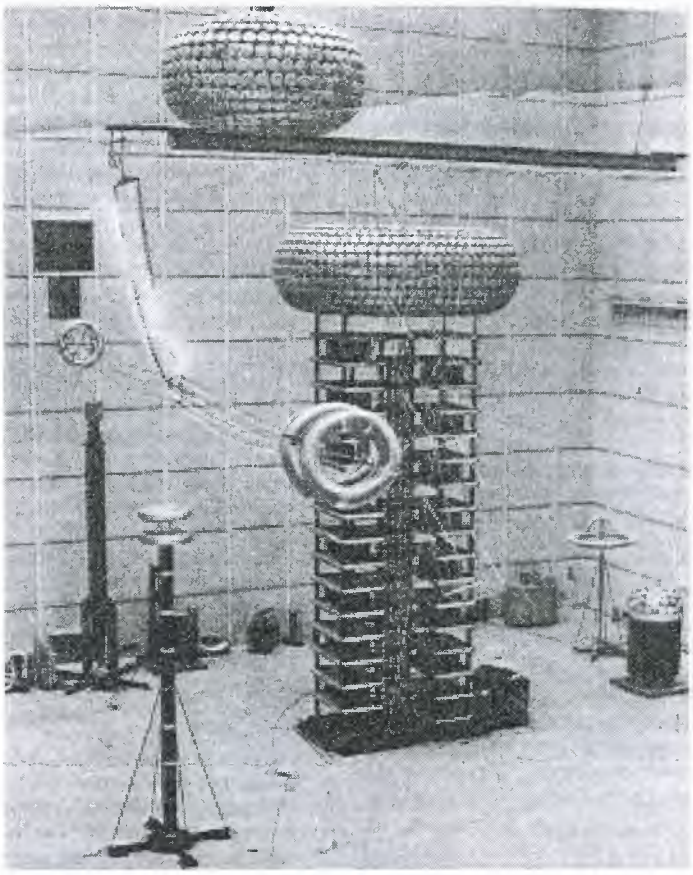


FIGURE 1.9 A 4 000 000 V impulse causes a flashover across an insulator string rated at 500 KV , 60 Hz .Such impulse tests increase the reliability of equipment in the field .The powerful impulse generator in the center of the photo is 24 m high and can deliver 400 kj of energy at a potential of 6.5 mV.

The peak voltage is used to specify the basic impulse insulation levels (BIL) of equipment. Thus, a piece of equipment (transformer, insulator, capacitor, resistor, bushing, etc.) that can withstand a 1.2 x 50 microsecond wave of 900 kV, is said to possess a basic impulse insulation level (or BIL) of 900 kV. Figure 1-9 shows an insulator string being subjected to a BIL impulse test.

The BIL of a device is sometimes several times higher than its nominal ac operating voltage. For example, a 69 kV distribution transformer must have a BIL of 350 kV. However, there is no special relationship between BIL and nominal voltage. As the BIL rises, we must increase the amount of insulation which, in turn, increases the size and cost of equipment.

In conclusion, the peak voltage across an arrester must never exceed the BIL of the apparatus it is intended to protect.

1.9 Fundamental objectives of a transmission line

The fundamental purpose of a transmission or distribution line is to carry *active* power from one point to another. If it also has to carry reactive power, the latter should be relatively small. In addition, a transmission line should possess the following basic characteristics:

1. The voltage should remain as constant as possible over the entire length of the line, from source to load, and for all loads between zero and rated load.

2. The line losses must be small so as to attain high transmission efficiency.

3. The I^2R losses must not overheat the conductors.

If the line alone cannot satisfy the above requirements, supplementary equipment, such as capacitors and inductors, must be added until they are met.

1.10 Equivalent circuit of a line

In spite of their great differences in power rating, voltage levels, lengths and mechanical construction, transmission lines possess similar electrical properties. In effect, an ac line possesses a resistance *R*, an inductive reactance X_L, and a capacitive reactance X_c. These impedances are uniformly distributed over the entire length of the line; consequently, we can represent the line by a series of identical sections, as shown in Figure 1-10. Each section represents a portion of the line (1 km, for example), and elements r, X_L, X_C represent the impedances corresponding to this unit length. We can simplify the circuit of Figure 1-10 by lumping the individual resistances r together to yield a total resistance R. In the same way, we obtain a total inductive reactance X_L equal to the sum of the individual reactance x_L. On the other hand, the total capacitive reactance X_c is equal to the sum of the x_c reactances connected in parallel. It is convenient to assume that the total capacitive reactance X_c of the line is composed of two parts, each having a value $2X_C$ located at each end of the line. The resulting equivalent circuit of Figure 1-11 is a good approximation of any 50 Hz or 60 Hz power line, provided its length is less than 250 km. (Note that R and X_L increase as the length of the line increases, whereas X_c decreases with increasing length)

The equivalent circuit of Figure 1-11 can also be used to represent one phase of a 3-phase line. Current I correspond to the actual current flowing in one conductor and E is the voltage between the same conductor and neutral.

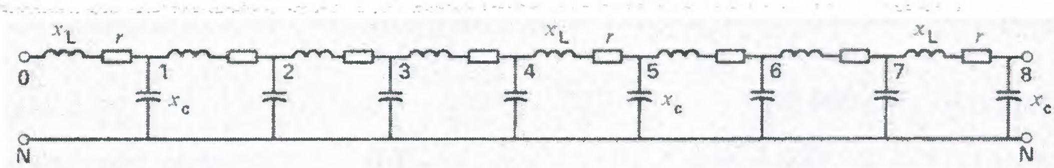


Figure 1.10 Distributed impedance of a transmission line

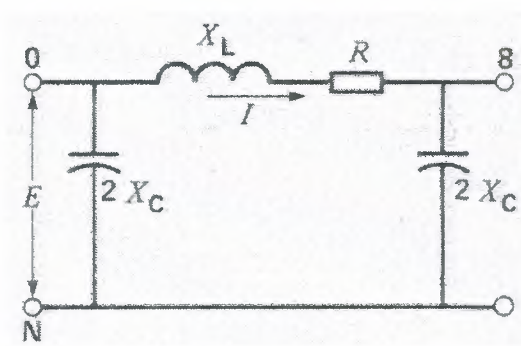


Figure 1.11 Equivalent lumped circuit of a transmission line.

1.11 Typical impedance values

Table 1C gives typical values of the inductive and capacitive reactances per kilometer for practical transmission lines operating at 60 Hz. Surprisingly, the respective impedances per unit length are reasonably constant for all aerial lines. Thus, X_L is about 0.5 Ω/km and x_c is about 300 000 Ω/km whether the transmission line voltage is high or low, or whether the power is great or small.

The same can be said of underground cables except that the inductive and capacitive reactances of three-phase cables are much smaller. Thus, x_c is about one hundred times smaller than that of aerial lines whereas x_L is about five times smaller. This fact has a direct bearing on the maximum distance that ac power can be transmitted by cable.

TABLE 1C

TYPICAL IMPEDANCE VALUES PER KILOMETER FOR 3-PHASE, 60 Hz LINES		
Type of line	x_L (Ω)	x_C (Ω)
Aerial line	0.5	300 000
Underground cable	0.1	3 000

The resistance per unit length varies greatly with conductor size and so it is impossible to give a "typical" value. Table 1D gives the resistance as well as the ampacity for several aerial conductors.

TABLE 1D

RESISTANCE AND AMPACITY OF SOME BARE AERIAL CONDUCTORS					
Conductor size		**Resistance per conductor At 75 C**		**Ampacity in free air ***	
AWG	**Cross section mm^2**	**Copper Ω /km**	**ACSR Ω /km**	**Copper A**	**ACSR A**
10	**5.3**	**3.9**	**6.7**	**70**	**-**
7	**10.6**	**2.0**	**3.3**	**110**	**-**
4	**21.1**	**0.91**	**1.7**	**180**	**140**
1	**42.4**	**0.50**	**0.90**	**270**	**200**
3/0	**85**	**0.25**	**0.47**	**420**	**300**
300 MCM	**152**	**0.14**	**0.22**	**600**	**500**
600 MCM	**304**	**0.072**	**0.11**	**950**	**750**
1000 MCM	**507**	**0.045**	**0.065**	**1300**	**1050**

*** The ampacity indicated is the maximum that may be used without weakening the conductor by overheating. In practice, the actual line current may be only 25 % of the indicated value.**

1.12 Voltage regulation and power transmission capability of transmission lines

Voltage regulation and power-handling capacity are two important features of a transmission line. Thus, the voltage of a transmission line should remain as constant as possible even under variable load conditions. Ordinarily, the voltage regulation from zero to full load should not exceed ± 5% of the nominal voltage (though we can sometimes accept a regulation as high as ±10%).

As regards power-handling capacity, it may come as a surprise that a transmission line can deliver only so much power and no more. The power that can be transported from source to load depends upon the impedance of the line. We are mainly interested in transmitting active power because only it can do useful work. In order to determine the voltage regulation and to establish their power transmission capability, we now examine four types of lines:

1. resistive line;
2. inductive line;
3. inductive line with compensation;
4. inductive line connecting two large systems.

In our analysis, the lines connect a load (or receiver) R to a source (or sender) S. The load can have all possible impedance values, ranging from no-load to a short-circuit. However, we are only interested in the *active* power the line can transmit. Consequently, the load can be represented by a variable resistance absorbing a power P. The sender voltage E_S is fixed but the receiver voltage E_R depends upon the resistance of the load.

1.12.1 Resistive line

The transmission line of Figure 1-12a possesses a resistance R, Starting from an open circuit, we gradually reduce the load resistance until it becomes zero. During this process, we observe the receiver voltage E_R across the load, as well as the active power p it absorbs. If numerical values were given, a few simple calculations would enable us to draw a graph of E_R as a function of P. However, we prefer to use a generalized curve that shows the relationship between E_R and P for *any* transmission line having an arbitrary resistance R.

The generalized shape of this graph is given in Figure 1-12 b. It reveals the following information:

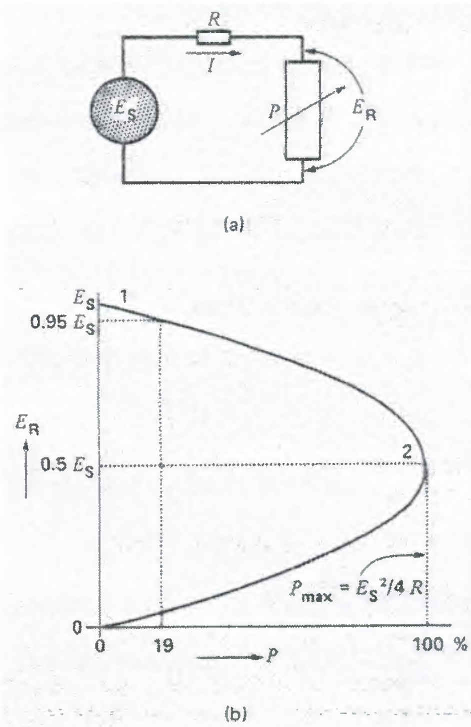


Figure 1.12 Characteristics of a resistive line.

a. There is an upper limit to the power the line can transmit to the load. In effect,

$$P_{max} = E_S^2/4R \qquad (1-1)$$

and this maximum is reached when the receiver voltage is $E_R = 0.5E_S$.

b. The power delivered to the load is maximum when the impedance of the load is equal to the resistance of the line.

c. If we permit a maximum regulation of 5 percent ($E_R = 0.95E_S$), the line can carry a load that is only 19% of P_{max}. The line could transmit more power, but the customer voltage E_R would then be too low.

Note that the sender must furnish the power P absorbed by the load, plus the I^2R losses in the line.

1.12.2 Inductive line

Let us now consider a line having negligible resistance but possessing an inductive reactance X (Fig. 1-13a). The receiver again operates at unity power factor, and so it can be represented by a variable resistance absorbing a power P. As in the case of a resistive line, voltage E_R diminishes as the load increases, but the regulation curve has a different shape (Fig. 1-13b). In effect, the generalized graph of E_R as a function of P reveals the following information:

a. The line can transmit a maximum power to the load given by

$$P_{max} = E_S^2/2X. \qquad (1\text{-}2)$$

The corresponding receiver voltage is, $E_R = 0.707E_s$.

Thus, for a given line impedance and sender voltage, the reactive line can deliver twice as much power as a resistive line can (compare $P = ES2/2X$ and $P = E_S^2/4R$).

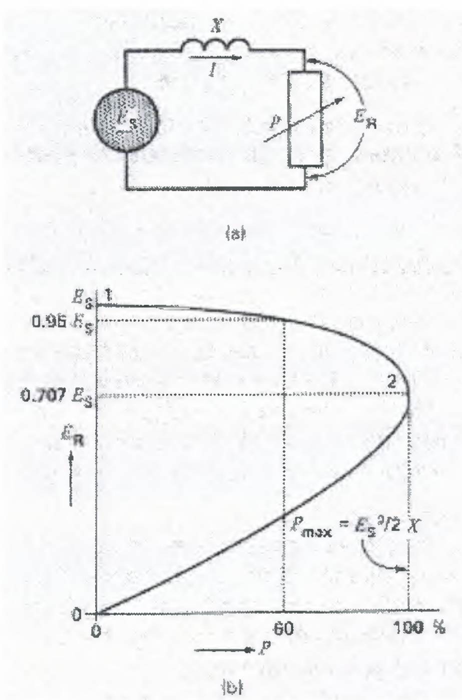


Figure 1.13 Characteristics of an inductive line.

b. The power delivered to the load is maximum when the resistance of the load is equal to the reactance of the line.

c. If we again allow a maximum regulation of 5 percent, we discover the line can carry a load that is 60% of P_{max}. Thus, for a given line impedance, and a regulation of 5 per cent, the inductive line can transmit *six* times as much active power as a resistive line can.

The sender has to supply the active power P consumed by the load plus the reactive power I^2X absorbed by the line.

1.12.3 Compensated inductive line

We can improve the regulation and power-handling capacity of an inductive line by adding a variable capacitive reactance X_c across the load (Figure 1-14a). All we have to do is to adjust the value of X_c *so* that the reactive power E_S^2/X_C supplied by the capacitor is at all times equal to one half the reactive power I^2X absorbed by the line. For such a compensated line the value of the receiver voltage E_R will always be equal to the sender voltage E_S, irrespective of the active power P absorbed by the load.

However, there still is an upper limit to the power the line can transmit. A detailed analysis shows that we can maintain a constant load voltage $(E_R = E_S)$ up to a maximum of

$$P_{max} = ES^2/X \qquad (1\text{-}3)$$

Beyond this limit, E_R gradually decreases to zero in a diagonal line, as shown by the graph of Figure 1-14b. Note that:

a. The voltage regulation is perfect until the load power reaches the limiting value $P_{max} = E_S^2/X$.

b. The compensated inductive line can deliver twice as much power (P_{max}) *as* an uncompensated line can. Moreover, it has the advantage of maintaining a constant load voltage.

Capacitor X_c supplies one-half the reactive lower I^2X_L absorbed by the line; the remaining half is supplied by the sender E_s. If necessary, we can add a second capacitor X_c (shown dotted in Fig. 1-14) at the input to the line. The source has then only to supply the active power while the reactive power is supplied by the capacitors at both ends.

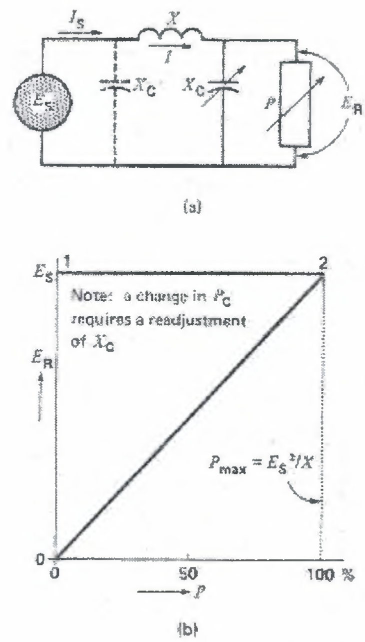


Figure 1.14 Characteristics of a compensated inductive line.

1.12.4 Inductive line connecting two systems

Large cities and other regional users of electrical energy are always interconnected by one or more transmission lines. Such a network improves the stability of the system and enables it to better endure momentary short-circuits and other disturbances. Interconnecting lines also permit energy exchanges between electrical utility companies.

On such lines, the voltages at each end remain essentially independent of each other, both in value and in phase. In effect, because of their enormous power the regional consumers at each end act as independent, infinite buses. Figure 1-15 shows the equivalent circuit of an inductive line connecting two such regional consumers S and R. We assume the terminal Cottages E_s and E_R are fixed, each possessing the same magnitude E. Regarding the exchange of active power between the two regional consumers, we examine three distinct cases:

1. E_s and E_R in phase;
2. E_s leading E_R by an angle δ
3. E_s lagging E_R by an angle δ .

1. E_s and E_R in phase. In this case, the line current is zero and no power is transmitted.

2. E_s leads £R by an angle 8 (Fig. 1-15).

Region S supplies power to region R and, from the phasor diagram, we can prove that the active power transmitted is given by:

$$P = E^2/X \sin \delta \qquad (1\text{-}4)$$

Where

P = active power transmitted per phase [MW]

E = line-to-neutral voltage [kV]

X = inductive reactance of the line, per phase [Ω]

S = Phase angle between the voltages at each end of the line [°]

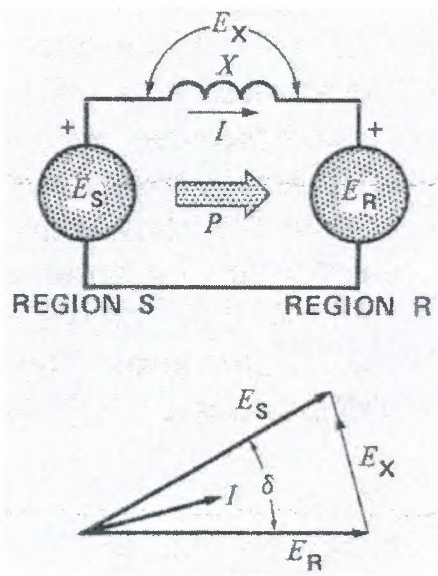


Figure 1.15 E_S leads E_R

Figure 1-16a shows the active power transmitted as a function of the voltage phase angle between the two regions. Note that the power increases progressively and attains a maximum value of E^2/X when the phase angle is 90°. In effect, just as in the other transmission lines we have studied, a line connecting two power centers can transmit only so much power and no more. The power limit is the same as that of a compensated inductive line. Although we can still transmit power when the phase angle exceeds 90°, we avoid this condition because it corresponds to an unstable mode of operation. When δ approaches 90°, the two regions are at the point of "pulling apart" and the line circuit-breakers will trip.

Figure 1-16b shows the load voltage E_R as a function of the active power transmitted. It is simply a horizontal line that stretches to a maximum value $P_{max} = E^2/X$ before falling back again to zero (dotted line). This regulation curve should be compared with that of Figure 1-14b.

Note that the line voltage drop E_X is quite large, even though the terminal voltages E_s and E_R are equal. Referring to Figure 1-15, it is clear that the line voltage "drop" increases as the phase angle between E_S and E_R increases.

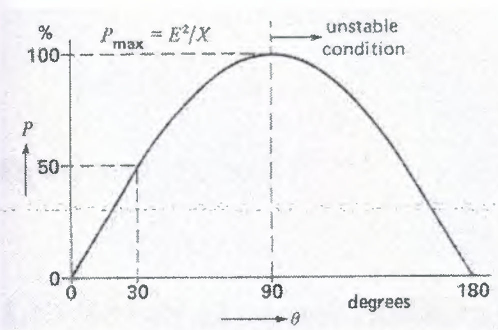


Figure 1.16a

Power versus angle characteristic.

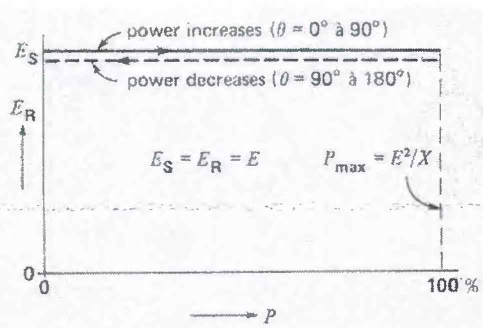


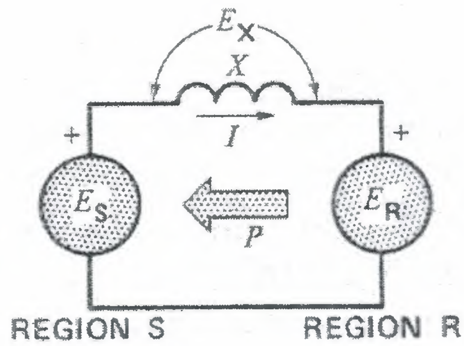
Figure 1.16b

Voltage versus power characteristics.

3. *E_S lags* behind *E_R by* an angle δ

The active power has the same value as before, but it now flows in the opposite direction, from region R towards region S (Fig. 1-17). The graph of active power versus phase angle is identical to that shown in Figure 1-16a.

If we compare Figures 1-15 and 1-17, we note that the direction of power flow does not depend upon the relative magnitudes of E_S and E_R (they are equal), but only upon the phase angle between them. On inductive lines, active power always flows from the leading to the lagging voltage side.



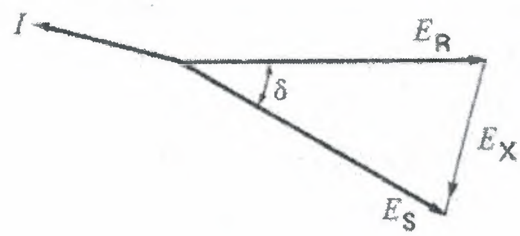


Figure 1.17 E_R leads E_S

1.13 Review of power transmission

In summary, there is always a limit to the amount of power a line can transmit. The maximum power is proportional to the square of the sender voltage and inversely proportional to the impedance of the line. Figure 1-18 enables us to compare actual values of power and voltage for the four types of transmission lines we have studied. Each line possesses an impedance of 10 Ω and the sender furnishes a voltage E_S of 1000V. It is clear that the E_R versus P curves become flatter and flatter as we progress from a resistive to an inductive to a compensated line.

The table next to the graph shows the maximum power that can be transmitted assuming a regulation of 5% or better. Thus, the resistive line can transmit 4.75 kW, whereas the inductive line can transmit 30 kW.

Because all lines possess some resistance, we also show the voltage-power curve of a compensated line having a reactance of 9.8 Ω and a resistance of 2 Ω (curve 5). This line also has an impedance of 10 Ω, but the maximum power it can transmit drops to 80 kW, compared to 100 kW for a line possessing no resistance.

In practice, the voltages and powers are much higher than those given in these examples.

Nevertheless, the method of analysis is the same.

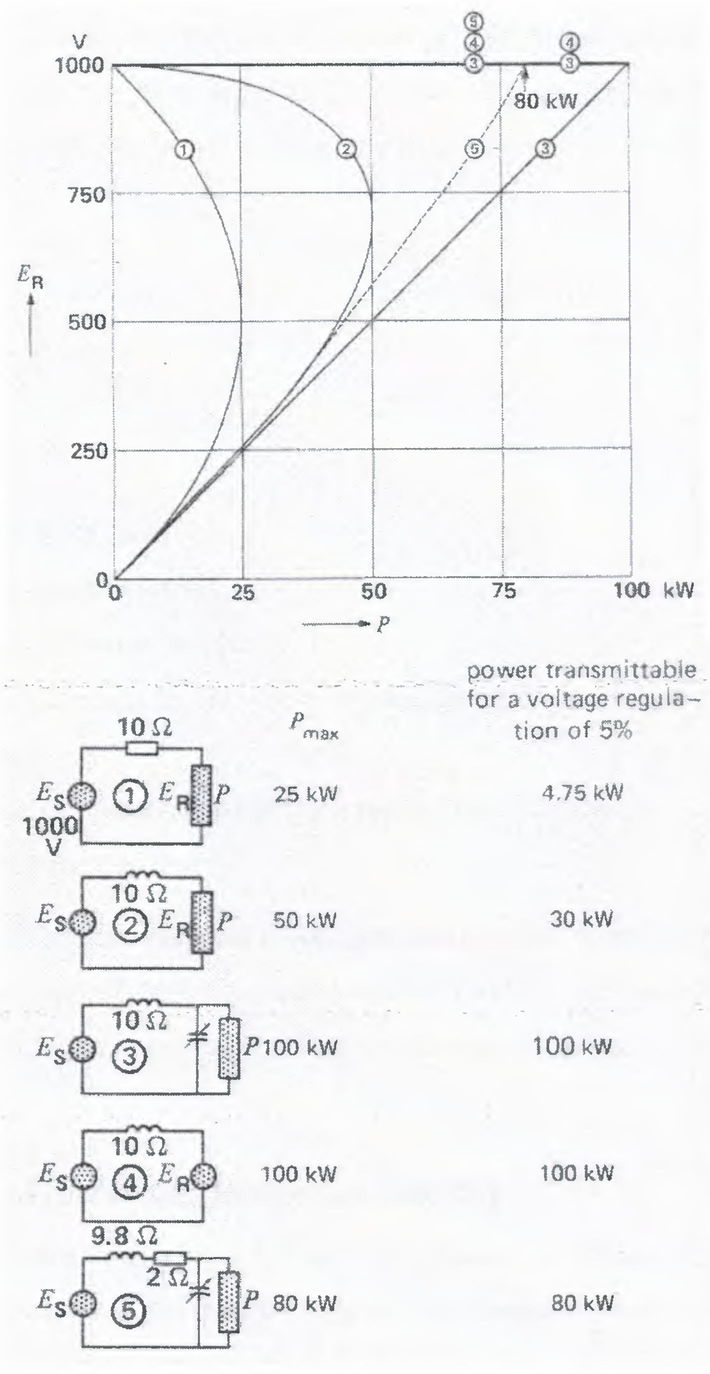


Figure 1.18 Comparison of the power-handling properties of various transmission lines.

1.14 Choosing the line voltage

We have seen that for a given transmission line and for a given voltage regulation, the power P that can be transmitted is proportional to E^2/Z, where E is the voltage of the line and Z, its impedance. Because Z is proportional to the length of the line, we deduce that the line voltage is given by:

$E^2 = k'Pl$

that is:

$E = k\sqrt{Pl}$ (1-5)

Where

E = 3-phase line voltage [kV]

P = power to be transmitted [kW]

l = length of the transmission line [km]

k = coefficient that depends on the type of line and the allowable voltage regulation.

Typical values are:

$k = 0.1$ for an uncompensated line having a regulation of 5 percent

$k = 0.06$ for a compensated line

Equation 1-5 is very approximate, but it does give an idea of the magnitude of the line voltage E. The value finally chosen depends upon economic factors as well as technical considerations; in general, the actual voltage selected will lie between 0.6 E and 1.5 E.

1.15 Methods of increasing the power capacity

High-voltage lines are mainly inductive and they possess a reactance of about 0.5 Ω/km. This creates problems when we have to transmit large blocks of power over great distances. Suppose, for example, that we have to transmit 4000 MW over a distance of 400 km. The reactance of the line is 400 km x 0.5 Ω/km = 200 Ω per phase. Since the highest practical voltage is about 800 kV, the line can transmit no more than:

$$
\begin{aligned}
P_{max} &= E^2/X \\
&= 800^2/200 \qquad \text{Eq. 1-3} \\
&= 3200 \text{ MW}
\end{aligned}
$$

To transmit 4000 MW, the only solution is to use two lines in parallel, one beside the other. Note that doubling the size of the conductors would not help, because for such a line it is the reactance and not the resistance of the conductors that determines the maximum power that can be transmitted.

Additional lines are also useful to provide system security in the event that a parallel line trips out, due to a disturbance. Thus, if one line is lost, the scheduled power can still be carried by the remaining line.

To carry large blocks of power, we sometimes erect two, three and even four transmission lines in parallel, which follow the same corridor across the countryside (Fig. 1-19). In addition to high cost, the use of parallel lines often creates serious problems of land expropriation. Consequently, we sometimes use special methods to increase the maximum power of a line. In effect, when we can no longer increase the line voltage, we try to reduce the line reactance X_L by greatly increasing the effective size of the conductors. This is done by using two or more conductors per phase, kept apart by spacers. Such bundled conductors can reduce the reactance by as much as 40 percent permitting an increase of 67 percent in the power-handling capability of the line. Another method uses capacitors in series with the three lines to artificially reduce the value of X_L. With this arrangement, the maximum power is:

$$P_{max} = E^2 / (X_L - X_{CS}) \qquad (1\text{-}6)$$

Where X_{CS} is the reactance of the series capacitors per phase. Such series compensation is also used to regulate the voltage of medium-voltage lines when the load fluctuates rapidly.

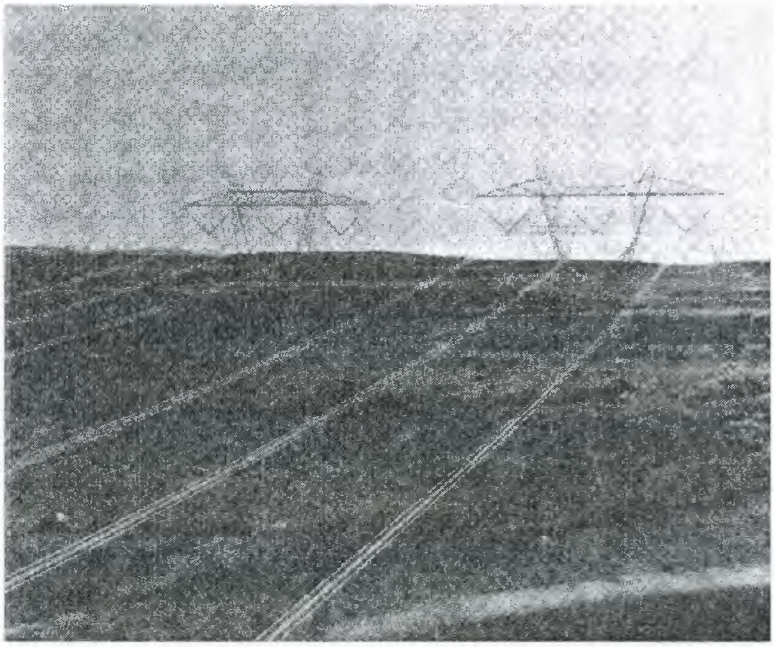


Figure 1.19 Two 735 kV transmission lines in parallel carrying electrical energy to a large city. Each phase is composed of 4 bundled conductors.

1.16 Extra high voltage lines

When electrical energy is transmitted at extra high voltages, special problems arise that require the installation of large compensating devices to regulate the voltage and to guarantee stability. Among these devices are synchronous capacitors, inductive reactors, static var compensators, and shunt and series capacitors.

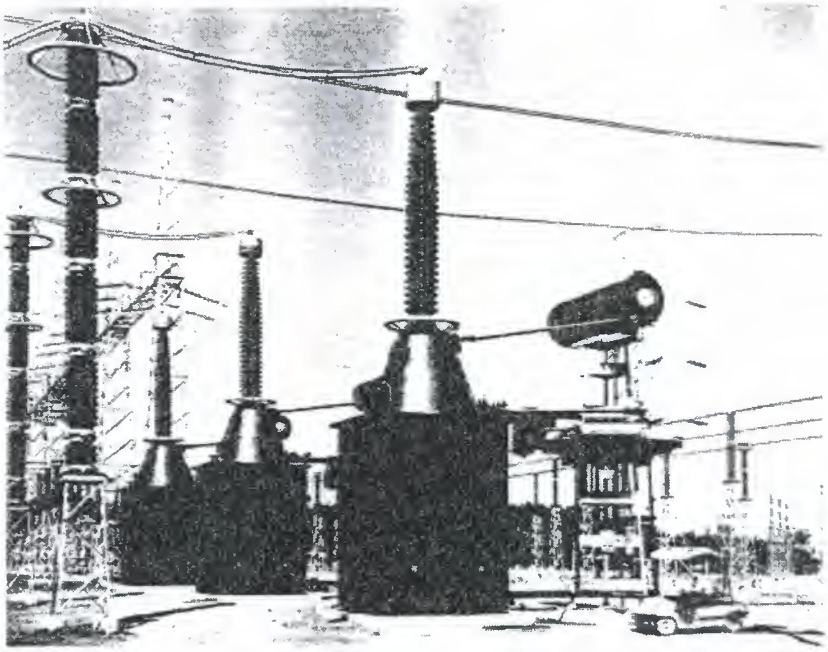


Figure 1.20 Three large 110 Mvar, single-phase reactors, installed in a substation to compensate the line capacitance of a very long 3-phase 735 kV transmission line.

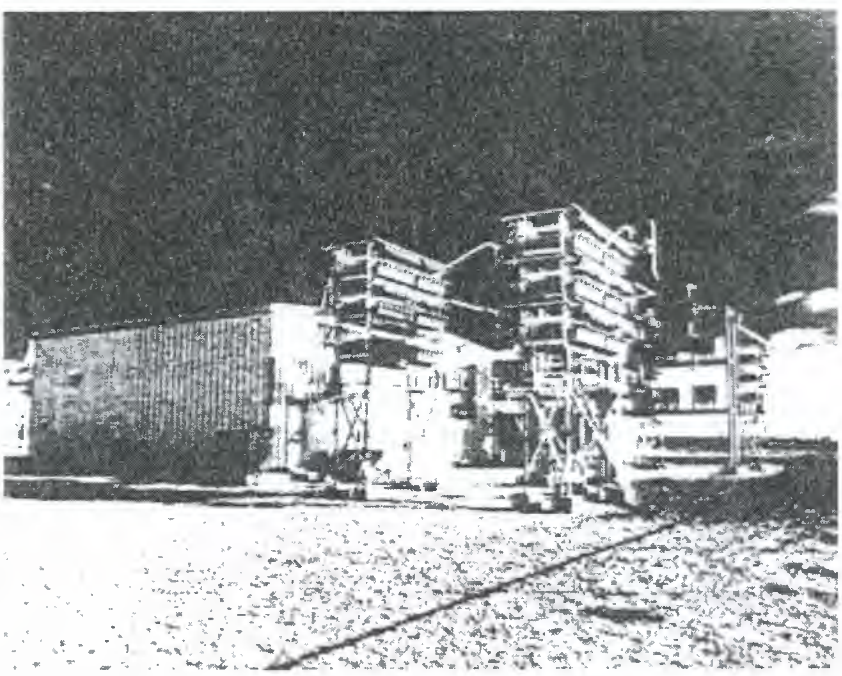


Figure 1.21 Static var compensator for HV line

1.17 Transmission Line Considerations

Electrical power transmission lines can be ac, dc, underground, or overhead. Overhead ac is the most used method of electrical power transmission. Transmission lines represent from 10 % to 20 % of the investment of a typical electric utility company. This significant amount must be carefully spent so as to assure reliable, efficient, and economical electric power transmission.

1.17.1 Overhead Line Considerations

Overhead transmission line construction is much less expensive than underground because it is simpler. Bare wires can be used in overhead transmission line construction with insulation used only at the points that the wire is suspended. The use of bare conductors alone cuts both the cost and losses for an overhead line compared to an underground line. Wood or galvanized steel towers are used to support the conductors. The insulators at the conductor support points are usually ball and socket porcelain or fiberglass rods covered with skirts made of a compound similar to silicon rubber.

Overhead transmission line must be very reliable because an outage on one leaves many homes and businesses without electricity. Thus transmission lines are well protected against lightning with lightning arresters placed periodically along, the line, and shield wires along the entire line. The conductors and conductor supports must be strong enough to withstand severe weather, which can subject the lines to considerable wind, snow, and ice loading. Bundled conductors, which are used almost universally at 230 kV and above, to reduce series reactance and corona, experience more weather related loading than single conductors. Thus bundled conductors must be supported better, at a higher cost, than single conductor lines.

There is a trade off between the losses on a transmission line and the cost of constructing the line. Lowering (I^2R) losses usually means using lager conductors or more conductors to increase conductor weight, which means the strength of the supporting towers and insulators must be greater. The increased strength required means that manufacturing cost, transportation cost, and construction cost of every line component is higher. Transmission line costs are also affected by the terrain that the line must pass through.

The rougher the terrain the higher the cost. Terrain such as swamp land that is not suitable for normal foundations or temporary access roads also increases the cost of construction because helicopter pole placement and special support guys become necessary.

The magnitude of the power that a transmission line carries makes the reduction of loss a major consideration. For example, a 2% loss on a 1000 kVA line, at 6 cents/kW-hr, costs only $1.20/hr. A 50% reduction in loss amounts to a savings of only 60 cents and hour. The same loss on a 1000 MVA line at 6 cent/kW-hr costs $1,200 /hr. A 50% reduction in this loss is a savings of $600/hr, or $600/hr * 24hr/day * 365 days/yr = 5.26 million dollars a year. Over the expected 40-year lifetime of a transmission line this is a savings of 210.4 million dollars. Thus the reduction in line loss must be carefully weighed against increased construction costs to plan a transmission line that is optimally economical.

Obtaining right of way is not a large problem for distribution system construction. The areas that do not grant right of ways do not get electric service. Very few distribution right of way requests are denied. Transmission lines do not affect people so immediately, are considered unsightly by some people, require larger right of ways that distribution line, and are considered a health hazard by few people, so people are not willing to grant transmission right of ways. The courts tend to agree and support the reluctance of people to grant right of ways for transmission lines. As a result the right of way cost is a very large portion of the cost of constructing a transmission line, especially when litigation is necessary.

1.17.2 Underground Line Considerations

Underground transmission lines are most commonly used to feed urban substations in high load density areas, such as downtown. Industrial plants use underground transmission and/or distribution lines in areas where overhead line are not practical because of the clearance required. The highest underground transmission line voltage is 525 kV. This installation used nine oil type cables (three circuits), running about 6500 feet to connect the generation plant to the switch yard at the Grand Coulee Dam. Since the cost of an underground transmission line is 9 to 15 times the cost of an overhead line, they are installed only where they offer a clear advantage, or there is no alternative.

Underground lines are more expensive than overhead for a variety of reasons. Underground cables must be insulated, and EHV insulation is expensive. It must be installed in pipe, which is expensive, and cooled with an oil circulation system, which is expensive both to install and maintain. Should a failure occur in an underground system, it is expensive to repair because of the difficulty in access.

The pipes used for underground transmission cable conduit are usually steel or bronze, 6 to 8 inches in diameter. Bronze, while more expensive, is not magnetic so it has less effect on cable reactance. The pipes are insulated on the outside to prevent cathodic currents (essentially from battery action in the soil involving the pipe as one electrode), and buried from 4 to 8 feet deep, enveloped within reinforced concrete. The pipe comes in 30 and 40 foot lengths. It must be welded securely enough to hold a vacuum and the joint must be insulated on the outside. After the run of pipe is in place a cup driven by compressed air, called a rabbit, is used to pull a lingt line through it. Then a mandril, called a pig, is pulled through the pipe to remove any wilding burrs. The pipe is then put under a vacuum to test for leaks. The cables are then installed. The pipe is then put under a vacuum with the cables installed and filled with oil.

The cables are constructed much like the oil impregnated paper insulted underground distribution cables, except that the transmission cables have more oil impregnated paper insulation in more layers. The cables has aspiral metal wire wound around the outside of the insulation to prevent damage to the cable when it is pulled through the pipe, or from movement caused by expansion or construction caused by heating or cooling as load current changes. The entire cable is covered with a thin lead sheath that keeps the oil impregnation in the insulation and prevents handling damage during shipping and installation. During cable pulling the lead sheath is removed just as the cable enters the pipe/ the cable must enter the pipe, and cable splices must be made, in a clean, humidity controlled environment so an air conditioned building is constructed where the cable is fed into the pipe.

After the cable is installed the pipe is filled with oil. The oil is pumped through the pipe to cool as well as insulate the cable. Pumping cool oil through the pipe can greatly increase the capacity of the cable. The oil circulation system includes pumps, filters, and oil tanks. Sulphur hexafluoride SF_6 is sometimes used to insulate underground transmission cables, but is not as popular as oil because it does not provide an increase in capacity as does cooled oil. The popularity of SF_6 is increasing because of its relative simplicity.

We see that all of the complexity associated with underground transmission lines causes them to be extremely expensive in comparison to overhead transmission lines. However, properly installed underground transmission lines are very reliable.

1.18 Transmission Line Parameters

Transmission lines consist of resistance, inductance, and capacitance. Thus a transmission line is an RLC circuit with values of R, L, and C constrained by the function and geometry of the line. The job of the transmission line is to transport large amounts of electrical power from one location to another with the lowest loss that can be economically attained. The materials available, cost restraints set by available capital, terrain the line must pass through, right of way availability and cost, and other factors prevent transmission lines from being optimized for electrical characteristics alone. The designers of transmission lines must obtain the lowest loss line that can be built to carry the needed load over the desired path at reasonable cost.

1.19 Power exchange between power centers

We sometimes have to install an additional transmission line on systems that are already tightly interconnected. Such a line may be required to meet the energy needs of a rapidly growing area or to improve the overall stability of the network. In such cases, we use special methods so that the additional line will transmit the required power.

Consider, for example, two major power centers A and B that are already interconnected by a grid of transmission lines (not shown) (Fig. 1-22). The respective voltages E_a and E_b are equal, but E_a leads E_b by an angle δ . If we decide to connect the two centers by an extra transmission line having a reactance X, the active power P will automatically flow from A to B because E_a leads E_b (see Sec. 1.12.4). Furthermore, phase angle δ and reactance X will completely dictate the magnitude of the power transmitted because $P = (E^2/X) \sin\delta$.

However, the magnitude and direction of P may not correspond at all to what we want to achieve. For example, if we wish to transmit energy from region B to region A, the installation of a simple line will not do, for reasons we have just explained.

However, we can *force a* power exchange in one direction or the other by artificially modifying the phase angle between the two regions. All we have to do is to introduce a phaseshift autotransformer at one end of the line; by varying the phase angle of this transformer, we can completely control the active power flow between the two centers.

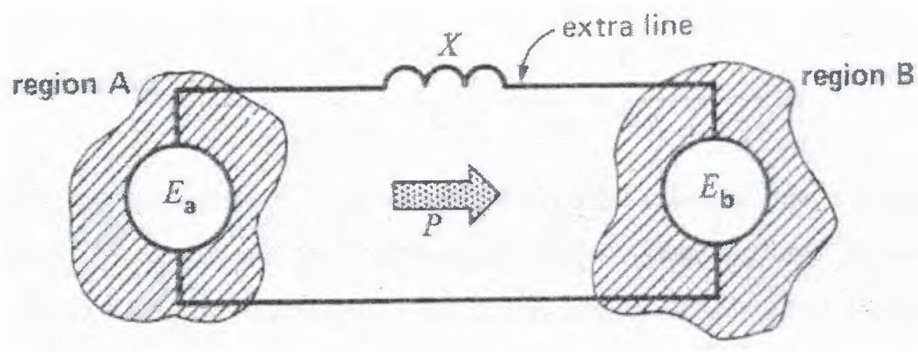


Figure 1.22 Power flow between two regions.

CHAPTER 2: DISTRIBUTION OF ELECTRICAL ENERGY

2.1 Distribution System

The supply system consists of the network of conductors and associated equipment over which energy is transmitted from the generating station to the consumer; it may be divided into distinct parts, the transmission system and the distribution system. The former may again be divided into primary and secondary transmission and the latter may be divided into primary, secondary and tertiary distribution. In general in an a.c. system there will be a change in voltage at each point where the subdivision takes place, the change being effected by transformation, usually at a substation, and therefore there may be several working voltages in the same system.

Although there is no "typical" electric power system, a diagram including the several components that are usually to be found in the makeup of such a system is shown in Fig. 2-1; particular attention should be paid to those elements which will make up the component under discussion, the distribution system.

While the energy flow is obviously from the power generating plant to the consumer, it may be more informative for our purposes to reverse the direction of observation and consider events from the consumer back to the generating source.

Energy is consumed by users at a nominal utilization voltage that may range generally from 110 to 125 V, and from 220 to 250 V (for some large commercial and industrial users, the nominal figures are 277 and 480 V). It flows through a metering device that determines the billing for the consumer, but which may also serve to obtain data useful later for planning, design, and operating purposes. The metering equipment usually includes a means of disconnecting the consumer from the incoming supply should this become necessary for any reason.

The energy flows through conductors to the meter from the secondary mains (if any); these conductors are referred to as the consumer's *service,* or sometimes also as the *service drop.*

Several services are connected to the secondary mains; the secondary mains now serve as a path to the several services from the distribution transformers which supply them. At the transformer, the voltage of the energy being delivered is reduced to the utilization voltage values mentioned earlier from higher *primary* line voltages that may range from 2200 V to as high as 46,000 V.

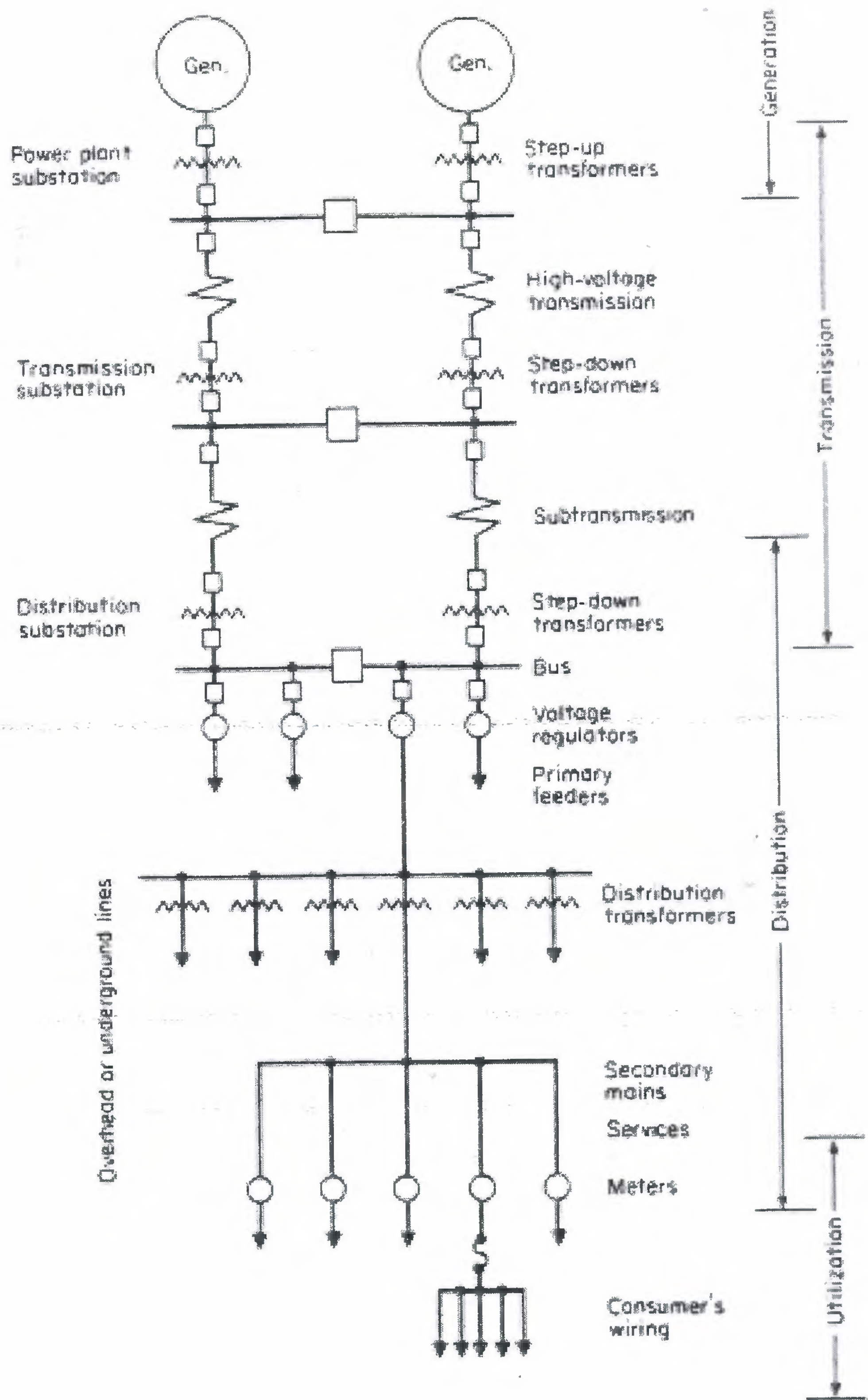


Figure 2-1 Typical electric system showing operational divisions.

The transformer is protected from overloads and faults by fuses or so-called weak links on the high-voltage side; the latter also usually include circuit-breaking devices on the low-voltage side. These operate to disconnect the transformer in the event of overloads or faults. The circuit breakers (where they exist) on the secondary, or low-voltage, side operate only if the condition is caused by faults or overloads in the secondary mains, services, or consumer's premises; the primary fuse or weak link in addition operates in the event of a failure within the transformer itself.

If the transformer is situated on an overhead system, it is also protected from lightning or line voltage surges by a surge arrester, which drains the voltage surge to ground before it can do damage to the transformer.

The transformer is connected to the primary circuit, which may be a lateral or spur consisting of one phase of the usual three-phase primary main. This is done usually through a line or sectionalizing fuse, whose function is to disconnect the lateral from the main in the event of fault or overload in the lateral. The lateral conductors carry the sum of the energy components flowing through each of the transformers, which represent not only the energy used by the consumers connected thereto, but also the energy lost in the lines and transformers to that point.

The three-phase main may consist of several three-phase branches connected together, sometimes through other line or sectionalizing fuses, but sometimes also through switches. Each of the branches may have several single-phase laterals connected to it through line or sectionalizing fuses.

Where single-phase or three-phase overhead lines run for any considerable distance without distribution transformer installations connected to them, surge arresters may be installed on the lines for protection.

Some three-phase laterals may sometimes also be connected to the three-phase main through *circuit reclosers.* The recloser acts to disconnect the lateral from the main should a fault occur on the lateral, much as a line or sectionalizing fuse. However, it acts to reconnect the lateral to the main, reenergizing it one or more times after a time delay in a predetermined sequence before remaining open permanently. This is done so that a fault which may be only of a temporary nature, such as a tree limb falling on the line, will not cause a prolonged interruption of service to the consumers connected to the lateral.

The three-phase mains emanate from a *distribution substation,* supplied from a *bus* in that station. The three-phase mains, usually referred to as a *circuit* or *feeder,* are connected to the bus through a protective circuit breaker and sometimes a voltage regulator. The voltage regulator is usually a modified form of transformer and serves to maintain outgoing voltage within a predetermined band or range on the circuit or feeder as its load varies. It is sometimes placed electrically in the substation circuit so that it regulates the voltage of the entire bus rather than a single outgoing circuit or feeder, and sometimes along the route of a feeder for partial feeder regulation. The circuit breaker in the feeder acts to disconnect that feeder from the bus in the event of overload or fault on the outgoing or distribution feeder.

The substation bus usually supplies several distribution feeders and carries the sum of the energy supplied to each of the distribution feeders connected to it. In turn, the bus is supplied through one or more transformers and associated circuit breaker protection. These substation transformers step down the voltage of their supply circuit, usually called the *subtransmission* system, which operates at voltages usually from 23,000 to 138,000 V.

The subtransmission systems may supply several distribution substations and may act as *tie feeders* between two or more substations that are either of the *bulk power* or *transmission* type or of the distribution type. They may also be tapped to supply some distribution load, usually through a circuit breaker, for a single consumer, generally an industrial plant or a commercial consumer having a substantially large load.

The transmission or bulk power substation serves much the same purposes as a distribution substation, except that, as the name implies, it handles much greater amounts of energy: the sum of the energy individually supplied to the subtransmission lines and associated distribution substations and losses. Voltages at the transmission substations are reduced to outgoing subtransmission line voltages from transmission voltages that may range from 69,000 to upwards of 750,000 V.

The transmission lines usually emanate from another substation associated with a power generating plant. This last substation operates in much the same manner as other substations, but serves to step up to transmission line voltage values the voltages produced by the generators. Because of material and insulation limitations, generator voltages may range from a few thousand volts for older and smaller units to some 20,000 volts for more recent, larger ones. Both buses and transformers in these substations are protected by circuit breakers, surge arresters, and other protective devices. In all the systems described, conductors should be large enough that the energy loss in them will not be excessive, nor the loss in voltage so great that normal nominal voltage ranges at the consumers' services cannot be maintained. In some instances, voltage regulators and capacitors are installed at strategic points on overhead primary circuits as a means of compensating for voltage drops or losses, and incidentally help in holding down energy losses in the conductors. In many of the distribution system arrangements, some of the several elements between the generating plant and the consumer may not be necessary. In a relatively small area, such as a small town, which is served by a power plant situated in or very near the service area, the distribution feeder may emanate directly from the power plant bus, and all other elements may be eliminated, as indicated in Fig. 2-2. This is perhaps one extreme; in many other instances only some of the other elements may not be necessary; e.g., a similar small area somewhat distant from the generating plant may find it necessary to install a distribution substation supplied by a transmission line of appropriate voltage only.

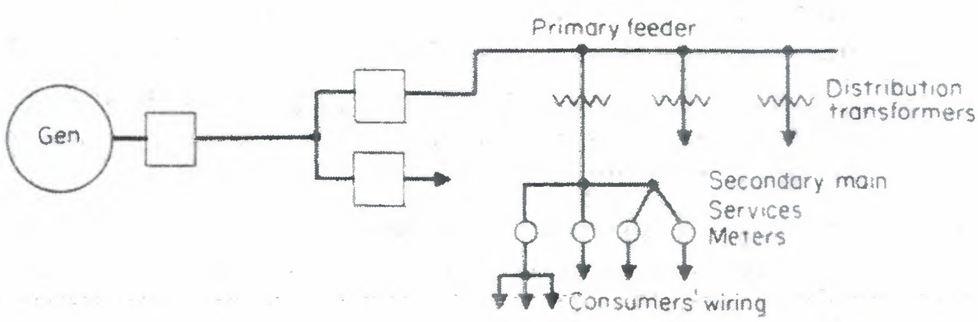


Figure 2-2 Abbreviated electric system

In the case of areas of high load density and rather severe service reliability requirements, the distribution system becomes more complex and more expensive. The several secondary mains to which the consumers' services are connected may all be connected into a mesh or network. The transformers supplying these secondary mains or network are supplied from several different primary feeders, so that if one or more of these feeders is out of service for any reason, the secondary network is supplied from the remaining ones and service to the consumers is not interrupted. To prevent a feeding-back from the energized secondary network through the transformers connected to feeders out of service (thereby energizing the primary and creating unsafe conditions), automatically operated circuit breakers, called *network protectors,* are connected between the secondary network and the secondary of the transformers; these open when the direction of energy flow is reversed.

The two examples cited here are perhaps the two extremes in the design of distribution systems, the first the simplest, the latter the most complex. There are many variations in between these, and the basic ones will be described by the time.

2.2 Design for Distribution System

In determining the design of distribution systems, three broad classifications of choices need to be considered:

1. The type of electric system: dc or ac, and if ac, single-phase or polyphase.
2. The type of delivery system: radial, loop or network. Radial systems include duplicate and throwover systems.
3. The type of construction: overhead or underground.

Electrical energy may be distributed over two or more wires. The principal features desired are safety; smooth and even flow of power, as far as is practical; and economy. The safety factor usually requires a voltage low enough to be safe when the electric energy is utilized by the ordinary consumer.

A steady, uniform, nonfluctuating flow of power is highly desirable, both for lighting and for the operation of motors for power purposes. Although a direct current system fills these requirements admirably, it is limited in the distance over which it can economically supply power at utilization voltage.

Alternating current systems deliver power in a fluctuating manner following the cyclic variations of the voltage generated. Such fluctuations of power are not objectionable for heating, lighting, and small motors, but are not entirely satisfactory for the operation of some devices such as large motors, which must deliver mechanical power steadily and therefore require a steady input of electric power. This may be done by supplying electricity to the motors by two or three circuits, each supplying a portion of the power, whose fluctuations are purposely made not to occur at the same time, thereby decreasing or damping out the effect of the fluctuations. These two or three separate alternating current circuits (each often referred to as a single-phase circuit) are combined into one polyphase (two- or three-phase) circuit. The voltages for polyphase circuits or systems are supplied from polyphase generators.

2.3 Types of Electric Systems

2.3.1 Direct Current Systems

Direct current systems usually consist of two or three wires. Although such distribution systems are no longer employed, except in very special instances, older ones now exist and will continue to exist for some time. Direct current systems are essentially the same as single-phase ac systems of two or three wires; the same discussion for those systems also applies to dc systems.

2.3.2 Alternating Current Single-Phase Systems

Two-Wire Systems: The simplest and oldest circuit consists of two conductors between which a relatively constant voltage is maintained, with the load connected between the two conductors (Fig. 2-2.)

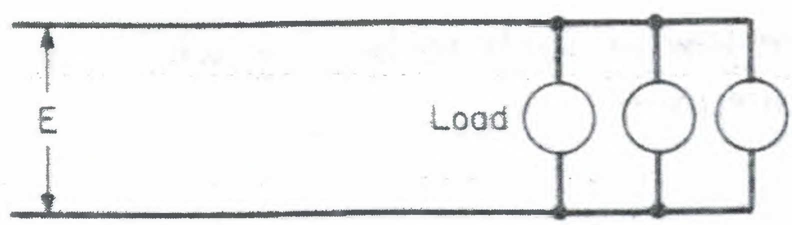


Figure 2-2 AC single-phase two-wire system.

In almost all cases, one conductor is grounded. The grounding of one conductor, usually called the *neutral,* is basically a safety measure. Should the live conductor come in contact accidentally with the neutral conductor, the voltage of the live conductor will be dissipated throughout a relatively large body of earth and thereby rendered harmless.

In calculating power (I^2R) losses in the conductors, the resistance of the conductors must be considered. In the case of the neutral conductor, because the ground, in parallel with the conductor, reduces the effective resistance, the "return" current will divide between the conductor and ground in inverse proportion to their resistances. Thus the I^2R loss in the neutral conductor will be lower than that in the live conductor; the I^2R loss in the earth may, for practical purposes, be disregarded.

In calculating voltage drop in the circuits, both the resistance and reactance of the two conductors must be considered. (In dc circuits, reactance does not exist during normal flow of current.) This combination of reactance and resistance, known as impedance, is measured in ohms (Ω). Because the current in the grounded neutral conductor may be less than the current in the live conductor, the voltage drop in the neutral conductor may also be less.

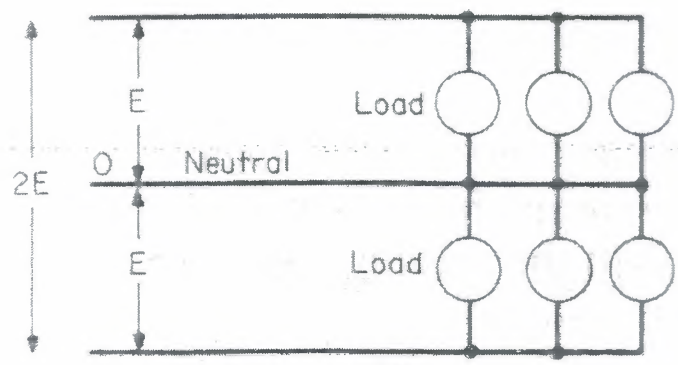


Figure 2-3 AC single-phase three-wire system.

Three-Wire Systems: Essentially the three-wire system is a combination of two two-wire systems with a single wire serving as the neutral of each of the two-wire systems. At a given instant, if one of the live conductors is E volts (say 120 V) "above" the neutral, the other live conductor will be E volts (120 V) "below" the neutral, and the voltage between the two live (or outside) conductors will be 2E (240 V). (Fig. 2-3)

If the load is balanced between the two (two-wire) systems, the common neutral conductor carries no current and the system acts as a two-wire system at twice the voltage of the component system; each unit of load (such as a lamp) of one component system is in series with a similar unit of the other system. If the load is not balanced, the neutral conductor carries a current equal to the difference between the currents in the outside conductors. Here again, the neutral conductor is usually connected to ground.

For a balanced system, power loss and voltage drop are determined in the same way as for a two-wire circuit consisting of the outside conductors; the neutral is neglected. Where the loads on the two portions of the three-wire circuit are unbalanced, voltages at the utilization or receiving ends may be different.

Series Systems: The series type of circuit is used chiefly for street lighting and, although being rapidly replaced by multiple-circuit lighting, nevertheless still exists in substantial numbers. It consists of a single-conductor loop in which the current is maintained at a constant value, the loads connected in series; see Fig. 2-4. The voltage between the conductors at the source or at any other point depends on the amount of load connected beyond that point. The voltage at the source is equal to the vectorial sum of the voltages across the various loads and the voltage drop in the conductor.

The voltage drop in each section of the conductor depends on the current flowing in it (which is constant in value) and the impedance of that section of the conductor.

The power supplied the circuit equals the sum of the power for the individual units of load and the line losses. Power loss in each section of the conductor will depend on the current (squared) and the resistance of that section of the conductor.

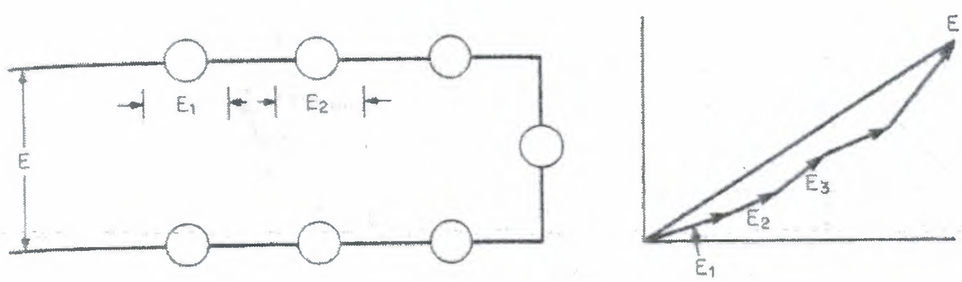


Figure 2-4 AC single-phase series system and voltage vector diagram.

2.3.3 Alternating Current Two-Phase Systems

Two-phase systems are rapidly becoming obsolete, but a good number of them exist and may continue to exist for some time.

Four-Wire Systems: The four-wire system consists of two single-phase two-wire systems in which the voltage in one system is 90° out of phase with the voltage in the other system, both usually supplied from the same generator. (Fig. 2-5)

In determining the power, power loss, and voltage drops in such a system, the values are calculated as for two separate single-phase two-wire systems.

Three-Wire Systems: The three-wire system is equivalent to a four-wire two-phase system, with one wire (the neutral) made common to both phases; (Fig. 2-6). The current in the outside or phase wires is the same as in the four-wire system; the current in the common wire is the vector sum of these currents but opposite in phase. When the load is exactly balanced in the two phases, these currents are equal and 90° out of phase with each other and the resultant neutral current is equal to $\sqrt{2}$ or 1.41 times the phase current.

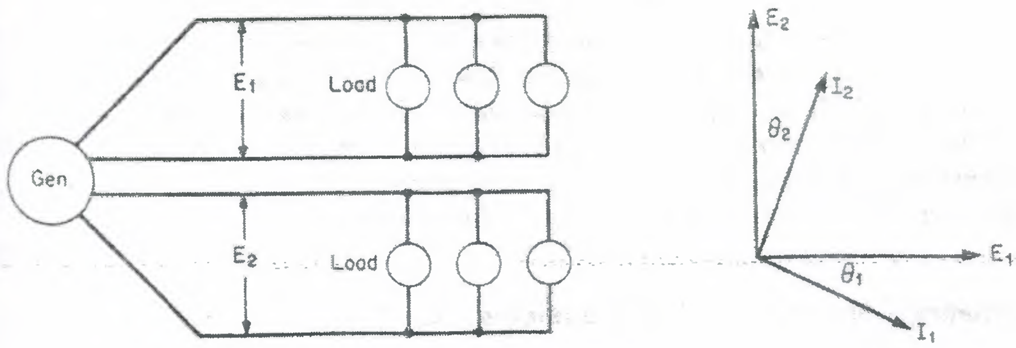


Figure 2-5 AC two-phase four-wire system and vector diagram.

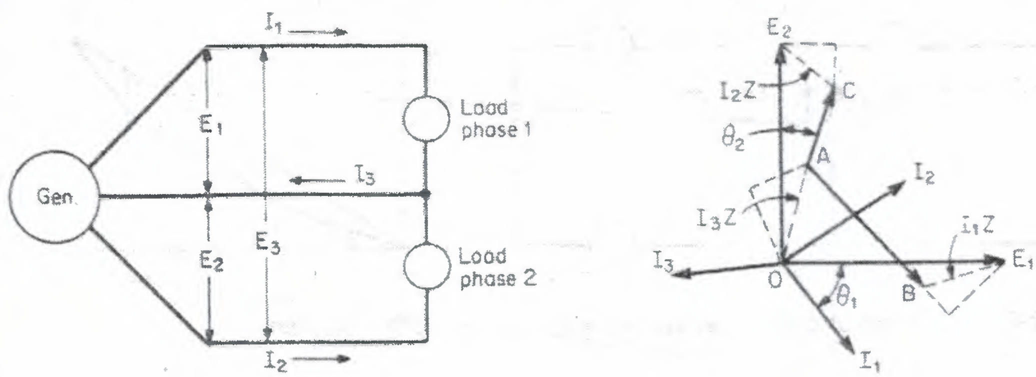


Figure 2-6 AC two-phase three-wire system and vector diagram.

The voltage between phase wires and common wire is the normal phase voltage, and, neglecting the difference in neutral *IR* drop, the same as in the four-wire system. The voltage between phase wires is equal to $\sqrt{2}$ or 1.41 times that voltage.

The power delivered is equal to the sum of the powers delivered by the two phases. The power loss is equal to the sum of the power losses in each of the three wires.

The voltage drop is affected by the distortion of the phase relation caused by the larger current in the third or common wire. In Fig. 2-6, if E_1 and E_2 are the phase voltages at the source and I_1 and I_2 the corresponding phase currents (assuming balanced loading), I_3 is the current in the common wire. The voltage *(IZ)* drops in the two conductors, subtracted vectorially from the source voltages E_1 and E_2, give the resultant voltages at the receiver of *AB* for phase 1 and *AC* for phase 2. The voltage drop numerically is equal to $E_1 — AB$ for phase 1 and $E_2 — AC$ for phase 2. It is apparent that these voltage drops are unequal and that the action of the current in the common wire is to distort the relations between the voltages and currents, the effect shown in Fig. 2-6 is exaggerated for illustration.

Five-Wire Systems: The five-wire system is equivalent to a two-phase four-wire system with the midpoint of both phases brought out and joined in a fifth wire. The voltage is of the same value from any phase wire to the common neutral, or fifth, wire. The value may be in the nature of 120 V, which is used for lighting and small motor loads, while the voltage between opposite pairs of phase wires, *E,* may be 240 V, used for larger-power loads. The voltage between adjacent phase wires is $\sqrt{2}$ or 1.41 times 120 V (about 170 V). See Fig. 2-7.

If the load is exactly balanced on all four phase wires, the common or neutral wire carries no current. If it is not balanced, the neutral conductor carries the vector sum of the unbalanced currents in the two phases.

2.3.4 Alternating Current Three-phase Systems

Four-Wire Systems: The three-phase four-wire system is perhaps the most widely used. It is equivalent to three single-phase two-wire systems supplied from the same generator. The voltage of each phase is 120° out of phase with the voltages of the other two phases, but one conductor is used as a common conductor for all of the system. The current I_n in that common or neutral conductor is equal to the vector sum of the currents in the three phases, but opposite in phase, as shown in Fig. 2-8.

If these three currents are nearly equal, the neutral current will be small, since these phase currents are 120° out of phase with each other. The neutral is usually grounded. Single-phase loads may be connected between one phase wire and the neutral, but may also be connected between phase wires if desired. In this latter instance, the voltage is $\sqrt{3}$ or 1.73 times the line-to-neutral voltage E. Three-phase loads may have each of the separate phases connected to the three phase conductors and the neutral, or the separate phases may be connected to the three phase conductors only.

Power delivered is equal to the sum of the powers in each of the three phases. Power loss is equal to the sum of the I^2R losses in all four wires.

The voltage drop in each phase is affected by the distortion of the phase relations due to voltage drop caused by the current in the neutral conductor. This is not so, however, when the neutral conductor is grounded at both the sending and receiving ends, in which case the neutral drop is theoretically zero, the current returning through ground. The voltage drop may be obtained vectorially by applying the impedance drop of each phase to its voltage. The neutral point is shifted from O to A by the voltage drop in the neutral conductor and the resulting voltages at the receiver are shown by E_{1R}, E_{2R} and E_{3R}. The voltage drops in each phase are numerically equal to the difference in length between E_{1S} and E_{1R}, E_{2S} and E_{2R}, and E_{3S} and E_{3R}. The effects of the distortion due to voltage drop in the neutral conductors are exaggerated in Fig. 2-8 for illustration.

Three-Wire Systems: If the load is equally balanced on the three phases of a four-wire system, the neutral carries no current and hence could be removed, making a three-wire system. It is not necessary, however, that the load be exactly balanced on a three-wire system.

Considering balanced loads, on a three-phase three-wire system, a three-phase load may be connected with each phase connected between two phase wires a

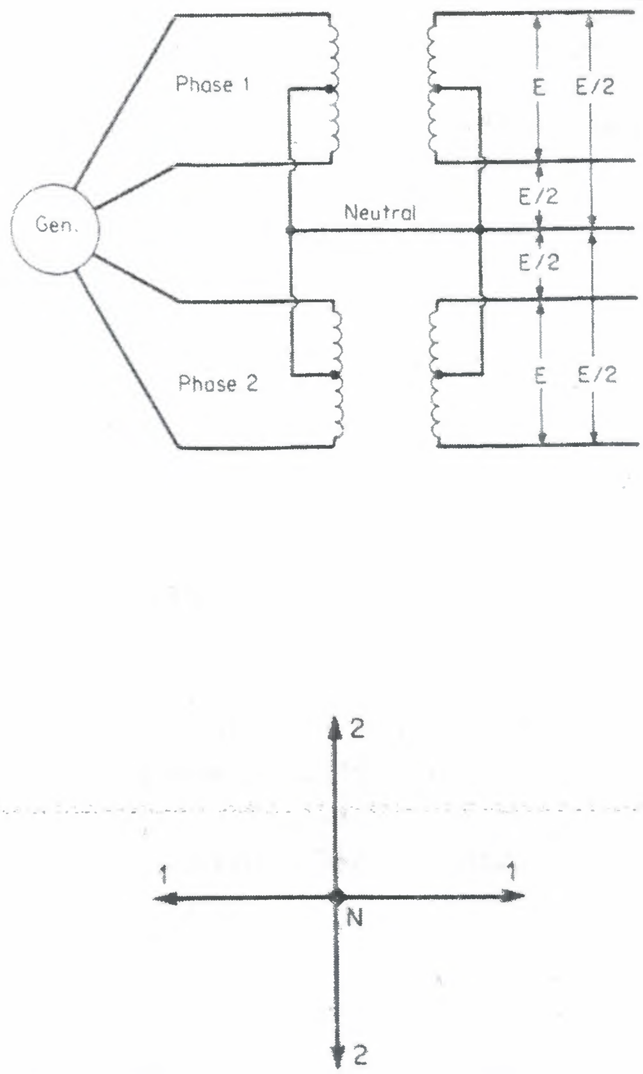
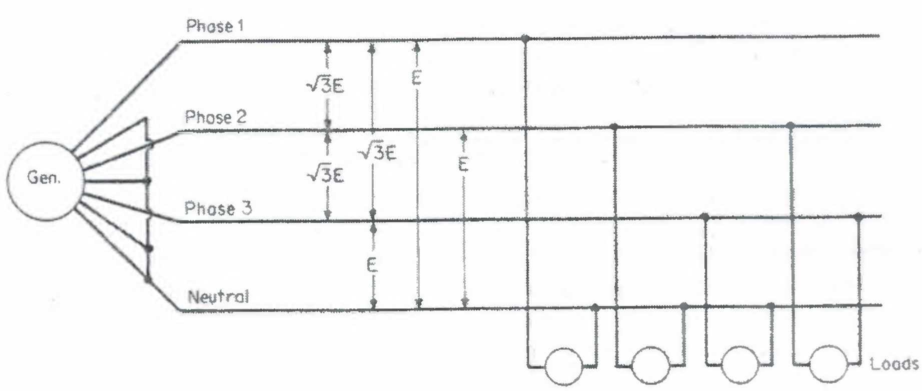
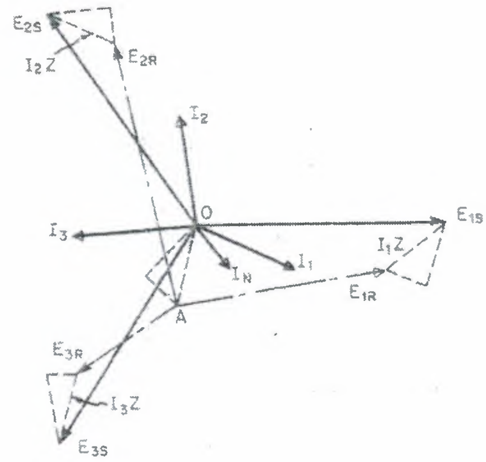


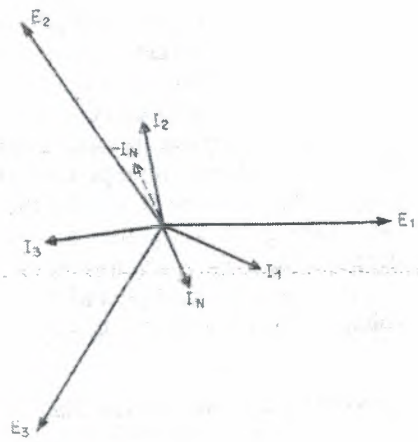
Figure 2-7 AC two-phase five-wire system and vector diagram



(a)



(b)



(c)

Figure 2-8 (a) AC three-phase four-wire system; (b) voltage and current vector diagram; (c) current vector diagram

delta (Δ) connection or with each phase between one phase wire and a common neutral point the star or wye *(Y)* connection, as shown in Fig. 2-9.

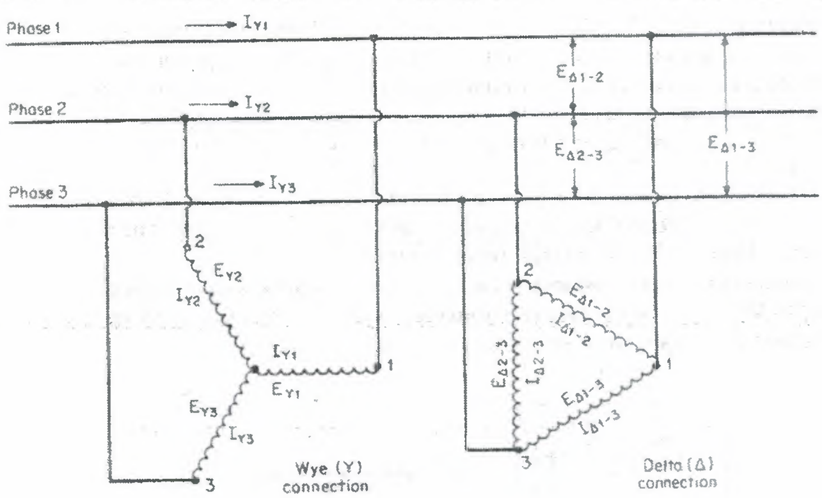
The voltage between line conductors is the delta voltage E_Δ, while the line current is the wye current I_Y. The relations in magnitude and phase between the various delta and wye voltages and currents for the same load are shown in Fig. 2-9. For the delta connection, I_Y is equal to the vector difference between the adjacent delta currents; hence:

$$I_Y = \sqrt{3} \text{ (or 1.73) times } I$$

And

$$E_\Delta = \sqrt{3} \text{ (or 1.73) times } E_Y$$

Power delivered, when balanced loads are considered, is equal to 3 times the power delivered by one phase. Power loss is equal to the sum of the losses in each phase, or when balanced conditions exist, it is 3 times the power loss in any one phase. The voltage drop in each phase, referred to the wye *(Y)* voltages, may be determined by adding the impedance drop in one conductor vectorially to E_Y, when balanced loads are considered. The same thing is done in determining voltages where unbalanced loads are considered. If $E_{\Delta S}$ is the voltage between phases at the source and E_{YS} the phase-to-neutral voltage, the drop due to conductor impedance IZ, is subtracted vectorially from E_{YS} for each of the three phases, and the resulting voltages between phases at the receiving end ($E_{\Delta R}$) are obtained. The effects shown in the vector diagram of Fig. 2-9 are exaggerated for illustration.



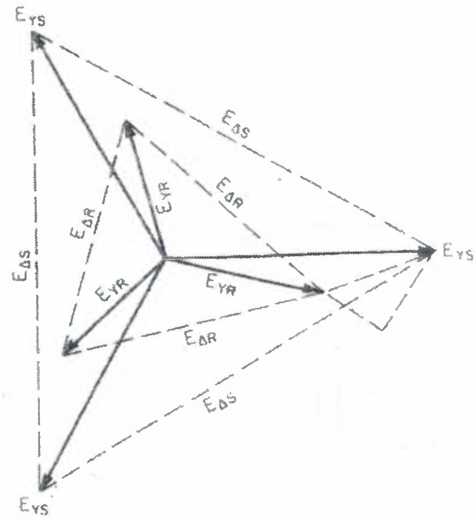


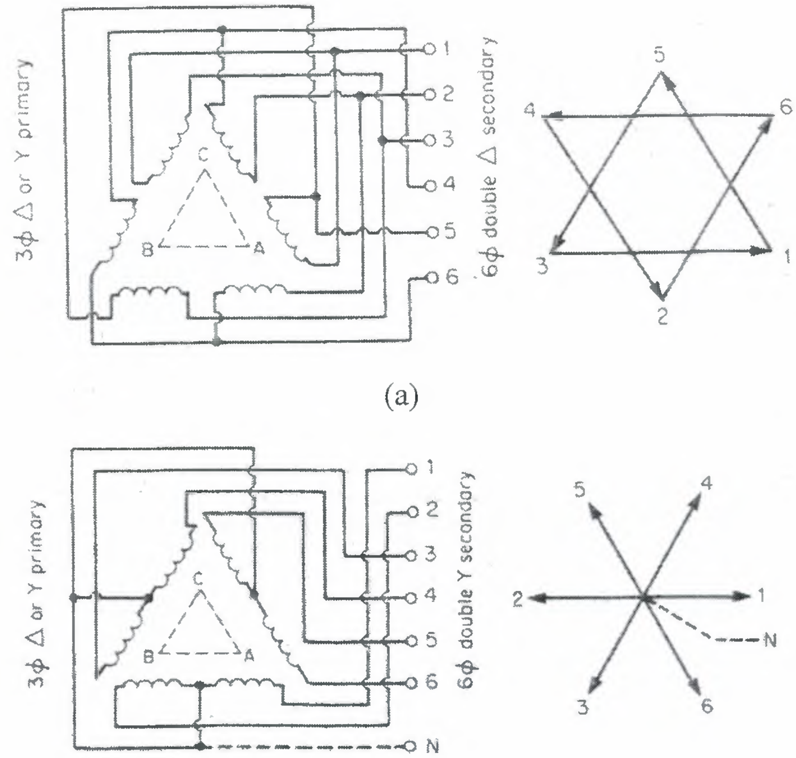
Figure 2-9 AC three-phase three-wire system and voltage vector diagrams.

2.3.5 Alternating Current Six-Phase Systems

Six-Wire Systems: Six-phase systems consist essentially of two three-phase systems connected so that each phase of one system will be displaced 180° with reference to the same phase of the other system. These may consist of two banks of three transformers connected separately with the polarity of one bank reversed with reference to the second bank; or one bank of transformers may be employed, with the secondary windings divided into two equal parts and both ends of each winding part brought out to separate terminals (for a total of 12 terminals).

The windings may be connected in a double-delta fashion as shown in Fig. 2-10a, or in a double-wye arrangement as shown in Fig. 2-10b. The associated vector diagrams of the voltage relationships are also indicated.

In the double-wye connection, it is not necessary to have the windings brought out to 12 terminals; the neutral connection may be made by connecting together the midtap from each of the three secondary windings.



(a)

(b)

Figure 2-10 AC six-phase six-wire double-delta system (a), AC six-phase six-wire (and seven-wire) double-wye system (b), and voltage vector diagrams.

Such systems are almost exclusively used in supplying rectifiers or synchronous converters to serve direct current loads; the synchronous converter also aids in improving power factor on the alternating current supply system.

Seven-Wire Systems: A seventh, or neutral, wire may be brought out from the common junction of the double-wye connection, as indicated by the dashed line in Fig. 2-10b. The seven-wire system may be used for distribution purposes, with the neutral connected to other common neutral systems. The disadvantage of the additional conductor is balanced against two major advantages:

1. The ability to serve single-phase loads from a source of higher voltage, i.e., twice the line-to-neutral voltage, compared with 1.73 times the line-to-neutral voltage in a three-phase system.
2. Reduction in overall line losses, as each conductor will carry only one-sixth

of the load, compared with one-third in a three-phase system, only half the load per conductor in a three-phase system. The losses, therefore, will be one-quarter those in a three phase (three or four-wire balanced) system.

The overall savings in fuel costs for supplying the lesser losses may exceed the increased carrying charges associated with the additional conductors. The improved voltage in supplying three-phase delta (power) loads from such a system also contributes to its acceptability. As fuel and operating costs increase, such systems may find wider application.

2.4 Comparison between Alternating Current Systems

A comparison of efficiencies for the several alternating current systems, assuming the same (balanced) loads, the same voltage between conductors, and the same conductor size is summarized in Table 2-1, which uses a single-phase two-wire circuit as a basis for comparison.

TABLE 2-1

Type of ac system		*Amount of conductor*	*Power loss*	*Voltage drop (approximate)*
Single-phase	2-wire	1.0	1.00	1.00
	3-wire	1.5	0.25	0.25
Two-phase	3-wire	1.5	0.50	0.50
	4-wire	2.0	0.25	0.25
	5-wire	2.5	0.25	0.25
Three-phase	3-wire *	1.5	0.167	0.167
	3-wire **	1.5	0.50	0.50
	4-wire *	2.0	0.167	0.167
Six-phase	6-wire	3.0	0.042	0.042
	7-wire	3.5	0.042	0.042

*Wye (Y) voltage same as single-phase.

**Delta (Δ) voltage same as single-phase.

2.5 Types of Delivery Systems

The delivery of electric energy from the generating plant to the consumer may consist of several more or less distinct parts that are nevertheless somewhat interrelated. The part considered "distribution," i.e., from the bulk supply substation to the meter at the consumer's premises, can be conveniently divided into two subdivisions:

1. Primary distribution, which carries the load at higher than utilization voltages from the substation (or other source) to die point where the voltage is stepped down to the value at which the energy is utilized by the consumer.

2. Secondary distribution, which includes that part of the system operating at utilization voltages, up to the meter at the consumer's premises.

2.5.1 Primary Distribution

Primary distribution systems include three basic types:

1. Radial systems, including duplicate and throwover systems
2. Loop systems, including both open and closed loops
3. Primary network systems

1. *Radial Systems:* The radial-type system is the simplest and the one most commonly used. It comprises separate feeders or circuits "radiating" out of the substation or source, each feeder usually serving a given area. The feeder may be considered as consisting of a main or trunk portion from which there radiate spurs or laterals to which distribution transformers are connected, as illustrated in Fig. 2-11.

The spurs or laterals are usually connected to the primary main through fuses, so that a fault on the lateral will not cause an interruption to the entire feeder.

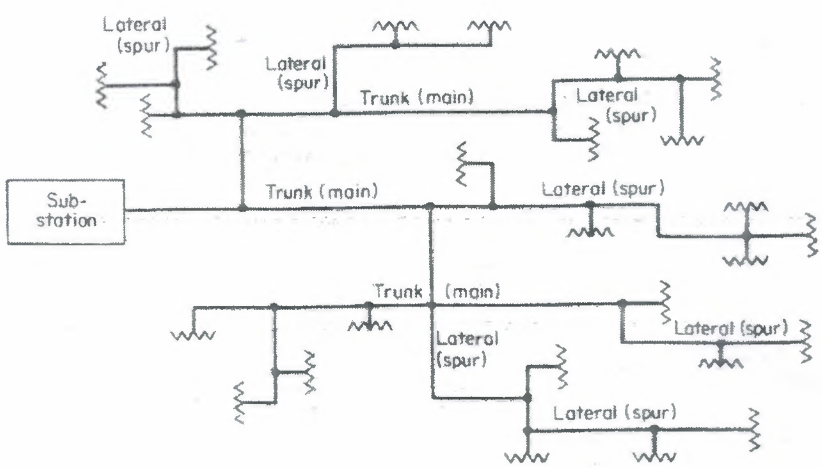


Figure 2-11 Primary feeder schematic diagram showing trunk or main feeds and laterals or spurs.

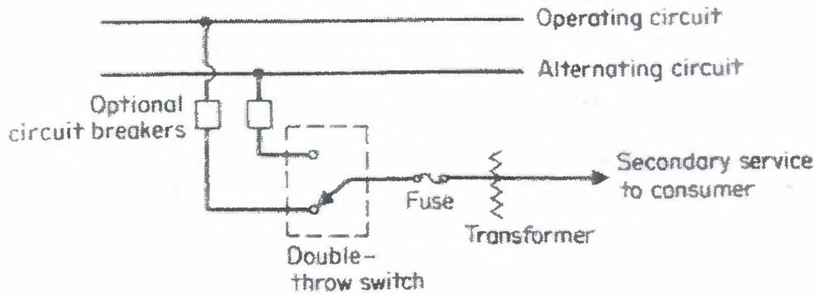


Figure 2-12 Schematic diagram of alternate feed-throwover arrangement for critical consumers.

Should the fuse fail to clear the line, or should a fault develop on the feeder main, the circuit breaker back at the substation or source will open and the entire feeder will be deenergized.

To hold down the extent and duration of interruptions, provisions are made to sectionalize the feeder so that unfaulted portions may be reenergized as quickly as practical. To maximize such reenergization, emergency ties to adjacent feeders are incorporated in the design and construction; thus each part of a feeder not in trouble can be tied to an adjacent feeder. Often spare capacity is provided for in the feeders to prevent overload when parts of an adjacent feeder in trouble are connected to them. In many cases, there may be enough diversity between loads on adjacent feeders to require no extra capacity to be installed for these emergencies.

Supply to hospitals, military establishments, and other sensitive consumers may not be capable of tolerating any long interruption. In such cases, a second feeder (or additional feeders) may be provided, sometimes located along a separate route, to provide another, separate alternative source of supply. Switching from the normal to the alternative feeder may be accomplished by a throwover switching arrangement (which may be a circuit breaker) that may be operated manually or automatically. In many cases, two separate circuit breakers, one on each feeder, with electrical interlocks (to prevent connecting a good feeder to the one in trouble), are employed with automatic throwover control by relays. See Fig. 2-12.

2. Loop Systems: Another means of restricting the duration of interruption employs feeders designed as loops, which essentially provide a two-way primary feed for critical consumers. Here, should the supply from one direction fail, the entire load of die feeder may be carried from the other end, but sufficient spare capacity must be provided in the feeder. This type of system may be operated with the loop normally open or with die loop normally closed.

Open Loop In the open-loop system, the several sections of the feeder are connected together through disconnecting devices, with the loads connected to the several sections, and both ends of the feeder connected to the supply. At a predetermined point in the feeder, the disconnecting device is intentionally left open. Essentially, this constitutes two feeders whose ends are separated by a disconnecting device, which may be a fuse, switch, or circuit breaker. See Fig. 2-13.

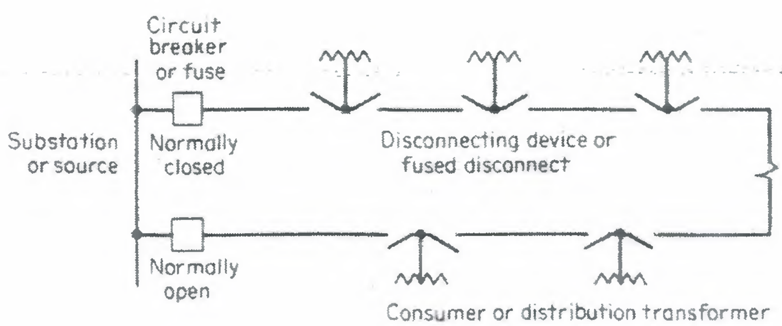


Figure 2-13 Open-loop circuit schematic diagram.

In the event of a fault, the section of the primary on which the fault occurs can be disconnected at both its ends and service reestablished to the unfaulted portions by closing the loop at the point where it is normally left open, and reclosing the breaker at the substation (or supply source) on the other, unfaulted portion of the feeder.

Such loops are not normally closed, since a fault would cause the breakers (or fuses) at both ends to open, leaving the entire feeder deenergized and no knowledge of where the fault has occurred. The disconnecting devices between sections are manually operated and may be relatively inexpensive fuses, cutouts or switches.

Closed Loop Where a greater degree of reliability is desired, the feeder may be operated as a closed loop. Here, the disconnecting devices are usually the more expensive circuit

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breakers. The breakers are actuated by relays, which operate to open only the circuit breakers on each end of the faulted section, leaving the remaining portion of the entire feeder energized. In many instances, proper relay operation can only be achieved by means of pilot wires which run from circuit breaker to circuit breaker and are costly to install and maintain; in some instances these pilot wires may be rented telephone circuits. See Fig. 2-14.

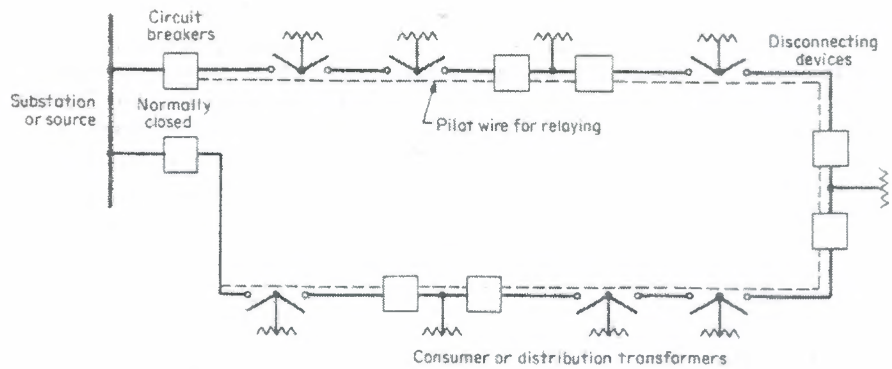


Figure 2-14 Closed-loop circuit.

To hold down costs, circuit breakers may be installed only between certain sections of the feeder loop, and ordinary, less expensive disconnecting devices installed between the intermediate sections. A fault will then deenergize several sections of the loop; when the fault is located, the disconnecting devices on both ends of the faulted section may be opened and the unfaulted sections reenergized by closing the proper circuit breakers.

3. Primary Network Systems: Although economic studies indicated that under some conditions the primary network may be less expensive and more reliable than some variations of the radial system, relatively few primary network systems have been put into actual operation and only a few still remain in service.

This system is formed by tying together primary mains ordinarily found in radial systems to form a mesh or grid. The grid is supplied by a number of power transformers supplied in turn from subtransmission and transmission lines at higher voltages. A circuit breaker between the transformer and grid, controlled by reverse-current and automatic reclosing relays, protects the primary network from feeding fault current through the transformer when faults occur on the supply subtransmission or transmission lines. Faults on sections of the primaries constituting the grid are isolated by circuit breakers and fuses. See Fig. 2-15.

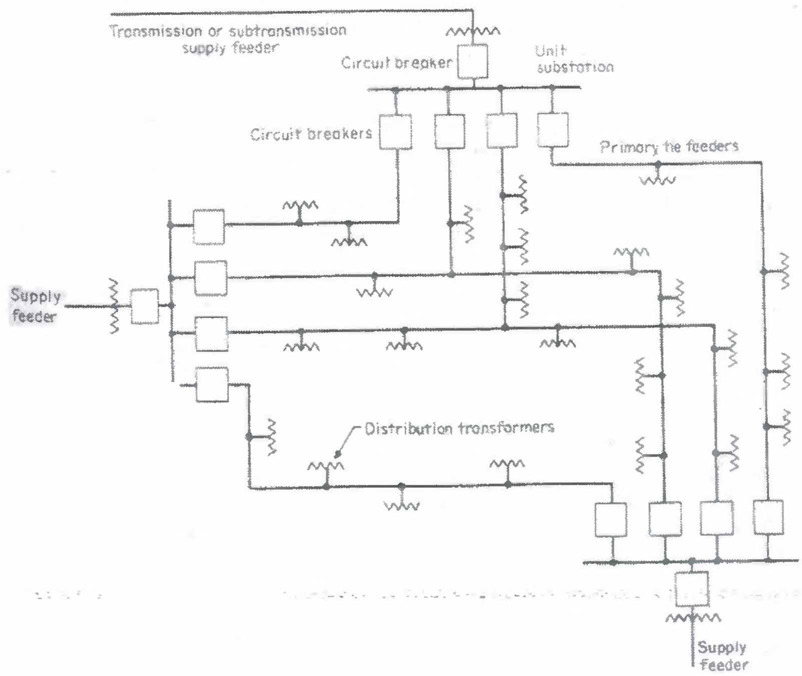


Figure 2-15 Primary network.

This type of system eliminates the conventional substation and long primary trunk feeders, replacing them with a greater number of "unit" substations strategically placed throughout the network. The additional sites necessary are often difficult to obtain. Moreover, difficulty is experienced in maintaining proper operation of the voltage regulators (where they exist) on the primary feeders when interconnected.

2.5.2 Secondary Distribution

Secondary distribution systems operate at relatively low utilization voltages and, like primary systems, involve considerations of service reliability and voltage regulation. The secondary system may be of four general types:

1. An individual transformer for each consumer; i.e., a single service from each transformer.

2. A common secondary main associated with one transformer from which a group of consumers is supplied.
3. A continuous secondary main associated with two or more transformers, connected to the same primary feeder, from which a group of consumers is supplied. This is sometimes known as *banking* of transformer secondaries.
4. A continuous secondary main or grid fed by a number of transformers, connected to two or more primary feeders, from which a large group of consumers is supplied. This is known as a *low-voltage* or *secondary* network.

Each of these types has its application to which it is particularly suited.

1. Individual Transformer-Single Service: Individual-transformer service is applicable to certain loads that are more or less isolated, such as in rural areas where consumers are far apart and long secondary mains are impractical, or where a particular consumer has an extraordinarily large or unusual load even though situated among a number of ordinary consumers.

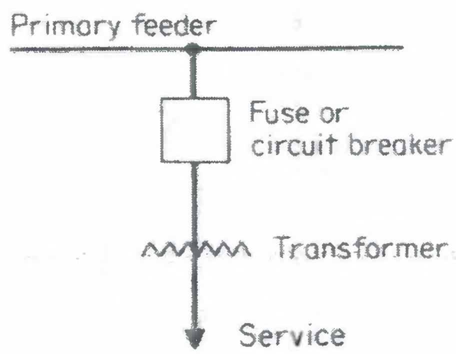


Figure 2-16 Single-service secondary supply.

In this type of system, the cost of the several transformers and the sum of power losses in the units may be greater (for comparative purposes) than those for one transformer supplying a group of consumers from its associated secondary main. The diversity among consumers' loads and demands permits a transformer of smaller

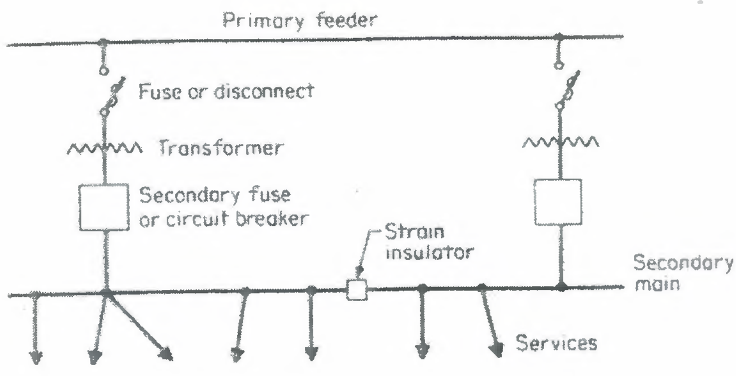


Figure 2-17 Common-secondary-main supply.

capacity than the capacity of the sum of the individual transformers to be installed. On the other hand, the cost and losses in the secondary main are obviated, as is also the voltage drop in the main. Where low voltage may be undesirable for a particular consumer, it may be well to apply this type of service to the one consumer. Refer to Fig. 2-16.

2. Common Secondary Main: Perhaps the most common type of secondary system in use employs a common secondary main. It takes advantage of diversity between consumer's loads and demands, as indicated above. Moreover, the larger transformer can accommodate starting currents of motors with less resulting voltage dip than would be the case with small individual transformers. See Fig. 2-17.

In many instances, the secondary mains installed are more or less continuous, but cut into sections insulated from each other as conditions require. As loads change or increase, the position of these division points may be readily changed, sometimes holding off the need to install additional transformer capacity. Also, additional separate sections can be created and a new transformer installed to serve as load or voltage conditions require.

3. Banked Secondaries: The secondary system employing banked secondaries is not very commonly used, although such installations exist and are usually limited to overhead systems.

This type of system may be viewed as a single-feeder low-voltage network, and the secondary may be a long section or grid to which the transformers are connected.

Fuses or automatic circuit breakers located between the transformer and secondary main serve to clear the transformer from the bank in case of failure of the transformer. Fuses may also be placed in the secondary main between transformer banks. See Fig. 2-18.

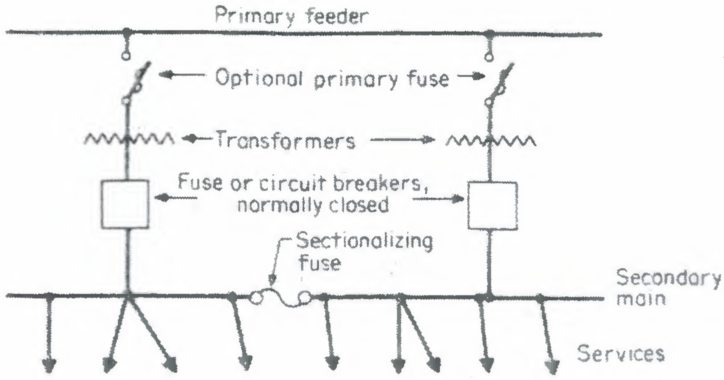


Figure 2-18 Banked secondary supply.

Some advantages claimed for this type of system include uninterrupted service, though perhaps with a reduction in voltage, should a transformer fail; better distribution of load among transformers; better normal voltage conditions resulting from such load distribution; an ability to accommodate load increases by changing only one or some of the transformers, or by installing a new transformer at some intermediate location without disturbing the existing arrangement; the possibility that diversity between demands on adjacent transformers will reduce the total transformer load; more capacity available for inrush currents that may cause flicker; and more capacity as well to burn secondary faults clear.

Some disadvantages associated with this type of system are as follows: should one transformer fail, the additional loads imposed on adjacent units may cause them to fail, and in turn their loads would cause still other transformers to fail (this is known as *cascading);* the transformers banked must have very nearly the same impedance and other characteristics, or the loads will not be distributed equitably among them; and sufficient reserve capacity must be provided to carry emergency loads safely, obviating the savings possible from the diversity of the demands on the several transformers.

Banked secondaries, while providing for failure of transformers, do not provide against faults on the primary main or feeder. Further, a hazard on any transformer disconnected for any reason may result from a back feed if the secondary energizes the primary (which may have been considered safe).

4. Secondary Networks: Secondary networks at present provide the highest degree of service reliability and serve areas of high load density, where revenues justify their cost and where this kind of reliability is imperative. In some instances, a single consumer may be supplied from this type of system by what are known as *spot networks.*

In general, the secondary network is created by connecting together the secondary mains fed from transformers supplied by two or more primary feeders. Automatically operated circuit breakers in the secondary connection between the transformer and the secondary mains, known as *network protectors,* serve to disconnect the transformer from the network when its primary feeder is de-energized; this prevents a back feed from the secondary into the primary feeder. This is especially important for safety when the primary feeder is deenergized from fault or other cause. The circuit breaker or protector is backed up by a fuse so that, should the protector fail to operate, the fuse will blow and disconnect the transformer from the secondary mains. See Fig. 2-19.

The number of primary feeders supplying a network is very important. With only two feeders, only one feeder may be out of service at a time, and there must be sufficient spare transformer capacity available so as not to overload the units remaining in service; therefore this type of network is sometimes referred to as a *single-contingency* network.

Most networks are supplied from three or more primary feeders, where the network can operate with the loss of two feeders and the spare transformer capacity can be proportionately less. These are referred to as *second-contingency* networks.

Secondary mains not only should be so designed that they provide for an equitable division of load between transformers and for good voltage regulation with all transformers in service, but they also must do so when some of the transformers are no longer in service when their primary feeders are deenergized. They must also be able to divide fault current properly among the transformers, and must provide for burning faults clear at any point while interrupting service to a minimum number of consumers; this often limits the size of secondary mains, usually to less than 500 cmil x 10^3, so that when additional secondary main capacity is required, two or more smaller size conductors have to be paralleled. In some networks, where insufficient fault current might cause long sections of secondary mains to be destroyed before the fault is burned clear, sections of secondary mains are fused at each end.

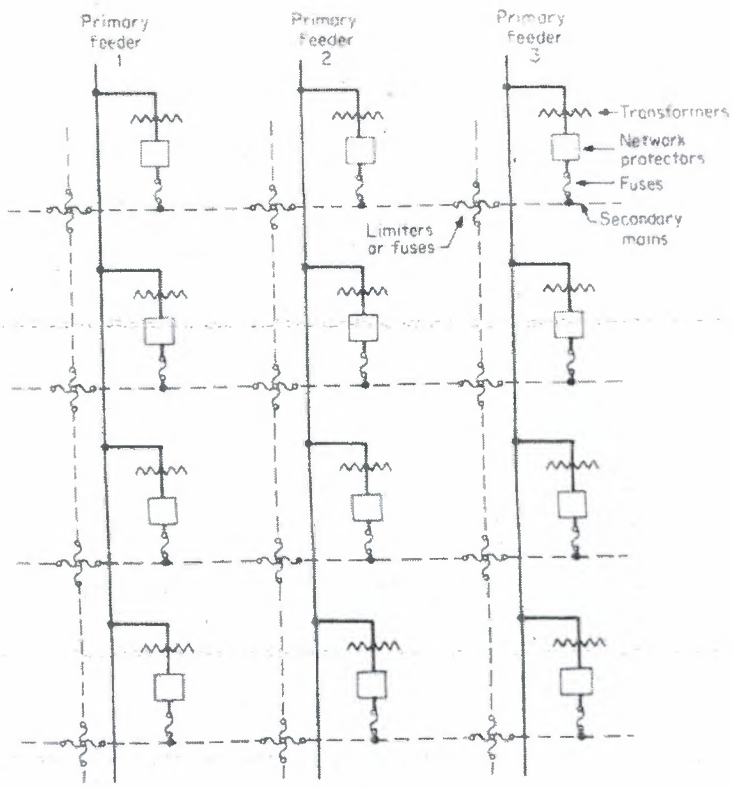


Figure 2-19 Low-voltage secondary network.

Because these networks may represent very large loads, their size and capacity may have to be limited to such values as can be successfully handled by the generating or other power sources should they become entirely deenergized for any reason. When they are deenergized for any length of time, the inrush currents are very large, as diversity among consumers may be lost, and this may be the limiting factor in restricting the size and capacity of such networks.

2.6 Primary and Secondary Voltages

For all types of service, primary voltages are becoming higher. Original feeder primary voltages of about 1000 V have climbed to nominal 2400, 4160, 7620, 13,800, 23,000, and 46,000 V. Moreover, primary feeders that originally operated as single-phase and two-phase circuits are all now essentially three-phase circuits; even those originally operated as delta ungrounded circuits are now converted to wye systems, with their neutral common to the secondary neutral conductor and grounded.

Secondary voltages have changed from nominal 110/220 V single-phase values to those now operating at 120/240 V single-phase and 120/208 or 120/240 V for three-phase circuits, the 120-V utilization being applied to lighting and small motor loads while the 208 and 240 V three-phase values are applied to larger motor loads. More recently, secondary systems have employed utilization voltage values of 277 and 480 V, with fluorescent lighting operating single-phase at 277 V and larger motors operating at a three-phase 480 V. To supply some lighting and small motors single-phase at 120 V, autotransformers of small capacity are employed to step down the 277 V to 120 V.

Chapter 3: DISTRIBUTION SUBSTATIONS AND EQUIPMENTS

Substations are used throughout an electrical system. Starting with the generating station, a substation raises the medium-voltage generated by the synchronous generators to the high-voltage needed to transmit the energy economically. The high transmission-line voltage is then reduced in those substations located close to the power consuming centers. The electrical equipment in such distribution substations is similar to that found in substations associated with generating plants.
The design of a distribution system is affected by the location and design of its supply substation. Indeed, the distribution substation is an integral part of the electrical distribution system.

3.1 Site Selection

The availability of land, annual costs, taxes, zoning laws, and environmental and public relations considerations are some of the factors that determine the ultimate location. The number and locations of the substations may affect the voltage selected for the primary distribution system. The fewer and farther apart the substations, the higher the primary voltage selected and the larger the loads supplied. Also, the length of distribution feeders (and the distance of consumers from the substation) and the number of consumers supplied from a feeder are reflected in the size of conductors, voltage-regulation measures, and equally important, the losses that may be incurred. Hence, the study of the most economical design of a distribution system must include substation and transmission supply costs as well as the effect of primary voltage on feeders, transformers, equipment, and methods of maintenance and operation.
In addition to the factors cited, other considerations should be taken into account in choosing a site for a substation:
1. It should be located as near as practical to the centers of the loads to be served; the summation of the loads (which are assumed to be concentrated at some points)

multiplied by their distances from the proposed substation site should be at a minimum.

2. It should be possible to supply the loads without undue voltage regulation and with available standard equipment.
3. Access for incoming transmission lines and outgoing distribution feeders should be available with a minimum of inconvenience, and should allow for future expansion of such facilities.
4. A shutdown of the substation should not affect an undue number of consumers; the substation location in relation to other, adjacent substations, both present and future, should permit ties to them in event of emergency.

3.2 General Design Features

Since the substation is the link between the transmission and distribution systems its continuous and uninterrupted operation is of prime importance. For this reason, multiple incoming supply feeders are provided, relays are installed to operate switches and circuit breakers automatically to disconnect faulted feeders and equipment, and spare equipment may be provided for rapid restoration of service in the event of failure.

3.2.1 Equipment Installation

Equipment may be connected in various arrangements by means of buses, switches, and circuit breakers. The arrangements are usually such as to insure safety to workers and reliability of operation, the usual arrangement in many substations permitting work on almost any piece of equipment without interruption to the incoming or outgoing feeders. The choice of arrangement is based on economics and the degree of reliability desired.

3.2.2 Insulation Coordination (BIL)

Circuit breakers and other equipment are subject to high-voltage surges resulting from lightning or switching operations and the insulation of their energized parts must be capable of withstanding them. Lightning or surge arresters are installed on the conductors and buses of each phase as close to the circuit breakers as practical, with the intent of draining off the voltage surge to ground before it reaches the breaker.
To provide adequate insulation economically and to restrict and localize possible damage to the circuit breaker, the insulation provided for the several parts is coordinated. Internal parts are insulated as equally as practical, but their insulation is

generally stronger than that of the bushings, which in turn is stronger than that of the "discharge" point of the associated arrester. Thus, a surge not drained to ground by the arrester will next tend to flash over at the bushings, outside the tank, where damage would be confined, comparatively light, and easier to repair. In general, the insulation of the weakest point in the circuit breaker should be weaker by such a margin as to ensure it will break down before the insulation of the principal equipment it is protecting.

The coordination of insulation requires the establishment of a basic insulation level (BIL) above which the insulation of the component parts of the system should be maintained, and below which lightning or surge arresters and other protective devices operate. Substation transformers also have their insulation coordinated with that of associated circuit breakers, buses, and other devices.

3.2.3 Protection Control

Instrument Transformers: The circuit breakers that serve to deenergize equipment require two sources of power for their proper operation: that which actuates the relays, and that which causes the mechanical operation of the equipment to take place.

The relays receive their actuating power (usually) from instrument transformers which measure the electrical quantities associated with the circuits or equipment they are to protect. These include current transformers, with a standard secondary current rating of 5 A, and, where a voltage input is required, potential transformers, with a standard secondary voltage rating of 120 V.

Auxiliary Circuits: While the instrument transformers furnish the power that actuates the protective relays, a separate source of auxiliary power is provided to operate the trip coils, solenoids, and motors that may be involved. This separate source of power must be as reliable as practical.

In substations in which the power supply bus is sectionalized into two or more parts, transformers supplying station power may be connected to two sections separated from each other, with the transformer supplying the auxiliaries connected to one section and the equipment connected to the other. In other instances, the station transformer may be equipped with a throwover switch, operated manually or automatically, in order to improve the reliability of the supply of auxiliary power.

Where reliability must be of the highest order, storage batteries, "floating" on the line, connected to an ac supply through rectifiers, are also installed to complement other power sources; here, the auxiliary circuit is a dc one.

In almost every instance, one or more of the distribution feeders supplied by the substation are so arranged in the field as to permit them to be energized from adjacent feeders emanating from a different substation. Should the entire substation become deenergized, such feeders may be utilized to reenergize the station power supply, enabling the circuit breakers and other equipment to be operated electrically. Where the substations involved are fed from different transmission or generating sources, care should be taken to avoid the interconnection of transmission and generating sources through the substation buses.

As a further precaution, control and auxiliary wiring systems are ungrounded and are provided with ground-detecting devices that actuate a light or alarm indicating the presence of a fault on the circuit involved. The auxiliary power supply may also supply some emergency station lighting.

3.2.4 Bus Design

***Electrical Considerations*:** The design of buses in a substation must take into account not only the current-carrying requirements under both normal and short-circuit conditions, but also voltage drops, power losses, and temperature rises (usually a maximum of 30°C above a 40°C ambient). The current-carrying ability of buses, especially for the higher-capacity and higher-voltage circuits, must also take into account the skin effect of the ac flowing through them. Also, where buses are very closely situated (between phases or between circuits), a proximity effect must also be considered which may further distort the distribution of the current flowing in the conductor and may affect the current-carrying ability of the bus.

Voltage drops must also take into account the reactance of the buses, including the self-reactance of the buses themselves (which may be affected by their shapes and composition) as well as the mutual reactance from adjacent buses.

The enclosure of buses, for fire or mechanical protection, may lower the current rating, since the heat generated by the I^2R losses is not as freely dissipated. Further, if the enclosures are metallic, or cause the buses to be spaced farther apart, reactance values may be changed, in turn affecting the voltage drop in the buses. Where individual-phase buses are separately enclosed, no part of the enclosure or any phase may form a loop of conductive material, since such a loop would form a short-circuited turn and would overheat under normal and fault-current flow in the bus.

***Mechanical Considerations*:** Buses are usually made of copper or aluminum. Their cross-sectional shapes may include flat bars (single, or several in parallel), tubing, channels, or hollow squares. Sections may be joined together by means of bolts or clamps, or may be brazed or welded together; at intervals, however, expansion-type joints are employed to take care of the expansion and contraction due to load cycles. The buses must also take into account the forces set up by short-circuit or fault currents that may flow through them (or in adjacent buses), as well as the voltage surges that may result from switching or lightning. The shape of the bus may provide sufficient rigidity and strength. They must also be supported on insulators capable of meeting both the electrical and mechanical requirements. Bus supports specified, therefore, usually include a fairly large safety factor, between 2 and 4.

Current transformers that are connected in these circuits must also withstand both the electrical and mechanical forces imposed on them.

3.2.5 Substation Electrical Grounds

Grounding at a substation is of the greatest importance. Because of the strong alternating magnetic fields set up by the heavy short-circuit currents that may flow in the several elements, voltages of appreciable values may be induced in the metallic structural members, in the equipment tanks and their supporting frames, in metal conduits for power and communication circuits, in metal fences, etc. All of these must be grounded, preferably to a common ground. The ground connections of the surge arresters, as well as the neutral conductors of the feeders, both incoming and outgoing, and of the grounded wye-connected transformers (if any), should also be connected to the common ground.

Draining of the induced voltages to ground prevents dangerously high voltage rises from forming, especially in the vicinity of the substation during fault conditions.

Grounds may consist of a multitude of metal rods driven into the ground at frequent locations and connected together, or of a mesh buried (usually) beneath the substation. The number, spacing, size, and depth of burial of the conductor making up the mesh will depend on the nature of the soil and the ground resistance desired. Both rods and mesh may be installed and connected together.

3.3 Substation Construction

Distribution substations may be constructed entirely indoors, entirely outdoors or in a combination of the two ways.

***Indoor*:** In purely indoor construction, all the equipment is completely enclosed within a structure, protected from the weather. Measures are taken to ensure that the failure of a piece of equipment does not spread and involve other units. Reinforced concrete fire and explosion-resistant walls or barriers are installed between major pieces of equipment, such as transformers, circuit breakers, and regulators. Sumps are usually provided beneath oil-filled equipment and connected to waste lines where they exist. The sumps should be of ample size to contain all of the oil in the equipment should its failure result in an oil spill. Control equipment, switchboards, batteries (if any), and other communication facilities may be located in separate fireproof compartments. Automatic fire-extinguishing systems may be installed to smother any oil fire that may ensue; foam, carbon dioxide, a high-pressure fine spray of water, and other materials may be specified.

Ventilation may be by natural circulation of air, or by means of fans that may operate at peak load periods or when the internal ambient temperature exceeds a predetermined value.

In general, the rating and capacity of the equipment, particularly transformers and circuit breakers, may be lower than for similar units installed outdoors. On the other hand, the units need not provide for inclement weather conditions (e.g., bushings may have shorter creepage distances, tanks need not be watertight, etc.).

Provision, in the form of rails, rollers, or other devices, is made to permit the replacement of the several pieces of equipment. Space around each unit is provided to permit safe access for the maintenance, repair, or replacement of the unit.

The architecture of the exterior should blend with the surroundings, as should the associated landscaping, lawns, or other environmental prerequisites. Incoming and outgoing feeders are installed underground, out of sight.

***Outdoor*:** Outdoor substations have all of the equipment located outdoors within a securely fenced off area. Here, too, provisions are made for the maintenance, repair, and replacement of the pieces of equipment. Sumps may be constructed beneath a unit, in the form of dikes or pits containing coarse gravel or crushed stone, of a sufficient volume to hold possible oil spillage from the unit. Depending on the availability of land

and the spacing between units, fire walls between major units may be found desirable. Transformers, circuit breakers, and other outdoor equipment are designed to operate in all kinds of weather. Tanks are usually hermetically sealed or are equipped with "breathing" devices; bushings and insulators have creepage paths sufficiently long to prevent flashover. Control facilities may be located in sealed compartments either associated with each unit or grouped together in outdoor-type housing. Small strip heaters may be required to keep condensation from forming in the compartments.
The location of the outdoor substation may present serious environmental problems. These include appearance; sometimes extensive and expensive landscaping is required to conceal the substation partially or entirely from neighboring observers. Another source of objection may be the sound emanating from the transformers; sound barriers then have to be erected around those units to deflect or mitigate the sound emissions in a particular direction.
***Combination Indoor and Outdoor*:** In the combined indoor and outdoor arrangement, the major units, usually the transformers only (with their associated surge arresters), but sometimes circuit breakers also, are located outdoors, and the remaining equipment is housed in a building of some kind. The requirements already outlined should be followed in connection with each portion of the substation. Such substations are located in areas where appearances may not be a major consideration and some equipment, sometimes concealed by landscaping, may be found acceptable.

3.3.1 Unit Substations

Unit substations are small, self-contained, metal-clad units, usually installed in residential areas where larger sites are unobtainable. They are usually well landscaped, and their incoming and outgoing feeders are placed underground. Primary feeders from one unit substation extend to meet those from other, adjacent unit substations so that, when one unit substation is out of service, its load can be picked up by the feeders from the adjacent unit substations. Each unit substation, therefore, must be designed with spare capacity to enable this transfer of load to be made during contingency conditions.

3.3.2 Mobile Substations

Substations are often designed for three single-phase transformers so that, where they are connected in delta on the incoming side, they can operate in open delta in the event of

failure of one of the units. In some instances, a spare single-phase transformer is installed at the substation so that, in the event of failure of one of the transformers, a replacement can be made readily.
With the advent of lighter transformers and improved transportation equipment, it has proven practical to mount a three-phase transformer and associated switching and surge arresters on a trailer especially designed for that purpose. Such a mobile substation can be readily transported to a substation where a failure has occurred. The terminal arrangements of both the mobile substation and the fixed substation are so designed that often service can be restored more quickly than by reconnecting the spare unit (which no longer need be provided) The mobile substation not only can be effective where the failure may involve more than one transformer, but can service a number of substations in a more economical fashion than the installation of spare transformers at many, if not all, substations. Further, it may also be installed as a separate, temporary substation, picking up portions of the load of one or more substations whose facilities may be overloaded.

3.4 One-Line Diagrams Of Connections

The connection of apparatus in a substation is usually drawn in the form of a "one-line diagram" for convenience and simplicity. Inasmuch as all the phase connections in a polyphase system are alike, it is only necessary to show the connections for one phase to indicate the simultaneous operation (as nearly as practical) of all the phases.
There are two types of one-line diagrams. The first, usually referred to as an operating diagram, merely indicates all the major equipment and connections, with such pertinent information as will enable the engineer, field supervisor, and operator to call for and complete the desired switching.
The second type is an elaboration of the first and includes additional information, such as fusing, relaying, and location and rating of instrument transformers and other auxiliary equipment. Such a diagram lends itself to rapid analysis in the event of improper operation of equipment.

3.5 Substation equipment

A medium-voltage substation usually contains the following major apparatus:
Transformers, Circuit breakers, Surge arresters, Current-limiting reactors, Relays and

protective devices, Horn-gap switches, Disconnect switches and Grounding switches.
In the description which follows, we study the basic principles of this equipment. Furthermore, to understand how it all fits together, we conclude our study with a typical substation that provides power to a large suburb.

3.6 Transformers

Substation transformers function in a manner similar to distribution transformers, but have significant differences in their construction and operation. Features shared by both categories include the usual employment of oil (sometimes air or askarels) for insulating and cooling purposes, taps for changing the ratio of transformation, and insulation coordination together with basic insulation levels. Transformers may be of the single-phase or three-phase types.
Substation transformers, and especially the polyphase units, are usually constructed with shell-type cores which surround the windings, as compared with the usual distribution transformer, in which the windings surround the core.
Substation transformers are usually wound for additive polarity, in accordance with EEI, NEMA, and other standards, as contrasted with the subtractive polarity of distribution transformers.
The bushings of substation transformers on the low-voltage side are usually made of porcelain and are similar to the primary bushings found on distribution transformers, but of greater current-carrying capacity. The high-voltage-side bushing, however, in addition to the greater current-carrying capability, depending on the magnitude of the voltage, may consist of a solid porcelain cylinder (with petticoats) as insulation for voltages up to about 35 kV, or an oil-filled hollow porcelain cylinder for values up to about 69 kV; for 69 kV and higher voltages, the hollow porcelain cylinder may contain layers of oil-impregnated paper insulation with metal foil inserted at several locations among the layers, forming a series of capacitors which serve to even out and equalize the electrostatic stresses set up within the bushing; (Fig. 3-1). Other high-voltage bushings may be filled with an inert gas such as sulfur hexafluoride (SF_6).
Like distribution transformers designed for line-to-ground operation, single-phase transformers may have only one bushing on both the high- and low-voltage sides; three-phase transformers may have only three high- and three low-voltage bushings, with a neutral stud as a common terminal for both high- and low-voltage windings.

Substation transformers may also show evidence of greater precaution taken in keeping air and moisture from the oil. In some units, an inert gas, such as nitrogen, fills the space above the oil, and the transformer tank is sealed. A "relief diaphragm" is sometimes installed in a vent in the sealed transformer which ruptures when the internal pressure exceeds some predetermined value, indicating possible deterioration of the insulation. In some units, a pressure relay is installed to give an indication of pressure rise in the tank.

Some outdoor units are equipped with a tank on top of the transformer, called a *conservator,* in which the expansion and contraction of the oil takes place. The tank is sometimes open to the atmosphere through a breathing device. The condensation of moisture and the formation of sludge take place in the tank, which is also provided with a sump from which the condensation and sludge may be drawn off. (Fig 3-2).

Substation transformers may be equipped with fins or radiators to enhance the ability of the transformers to dissipate the heat generated by their copper and iron losses. Both the fins and

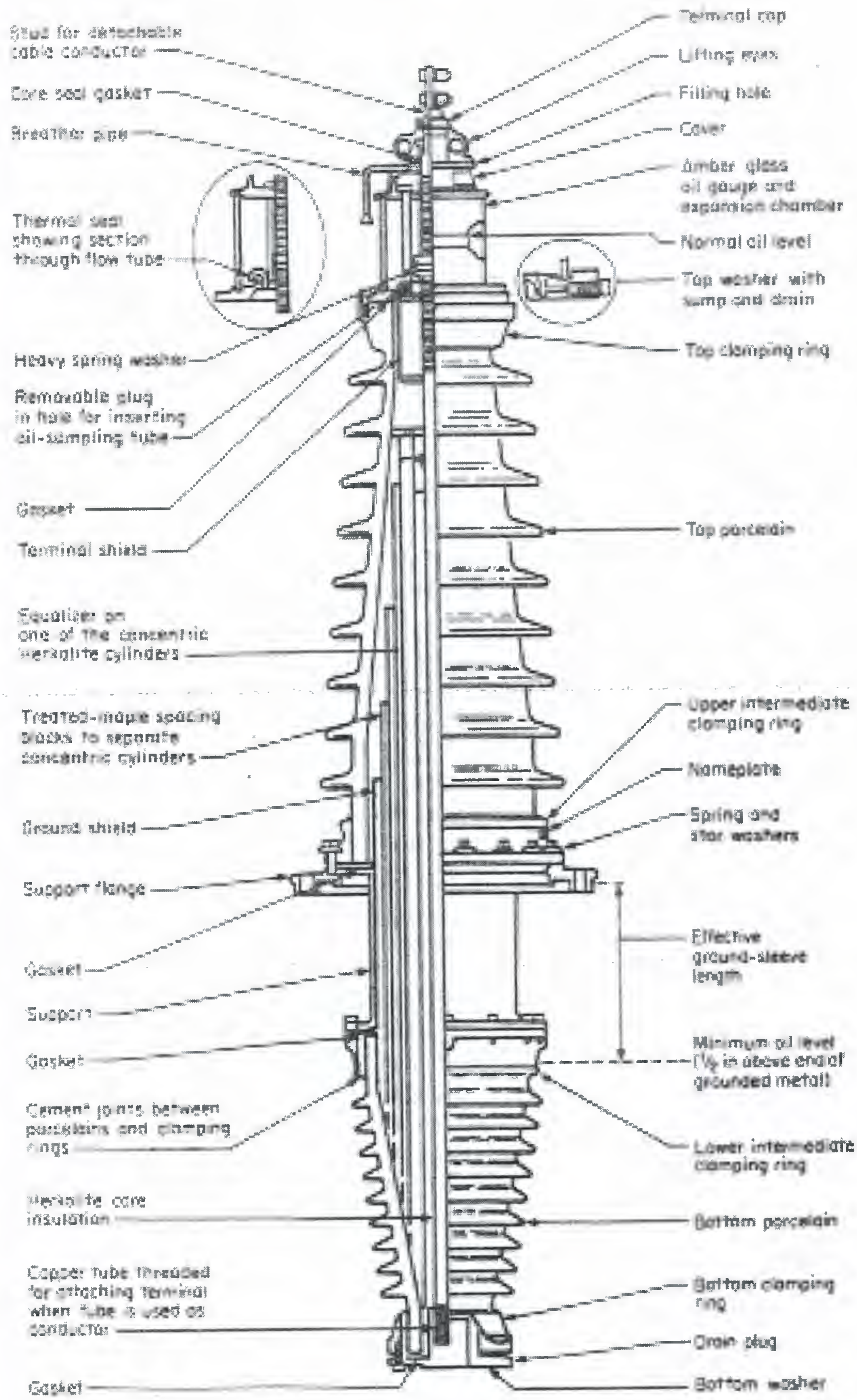


Figure 3.1 Typical Oil-filled bushing for a 69-KV transformer.

the radiators increase the surface area transferring heat to the atmosphere. The radiator, in addition, increases the natural circulation of oil by the convection currents set up within the unit. This cooling capability may be further increased by fans blowing against the fins and radiators, increasing the rate of heat transfer to the surrounding atmosphere. Further cooling may be obtained by pumps forcibly increasing the rate of circulation of oil in the radiators. Both means are often used together. In some cases, resort is had to water cooling by means of pipes installed within the transformer tank through which water is circulated, or by means of an external heat exchanger through which the hot oil and water are separately circulated with the aid of pumps.

In addition to the voltage classification, substation transformers may have several ratings expressed in kVA, each rating associated with the type of cooling employed: a normal rating with no added means of cooling; a higher rating with forced air or forced oil circulation; and a still higher rating when both means are used in combination; for example, 10,000 kVA; 12,000 kVA-FA; 15,000 kVA-FA/FO. Ratings may also include permissible noise levels at maximum loads, expressed in decibels at standard distances from the unit.

The impedance of substation transformers is usually higher than that of distribution transformers in order to hold down the current that may flow during a fault on the system connected to its low side.

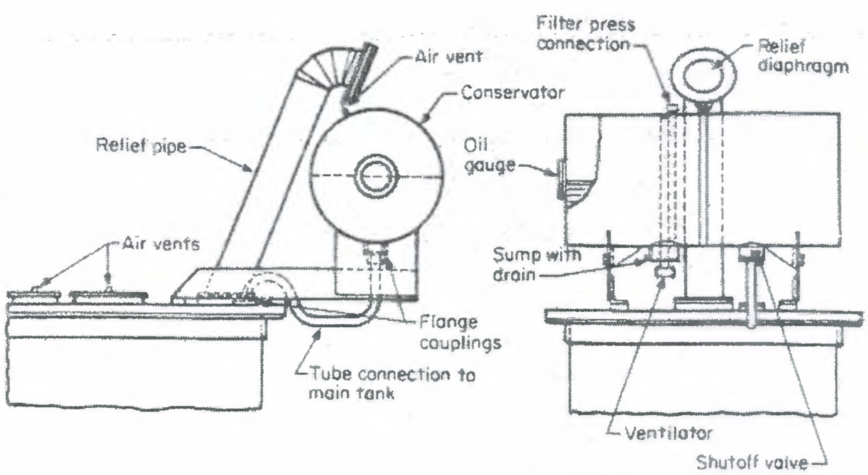


Figure 3-2 Diagram showing main features of a conservator.

We sometimes have to create a neutral on a 3-phase, 3-wire system, to change it into a 3-phase, 4-wire system. This can be done by means of a *grounding* transformer. It is basically a 3-phase autotransformer in which identical primary and secondary windings are connected in series in zigzag fashion on a 3-legged core (Fig. 3-3).

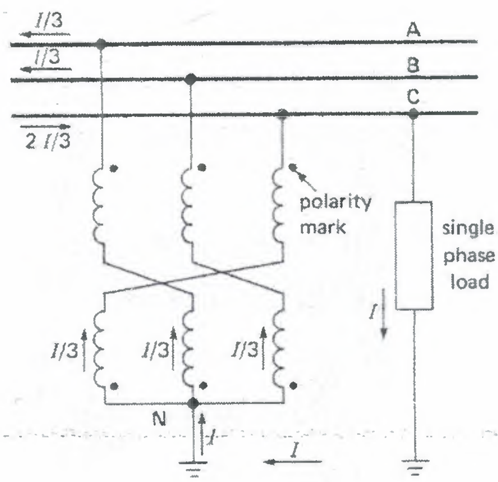


Figure 3.3 Grounding transformer to create a neutral.

If we connect a single-phase load between one line and neutral, load current / divides into three equal currents 7/3 in each winding. Because the currents are equal, the neutral point stays fixed and the line-to-neutral voltages remain balanced as they would be on a regular 4-wire system. In practice, the single-phase loads are distributed as evenly as possible between the three phases and neutral so that the unbalanced load current/remains relatively small.

3.7 Circuit-breakers

Circuit-breakers are designed to interrupt either normal or short-circuit currents. They behave like big switches that may be opened or closed by local push-buttons or by distant telecommunication signals emitted by the system of protection. Thus, circuit-breakers will automatically open a circuit whenever the line current, line voltage, frequency, etc., departs from a preset limit.

The most important types of circuit-breakers are:

1. Oil circuit-breakers (OCB's);
2. Air-blast circuit-breakers;
3. SF_6 circuit-breakers;
4. Vacuum circuit-breakers.

The nameplate on a circuit breaker usually indicates (1) the maximum steady-state current it can carry, (2) the maximum interrupting current, (3) the maximum line voltage, and (4) the interrupting time in cycles. The interrupting time may last from 3 to 8 cycles on a 60 Hz system. To interrupt large currents this quickly, we have to ensure rapid deionization of the arc, combined with rapid cooling. High-speed interruption limits the damage to transmission lines and equipment and, equally important, it helps to maintain the stability of the system when a contingency occurs.

The triggering action which causes a circuit-breaker to open is usually produced by means of an overload relay that can detect abnormal line conditions. For example, the relay coil in Figure 3-4 is connected to the secondary of a current transformer. The primary carries the line current of the phase that has to be protected. If the line current exceeds a preset limit, the secondary current will cause relay contacts C_1C_2 to close. As soon as they close, the tripping coil is energized by an auxiliary dc source. This causes the main line contacts to open, thus interrupting the circuit.

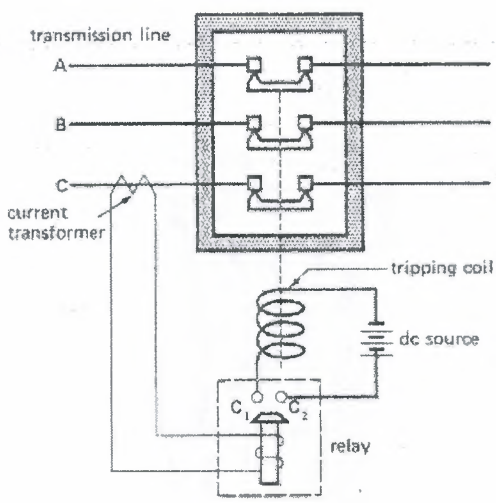


Figure 3-4 Elementary tripping circuit for a circuit-breaker.

1. Oil circuit-breakers: Oil circuit-breakers are composed of a steel tank filled with insulating oil. In one version (Fig. 3-5), three porcelain bushings channel the 3-phase line currents to a set of fixed contacts. Three movable contacts, actuated simultaneously by an insulated rod, open and close the circuit. When the circuit-breaker is closed, the line current for each phase penetrates the tank by way of one porcelain bushing, flows through the first fixed contact, the movable contact, the second fixed contact, and then on out by a second bushing. If an overload occurs, the tripping coil releases a powerful spring which pulls on the insulated rod, causing the contacts to open. As soon as the contacts separate, a violent arc is created, which volatilizes the surrounding oil. The pressure of the hot gases creates turbulence around the contacts. This causes cool oil to swirl around the arc, thus extinguishing it. In modern high-power breakers, the arc is confined to an explosion chamber so that the pressure of the hot gases produces a powerful jet of oil. The jet is made to flow across the path of the arc, to extinguish it. Other types of circuit-breakers are designed so that the arc is deflected and lengthened by a self-created magnetic field. The arc is blown against a series of insulating plates that break up the arc and cool it down. Figures 3-6 and 3-7 show the appearance of two typical OCB's.

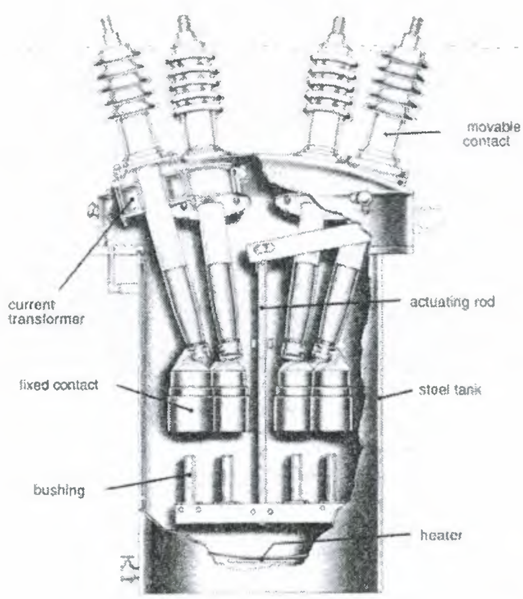


Figure 3-5 Cross section of an oil circuit-breaker. The diagram shows four of the six bushings; the heater keeps the oil at a satisfactory temperature during the cold weather.

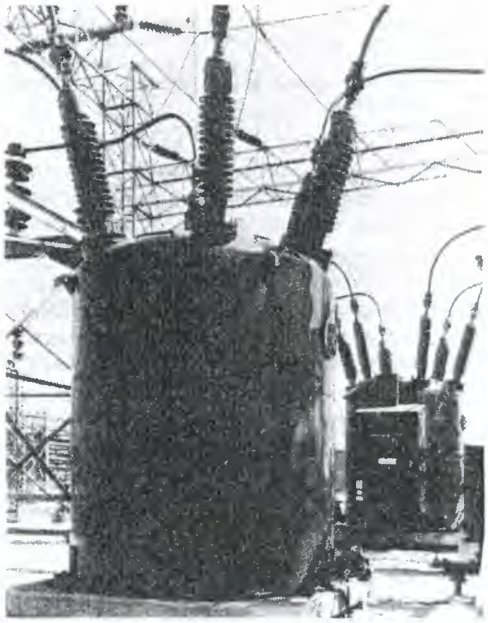


Figure 3-6 Three-phase oil circuit-breaker rated at 1200 A at 115 KV. It can interrupt a current of 50 KA in 3 cycles on a 60 Hz system.

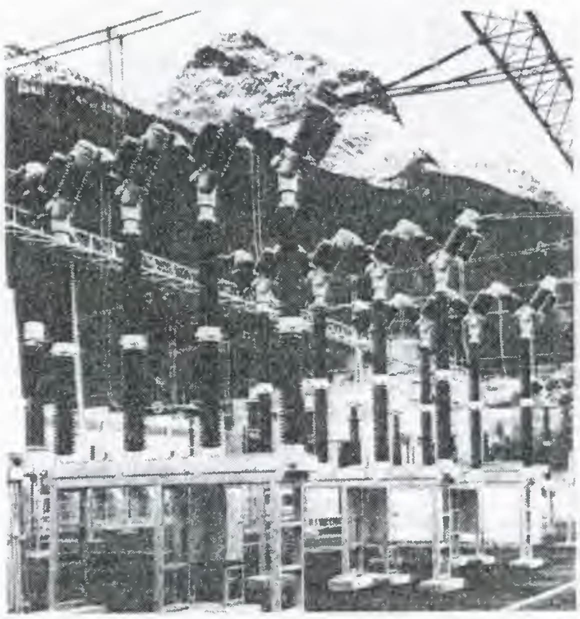


Figure 3-7 Minimum oil circuit-breaker installed in a 420 kV, 50 Hz substation. Rated current: 2000 A; rupturing capacity: 25 kA; height (less support): 5400 mm; length: 6200 mm; 4 circuit breaking modules in series per circuit-breaker.

2. Air-blast circuit-breakers: These circuit-breakers interrupt the circuit by blowing compressed air at supersonic speed across the opening contacts. Compressed air is stored in reservoirs at a pressure of about 3 MPa (~ 435 psi) and is replenished by a compressor located in the substation. The most powerful circuit-breakers can typically open short-circuit currents of 40 kA at a line voltage of 765 kV in a matter of 3 to 6 cycles on a 60 Hz line. The noise accompanying the air blast is so loud that noise-suppression methods must be used when the circuit-breakers are installed near residential areas. Figure 3-8 shows a typical 3-phase air-blast circuit-breaker. Each phase is composed of three contact modules connected in series.

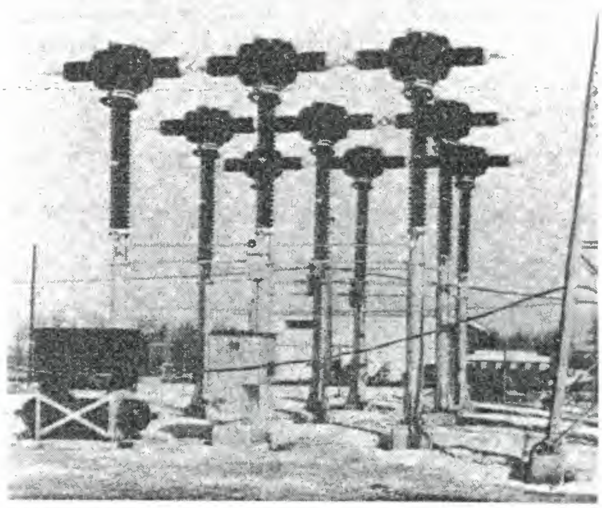


Figure 3-8 Air blast circuit-breaker rated 2000 A at 362 kV. It can interrupt a current of 40 kA in 3 cycles on a 60 Hz system. It consists of 3 identical modules connected in series, each rated for a nominal voltage of 121 kV. The compressed-air reservoir can be seen at the left. Other characteristics: height: 5640 mm; overall length: 9150 mm; BIL 1300 kV.

4. **SF_6 circuit-breakers:** These totally enclosed circuit-breakers, insulated with SF_6 gas, are used whenever space is at a premium, such as in downtown substations (Fig. 3-9). They are much smaller than any other type of circuit-breaker of equivalent power and

are far less noisy than air circuit-breakers.

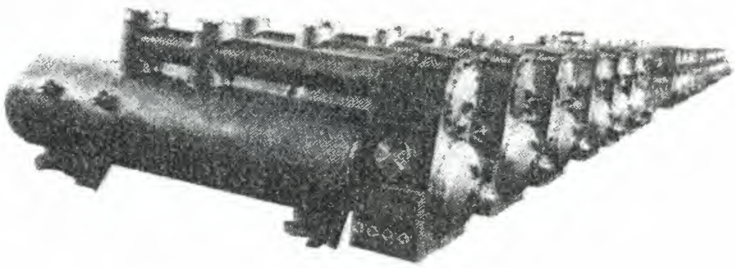


Figure 3-9 Group of 15 totally enclosed SF_6 circuit breakers installed in an underground substation of a large city. Rated current: 1600 A; rupturing current: 34 kA; normal operating pressure: 265 kPa (38 psi); pressure during arc extinction: 1250 kPa (180 psi). These SF_6 circuit-breakers take up only 1/16 of the volume of conventional circuit-breakers having the same interrupting capacity.

4. Vacuum circuit breakers: These circuit-breakers operate on a different principle from other breakers because there is no gas to ionize when the contacts open. They are hermetically sealed; consequently, they are silent and never become polluted (Fig. 3-10). Their interrupting capacity is limited to about 30 kV. For higher voltages, several circuit-breakers are connected in series.

Vacuum circuit-breakers are often used in underground systems.

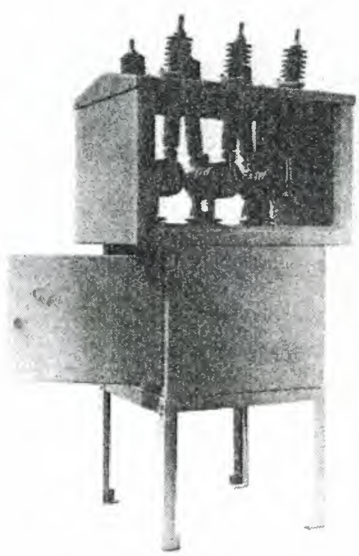


Figure 3-10 Three-phase vacuum circuit-breaker having a rating of 1200 A at 25.8 kV. It can interrupt a current of 25 kA in 3 cycles on a 60 Hz system. Other characteristics: height: 2515 mm; mass: 645 kg; BIL: 125 kV.

3.8 Air-break switches

Air-break switches can interrupt the exciting currents of transformers, or the moderate capacitive currents of unloaded transmission lines. They cannot interrupt normal load currents.

Air-break switches are composed of a movable blade that engages a fixed contact. Two arcing horns are attached to the fixed and movable contacts, so that when the main contact is broken, an arc is set up between the arcing horns. The arc moves upward due to the combined action of the hot air currents it produces and the magnetic field. As the arc rises, it becomes longer until it eventually blows out (Fig. 3-11). Although the arcing horns become pitted and gradually wear out, they can easily be replaced.

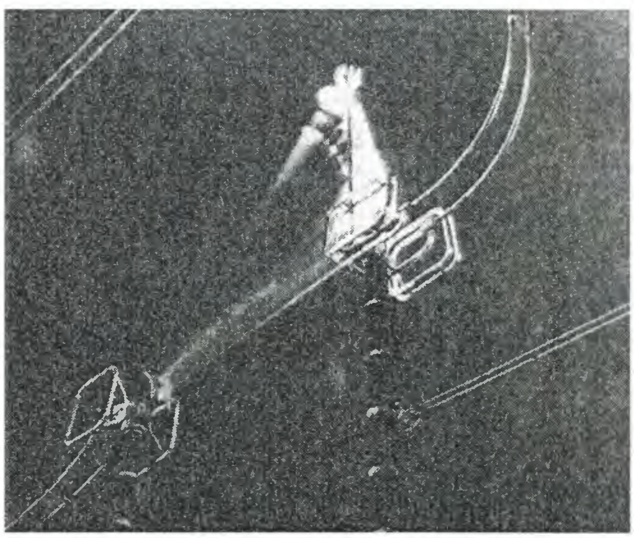


Figure 3-11 The arc produced between the horns of a disconnecting switch as it cuts the exciting current of a HV transformer provides the light to take this night picture.

3.9 Disconnecting switches

Unlike air-break switches, disconnecting switches are unable to interrupt any current at all. They must only be opened and closed when the current is zero. They are basically isolating switches, enabling us to isolate oil circuit-breakers, transformers, transmission lines, and

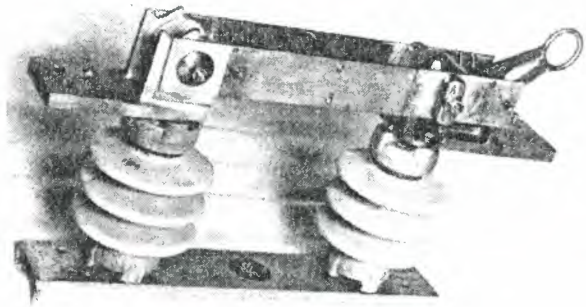


Figure 3-12 This hookstick-operated disconnecting switch is rated 2000 A, 15 KV and has a BIL of 95 KV.

so forth, from a live network. Disconnecting switches are essential to carry out maintenance work and to reroute power flow.

Figure 3-12 shows a 2000 A, 15 kV disconnecting switch. It is equipped with a latch to prevent the switch from opening under the strong electromagnetic forces that accompany short-circuits. The latch is disengaged by inserting a hookstick into the ring and pulling the movable blade out of the fixed contact.

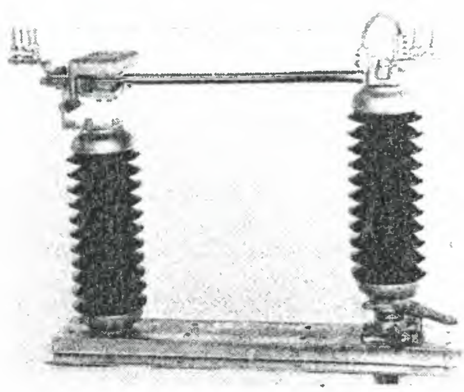


Figure 3-13 Disconnecting switch rated 600 A, 46 KV for sidewise operation.

3.10 Grounding switches

Grounding switches are safety switches that ensure a transmission line is definitely grounded while repairs are being carried out. Figure 3-14 shows such a 3-phase switch with the blades in the open (horizontal) position. To short-circuit the line to ground, all three grounding blades swing up to engage the stationary contact connected to each phase. Grounding switches are opened and closed only after the lines are de-energized.

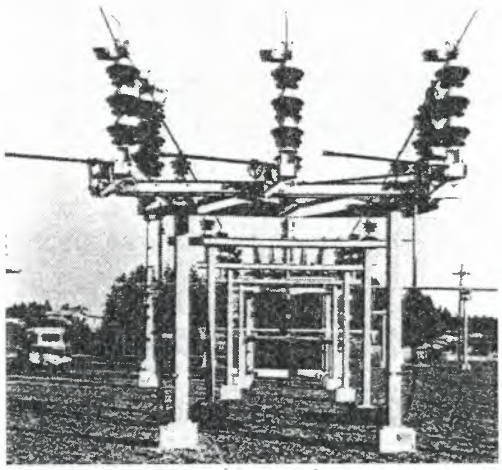


Figure 3-14 Combined disconnecting switch and grounding switch rated at 115 KV.

3.11 Surge arresters

The purpose of a surge arrester (also called lightning arrester or surge diverter) is to limit the overvoltages that may occur across transformers and other electrical apparatus due either to lightning or switching surges. The upper end of the arrester is connected to the line or terminal that has to be protected, while the lower end is solidly connected to ground. The arrester is composed of an external porcelain tube containing an ingenious arrangement of stacked discs, air gaps, ionizers, and coils. The discs (or valve blocks) are composed of a silicon carbide material known by trade names such as thyrite®, autovalve®, etc. This material has a resistance that decreases dramatically with increasing voltage. The typical E-I characteristic of a surge arrester is given in Figure 3-15.

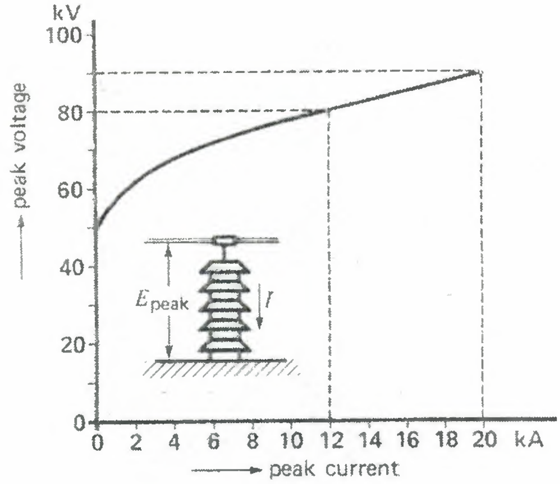


Figure 3-15 Voltage-current characteristic of a surge arrester having a nominal rating of 30 kV (42.4 kV peak), used on a 34.5 kV line.

Under normal voltage conditions, spark gaps prevent any current from flowing through the tubular column. If an overvoltage occurs, the spark gaps break down and the surge discharges to ground. The 60 Hz follow-through current is limited by the resistance of the valve blocks and the arc is simultaneously stretched and cooled in a series of arc chambers. The arc is quickly snuffed out and the arrester is then ready to protect the line against the next voltage surge. The discharge period is very short, rarely lasting more than a fraction of a millisecond.

Zinc-oxide arresters are also used. They are composed of stacked circular discs enclosed in a porcelain tube. The *E-I* characteristics are similar to those of silicon-carbide arresters. However, ZnO arresters do not require air gaps or other auxiliary devices.

Lightning arresters also enable us to reduce the BIL requirements of apparatus installed in substations. On HV and EHV systems, the reduction in BIL significantly reduces the cost of the installed apparatus. Figure 3-16 shows a lightning arrester installed in an EHV substation.

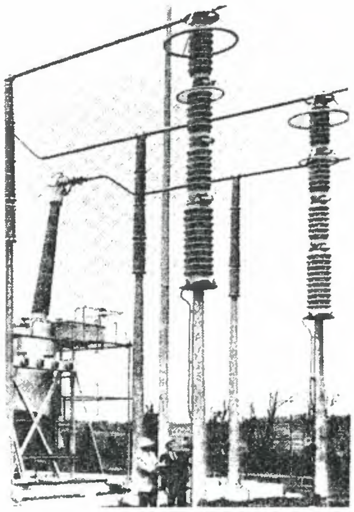


Figure 3-16 Surge arresters protect this EHV transformer.

3.12 Current-limiting reactors

The MV bus in a substation usually energizes several feeders which carry power to various load centers around the substation. It so happens that the output impedance of the MV bus is usually very low. Consequently, if a short-circuit should occur on one of the feeders, the resulting short-circuit current can be disastrous.

Consider, for example, a 3-phase 69 MVA, 220 kV/24.9 kV transformer having an impedance of 8% and a nominal secondary current of 1600 A. It supplies power to eight 200 A feeders connected to the common MV bus (Fig. 3-17). Each feeder is protected by a 24.9 kV, 200 A circuit-breaker having an interrupting capacity of 4000 A. Because the transformer impedance is 8%, it can deliver a secondary short-circuit current of:

$$I = 1600 \times (1/0.08) = 20\ 000 \text{ A}$$

This creates a problem because if a feeder becomes short-circuited, the resulting current flow could be as high as 20 000 A, which is 5 times greater than the interrupting capacity of the circuit-breaker. The circuit-breaker could be destroyed in attempting to interrupt the circuit. Furthermore, the feeder might burn over its entire length, from the circuit-breaker to the fault. Finally, a violent explosion would take place at the fault itself owing to the tremendous amount of thermal energy released by the burning arc.

To prevent this from happening, a current-limiting reactor is connected in series with each phase of the feeder (Fig. 3-18). The reactance must be high enough to keep the current below the interrupting capacity of the circuit-breaker, but not so high as to produce a large voltage drop under normal full-load conditions. Figure 3-19 shows three current-limiting reactors in series with a HV line.

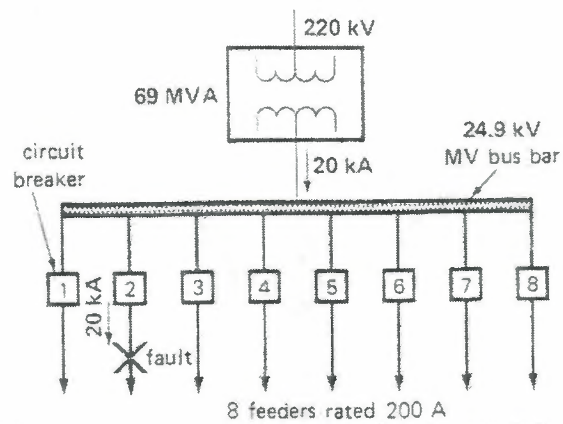


Figure 3-17 MV bus bar feeding 8 lines, each protected by a circuit-breaker.

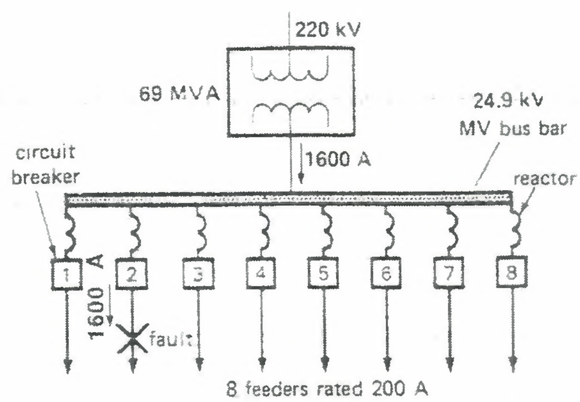


Figure 3-18 Current-limiting reactors reduce the short-circuit current.

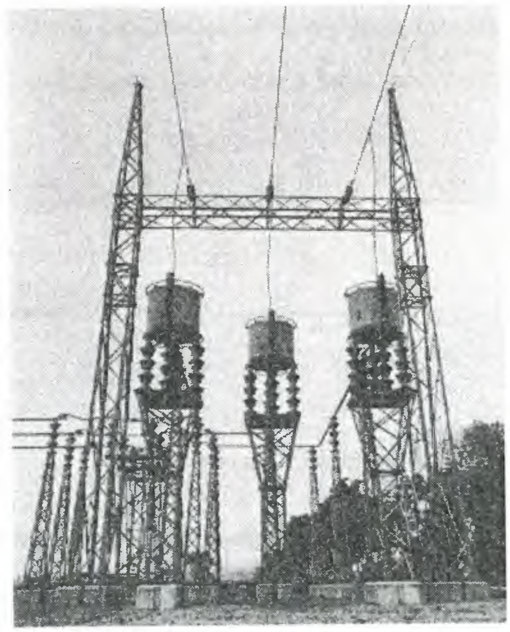


Figure 3-19 Three 2.2 Ω reactors rated 500 A are connected in series with a 120 kV, 3-phase, 60 Hz line. They are insulated from ground by four insulating columns and each is protected by a surge arrester.

3.13 Example of a substation

Figure 3-20 shows the principal elements of a typical modern substation providing power to a large suburb. Power is fed into the substation at 220 kV and is distributed at 24.9 kV to various load centers within about a 5 km radius.

The substation is fed by 3 different lines, all operating at 220 kV. It contains six 3-phase transformers rated at 36/48/60 MVA, 220 kV/24.9 kV. The windings are connected in wye-delta and automatic tap-changers regulate the secondary voltage.

A neutral is established on the MV side by means of 3-phase grounding transformers. Consequently, single-phase power can be provided at $24.9/\sqrt{3} = 14.4$ kV.

Minimum-oil circuit-breakers having an interrupting capacity of 32 kA protect the HV side. Conventional oil circuit-breakers having an interrupting capacity of 25 kA are used on the MV side. Furthermore, all the outgoing feeders are protected by circuit-breakers having an interrupting capacity of 12 kA.

This completely automatic and unattended substation covers an area of 235 m x 170 m. However, line switching and other operations can be carried out by telecommunications from a dispatching center.

The substation provides service to hundreds of single-family homes, dozens of apartment buildings, several business and shopping centers, a large university and some industries.

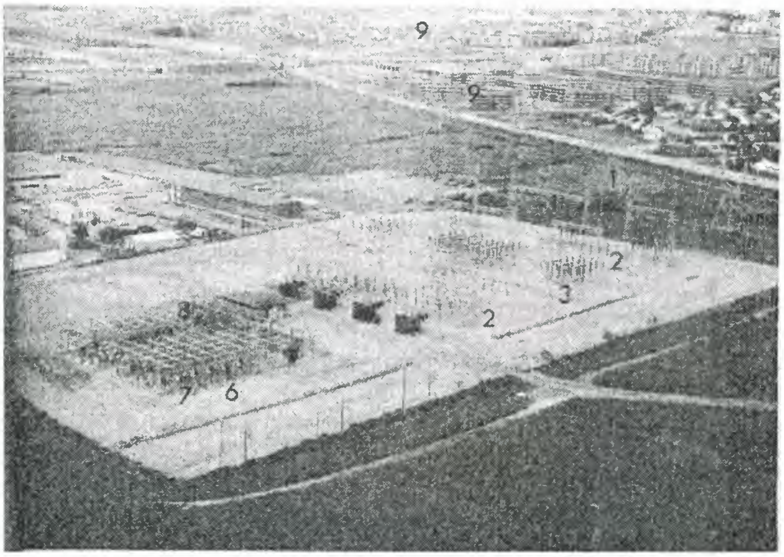


Figure 3-20 Aerial view of a substation serving a large suburb. The 220 kV lines (1) enter the substation and move through disconnecting switches (2) and circuit-breakers (3) to energize the primaries of the transformers (4). The secondaries are connected to a MV bus (5) operating at 24.9 kV. Grounding transformers (6) and MV circuit-breakers (7) feed power through current limiting reactors (8). The power is carried away by 36 aerial and underground feeders to energize the suburb (9).

Chapter 4: Load Characteristics

A load study is the determination of the voltage, current, power and power factor or reactive power at various points in an electric network under existing or contemplated conditions of normal operation. Load studies are essential in planning the future development of the system because satisfactory operation of the system depends on knowing the effects of interconnections with other power systems of new loads, new generating stations, and new transmission lines before they are installed.

In the planning of an electrical *distribution system*, as in any other enterprise, it is necessary to know three basic things:

1. The quantity of the product or service desired (per unit of time)
2. The quality of the product or service desired
3. The location of the market and the individual consumers

Logically, then, it would be well to begin with the basic building blocks, the individual consumers, and then determine efficient means of supplying their wants, individually and collectively.

4.1 Connected Loads

A good place to start is the tabulation of all electric devices (lamps, appliances, equipment, etc.) that consumers can connect to their supply system. The ratings of the devices at specified voltages (and sometimes frequency and temperature) limits are usually contained in the nameplate or other published data accompanying the devices. The devices can be classified into four broad general categories:

Each of these has different characteristics and requirements

4.1.1 Lighting Loads

Included under lighting are incandescent and fluorescent lamps, neon lights, and mercury vapor, sodium vapor, and metal halide lights. Nominal voltages specified for lighting are usually 120, 240, and 277 Volts (variations may exist from the base 120-V value, e.g., 115 and 125 V). All operate with dc or single-phase ac; the discussion will be in terms of ac, with comments concerning dc operation where applicable.

(a) Incandescent Lighting

Incandescent lamps operate at essentially unity power factor. Their light output drops considerably at reduced voltage, being some 16 percent less with a 5 percent lowered voltage, and decreasing at a geometrically faster rate from then on. They are also sensitive to sudden rapid voltage variations, producing a noticeable (and annoying) flicker at variations of as little as 3 Volts (on a 120-V base). Street lighting of the incandescent type can be operated in a multiple or a series fashion. The former operates as other lighting in a multiple or parallel circuit, while the light output for the series type depends on the amount of deviation from the standard value of current flowing through it (usually 6.6, 15, or 20 A); it is sensitive to variations of as little as 1 percent in the value of the current. The life of incandescent lamps is considerably reduced at voltages appreciably above normal.

(b) Fluorescent and Neon Lighting

Fluorescent lamps and neon lights operate at power factors of about 50 percent, but usually have corrective capacitors included so that, for planning purposes, they may also be considered to operate at 100 percent or unity power factor. Their light output, per unit input of electrical energy, is considerably greater (25 percent or more) than that of a similarly rated incandescent lamp. The life of fluorescent lamps and neon lights is affected by the number of switching operations they undergo. If fluorescent lamps are used on dc circuits, special auxiliaries and series resistance must be employed; operation is inferior to that on ac, with much less light produced per unit of energy and rated life reduced 20 percent. Neon lights are not usually employed on dc circuits. Fluorescent lamps, neon lights, mercury and sodium vapor, and metal halide lights may, if improperly installed or when deteriorating, cause radio and TV interference.

(c) High-Intensity Vapor Lighting

Mercury vapor (high pressure) and sodium vapor (high and low pressure) and metal halide lights operate at power factors of 70 to 80 percent, but also are associated with capacitors to raise the effective value to 100 percent. They are not as susceptible to voltage variations as are incandescent lamps. Their light output and life expectancy are greater than those for fluorescent lamps. They may be employed on dc circuits, but require additional starting auxiliaries. They are generally restricted to applications where large amounts of lighting are desirable, such as on expressways, in large manufacturing areas, or in photographic work; they are somewhat more expensive than other types and have the disadvantage of taking some time after being energized before maximum light output occurs.

4.1.2 Power Loads

Generally included in power loads are motors of all sizes: direct current shunt, compound and series types; alternating current single-phase and polyphase, induction and synchronous types; and universal (series) for both dc and ac Operation.

(a) Single-Phase Fractional-Horsepower Motors

The majority of fractional horsepower motors, generally used in appliances of various kinds, are single-phase and operate at power factor values of 50 to 70 percent, but many have corrective capacitors associated with them. When they operate without speed controls or starters, their starting currents may cause lights on the same circuit to flicker; where starts are relatively frequent, as with refrigerators and oil burners, the flicker may be annoying.

(b) Induction Motors

Most commercial and industrial ac motors are of the induction type; limited speed control may be obtained in some types by varying the applied voltage. Where accurate speed control is desirable, such as for elevators and printing presses, dc motors are employed, sometimes served from ac sources through motor-generator sets. Induction motors may operate at power factors of 50 to 95 percent but generally operate on the order of 80 to 90 percent; at less than full load, the power factors may drop to 50 to 60 percent. Most large motors for industrial loads (from about 2 hp and larger) are usually three-phase (although many older two-phase motors still exist). Voltage variations of about - 10 percent can be accommodated with little lowering of motor efficiency and power factor values.

(c) Synchronous Motors

Synchronous motors, usually of large sizes, can operate at power factors leading or lagging 100 percent by adjusting their excitation:
Overexcitement draws leading current, under excitement lagging current. Often this type of motor is used for power factor correction for the entire installation.

Since larger motors are apt to cause voltages to dip when starting, circuits separate from lighting circuits are provided to eliminate flicker problems; sometimes separate supply transformers are also provided. Also causing similar flicker problems are chemical and electrolytic devices and mechanical devices operated by coils or solenoids. Table 4-1 summarizes the characteristics and general application of these various types of motors.

TABLE 4-1 SUMMARY OF MOTOR GENERAL CHARACTERISTICS

[redacted]			
DC shunt	Up to 200	Constant speed or variable speed by armature or field control	Light or medium starting duty
DC compound	Up to 200	Varying speeds up to 25% from no load to full load	Heavy starting duty, heavy loads for short periods
DC series	Up to 200	Variable speeds	Heavy intermittent starting or heavy loads for short periods
AC 1-Phase	1/50 or less to 10	Constant speed; usually with some line means for varying speed	Constant speed; no speed control for light or heavy starting duty
AC polyphase (2-phase or 3-phase) induction	Squirrel-cage to 200; wound rotor to 1000	Speed change by field controls or reduced voltage; available for constant torque and constant hp	Constant speed; light, medium, and heavy starting duty
AC 3-phase synchronous	Usually 300 to 5000 +	Constant speed; for power factor control by over- or under excitation	Constant speed; light, medium, and heavy starting duty and loads

4.1.3 Heating Loads

The heating category may be conveniently divided into residential (small) and industrial (large) applications.

(a) Residential Heating

Residential heating includes ranges for cooking; hot water heaters; toasters, irons, clothes dryers, and other such appliances; and house heating. These are all resistance loads, varying from a relatively few watts to several kilowatts, most of which operate at 120 V, while the larger ones are served at 240 V; all are single-phase. The power factor of such devices is essentially unity. The resistance of the elements involved is practically constant; hence current will vary directly as the applied voltage. The effect of reduced voltage and accompanying reduced current is merely to cause a corresponding reduction in the heat produced or a slowing down of the operation of the appliance or device. While voltage variation, therefore, is not critical, it is usually kept to small values since very often the smaller devices are connected to the same circuits as are lighting loads, although hot water heaters, ranges, and other larger loads are usually supplied from separate circuits. (Microwave ovens employ high frequency induction heating and are described below.)

(b) Industrial Heating

Industrial heating may include large space heaters, ovens (baking, heat-treating, enameling, etc.), furnaces (steel, brass, etc.), welders, and high-frequency heating devices. The first two are resistance-type loads and operate much as the smaller residential devices, with operation at 120 or 240 V, single-phase, and at unity power factor. Ovens, however, may be operated almost continuously for reasons of economy, and some may be three-phase units.

Electric Furnaces: Furnaces may draw heavy currents more or less intermittently during part of the heat process and a fairly steady lesser current for the rest; on the whole, the power factor will be fairly high since continuous operation is indicated for economy reasons. The power factor of a furnace load varies with the type of furnace from as low as 60 percent to as high as 95 percent; with the greater number about 75 or 80 percent. Sizes of furnaces vary widely; smaller units with a rating of several hundred kilowatts are single-phase, while the larger, of several thousand kilowatts, are usually three-phase. Voltage regulation, while not critical, should be fairly close because of its possible effect on the material in the furnace.

Welders: Welders draw very large currents for very short intermittent periods of time. They operate at a comparatively low voltage of 30 to 50 V, served from a separate transformer having a high current capacity. Larger welders may employ a motor-generator set between the welder and the power system to prevent annoying voltage dips. The power factor of welder loads is relatively low, varying with the load. The timing of the weld is of great importance and may be regulated by electronic timing devices.

High-Frequency Heating: High-frequency heating generates heat in materials by high-frequency sources of electric power derived from the normal (60-Hz) power supply. High-frequency heating is of two types: induction and dielectric.

Induction heating: In induction heating, the material is conducting (metals etc.) and is placed inside a coil connected to a high-frequency source of power; the high-frequency magnetic field induces in the material high-frequency eddy currents which heat it. Because of the skin effect, the induced currents will tend to crowd near the surface; as the frequency is increased, the depth of the currents induced will decrease, thus providing a method of controlling the depth to which an object is heating.

Dielectric heating: In dielectric heating, a poor conducting material (plastic, plywood, etc.) is placed between two electrodes connected to a high-frequency source; the arrangement constitutes a capacitor, and an alternating electrostatic field will be set up in the material. (Some slight heating will also be set up from the induction effect described above, depending on the conducting ability of the material.) The alternating field passing uniformly through the material displaces or stresses the molecules, first in one direction and then in the other as the field reverses its polarity. Friction between the molecules occurs and generates heat uniformly throughout the material. Such friction and heat are proportional to the rate of field reversals; hence, the higher the frequency, the faster the heating. Because of heat radiation from the surface, however, the center may be hotter than the outside layers. Residential-type microwave ovens are an application of dielectric heating.

Oscillators: Oscillators are used as the source of high-frequency power required for both induction and dielectric heating. This is an electronic application, and its characteristics and requirements are described in the following section.

4.1.4 Electronic Loads

The electronic load category includes radio, television, x-rays, laser equipment, computers, digital time and timing devices, rectifiers, oscillators for high-frequency current production, and many other electronically operated devices. In general, these employ electron tubes or solid-state devices such as transistors, semiconductors, etc. Practically all of these devices operate at voltages lower than the commercial power sources and employ transformers or other devices to obtain their specific voltages of operation. They are all affected by voltage variations.

Voltage variations may have a marked effect on electron tubes, affecting their current-carrying abilities or emissions as well as their life expectancy. Because of the reduced life of the heater element and higher rate of evaporation of active materials from the cathode surface, the cathode life of electron tubes may be reduced as much as one-half by only a 5 percent rise in cathode voltage. Industrial-type tubes are normally designed to operate with a voltage tolerance of ±5 percent, though closer tolerances are often specified.

While voltage variations also affect the operation of solid-state devices, the effect on their life expectancy is not as serious as in the case of electron tubes.

On the other hand, variations in frequency of the power supply have little effect on electron tubes but may have a pronounced effect on solid-state devices.

Both types of devices are very sensitive to voltage dips, and, from the power supply viewpoint, operate at essentially unity power factor. Some applications, such as computers, may require an uninterrupted source of supply, and various schemes are employed to achieve this, including the use of motor-generator sets capable of running on batteries for a limited time; the motor-generator set also eliminates the problems of voltage dips on the commercial power supply.

Except for some rectifier applications, most of these devices operate from single-phase ac supply circuits; large rectifiers may be supplied from three-phase sources.

Oscillators for commercial purposes employ industrial-type electron tubes in conjunction with capacitors and inductances that may be varied to produce the desired high-frequency sources. The regular tolerances in voltage supply from commercial power sources are suitable for this application.

4.2 Consumer Factors

It is obvious that an individual consumer is not apt to be using all of the electrical devices that constitute his or her "connected load" at the same time, or to their full capacity. It would evidently be unnecessary to provide facilities to serve such a total possible load, and much more economical to provide only for a probable load, the load creating the demand on the distribution facilities.

The actual load in use by a consumer creates a demand for electric energy that Varies from hour to hour over a period of time but reaches its greatest value at Some point. This may be called the consumer's instantaneous maximum demand; in practice, however, the maximum demand is taken as that which is sustained over a more definite period of time, usually 15, 30, or 60 min. These are referred to as 15-, 30-, or 60- min integrated demands, respectively.

4.2.1 Demand Factor

The ratio of the maximum demand to the total connected load is called the Demand factor. It is a convenient form for expressing the relationship between connected load and demand. For example, a consumer may have ten 10-hp motors installed; at any one time, some will not be in use and others will not be fully loaded, so that the actual demand may be only 50 hp; the demand factor is 50 divided by 100, or 50 percent.

The demand factor differs for different types of loads, and by averaging a Large number of loads of each type, typical demand factors can be obtained. These values are important in determining the size of facilities to be installed For a particular service; they are extremely useful in making estimates in planning new distribution systems or in expanding existing ones.

4.2.2 Load Factor

The load factor is a characteristic related to the demand factor, expressing the Ratio of the average load or demand for a period of time (say a day) to the maximum demand (say 60 min) during that period. For example, a consumer Household may have a maximum demand of 2 kW during the evening when Many of its lights, the TV, the dishwasher, and other appliances are in use.

During the 24-h period, the energy consumed may be 12 kWh; thus the average demand or load is 12 kWh divided by 24 h, or 0.5 kW and the load factor in this case is 0.5 kW divided by 2 kW, or 25 percent. This provides a means of estimating particular consumers' maximum demand if both their consumption and a typical load factor for their kind of load are known.

4.2.3 Diversity Factor

The diversity factor is the ratio of the sum of maximum demands of each of the component loads to the maximum demand of the load as a whole (or the coincident maximum demand). For example, each of the loads mentioned above may have a maximum demand of 100 kW, while the coincident maximum demand on the system supplying the three may be only 150 kW. The diversity factor is then 300 (100 + 100 + 100) divided by 150, or 2, or 200 percent. Such diversity exists between consumers, between transformers, and between feeders, substations, etc. Note that the demand factor is defined so that it is always less than 1 or 100 percent, while the diversity factor is the reciprocal of the demand factor and is always greater than 1 or 100 percent. This is a most important factor in the economical planning and design of distribution facilities.

4.2.4 Coincidence Factor

The coincidence factor is the ratio of the maximum coincident total demand of a group of consumers to the sum of the maximum demands of each of the Consumers.

4.2.5 Utilization Factor

The ratio of the maximum demand of a system to the rated capacity of the system is known as the utilization factor. Both the maximum demand and the rated capacities are expressed in the same units. The factor indicates the degree to which a system is being loaded during the load peak with respect to its capacity. The rated capacity of a system is usually determined by its thermal capacity, but may also be determined by voltage drop limitations, the smaller of the two determining the capacity.

4.2.6 Power Factor

The ratio of power (in watts) to the product of the voltage and current (in volt-amperes) is called the power factor. It is a measure of the relation between current and voltage out of phase with each other brought about by reactance in the circuit (including the device served). Since facilities must be designed to carry the current and provide for losses which vary as the square of the current, and for voltage drops which are approximately proportional to the current, it is necessary that current values be known. The power factor enables loads and losses designated in watts to be converted to amperes. Transformer sizes, wire and cable sizes, fuses, switch ratings, etc., are all based on values of current they must carry safely and economically.

4.3 Consumer Classification

As aids in planning, consumers may be conveniently classified into certain categories and certain ranges of load densities expressed in kVA per square mile (where this unit is too broad to be useful, watts per square foot for specific occupancies may be used).

TABLE 4.1

Residential	
Downtown, apartment buildings, hotels	10 to 50,000 kVA/mi^2
Urban, suburban:	
Large homes (plots)	1 to 5,000 kVA/mi^2
Small homes	0.5 to 1,000 kVA/mi^2
Two-family homes	1 to 5,000 kVA/mi^2
Rural, including farm loads	Less than 0.1 to 5 kVA/mi^2
Commercial	
Stores and shopping centers	10 to 500,000 kVA/mi^2
Office buildings	10 to 500,000 kVA/mi^2
Service centers, warehouses	10 to 500,000 kVA/mi^2
Hospitals, nursing homes	1 to 50,000 kVA/mi^2
Schools, churches, clubs, etc.	1 to 500 kVA/mi^2
Street and area lighting	1 to 500 kVA/mi^2
Industrial	
Large manufacturing plants	Extremely wide variations;
Small manufacturing plants	consider them as spot
Military Bases	Concentrations of loads.

Further classifications may be based on such items as the dependence on Electric service because of the critical nature of the consumer's operations, under either normal or emergency conditions; the resultant cost if critical processes are interrupted; or the sensitivity of loads to small voltage deviations.

4.4 Fluctuation In Demand

There are three main factors that greatly influence the magnitude of maximum demand and the time of its occurrence. The most frequent is the weather as it affects light intensity during daylight hours and temperatures throughout the day and year. The sharpest factor and perhaps that of least duration is special events which result in a temporary slowdown of activities or a greatly increased usage of lighting, radio, and TV and associated increases in water pumping, cooking, and other loads. The largest factor is changes in business conditions accompanied by significant changes in industrial demands and consumption; while much less significant, fluctuations in both residential and commercial consumer demands also follow such changes in business conditions.

The nature, magnitude, and time of these fluctuations are generally unpredictable. Some estimate of them can be gleaned, however, from past experiences, which may vary widely in different areas of the country. Provision for these fluctuations should be taken into account in the planning of distribution systems.

4.5 Future Requirements

Good engineering requires that probable future growth of loads be considered in planning. This is usually provided for by spare capacity in the present design of the several elements, or by provisions for possible future additions or alterations, or both of these. Load growth is rarely uniform throughout an area, so that growths in various parts of a system will be different from each other and from that of the system as a whole.

(a) Economics

How far present capacity should provide for future load is largely a question of economics: the cost of carrying excess capacity until it is needed versus the cost of replacing smaller units with larger when it becomes necessary. This is a problem of the future worth of present expenditure, which is affected by fluctuations in rates of interest and inflation. Standard sizes of the materials and equipment involved automatically provide for a limited amount of spare capacity for growth, so that any economic analysis can only be approximate. The relatively large proportion of labor to material in the construction of a distribution system or its parts lends itself to the installation of capacity greater than its immediate need. Such spare capacity incidentally provides a cushion for accommodating some of the unforeseen fluctuations in demands described above.

(b) Past Performance

Data from past performances, such as total system loads, substation loads, and Feeder loads, can be used as a basis for estimating such growth. The variations From year to year, or from month to month, can furnish a trend for such growth; separate trends can be developed for different parts or areas. Where such data are nonexistent or patently unreliable, estimates can include a fixed percentage growth above the values on which planning is made.

(c) Future Performance

To obtain some idea of what may occur in the future, it may be well to look back a generation or two. Earlier, consumer's appliances could be contained in a relatively short table. To attempt to list all the electrically operated devices, appliances, and gadgets presently to be found in homes and commercial establishments would be an almost endless task. To attempt to foretell what may develop in the future would be an exercise in futility.

The advent of widespread air conditioning and space heating, together with the almost universal use of television, not only substantially changed consumer's maximum demands and consumption, but also materially affected loads, diversity, coincidence and (for larger units) power factors, and utilization factors as well.

While the demand factor may indicate how the connected loads are being Used, the utilization factor indicates how the capacity of the supply system is being used. Since the capacity of the supply system is determined by its thermal capability, the increased sustained demand on these facilities will lower their thermal capability, and hence the system capability.

The greater use of electronically operated computers will tend to call for narrower limits of voltage control (regulation and flicker) and a greater degree Of service reliability by stiffening the supply distribution system, or through the installation of auxiliary equipment owned and maintained by the consumer or rented as another service by the utility; the choice will be determined by future developments.

Chapter 5: OPERATING CONSIDERATIONS

There are many requirements which the design of distribution systems must meet, other than those of meeting the consumer's and community's needs and desires. The additional requirements, in the main, have arisen from the changing national economic and energy situations. Collected under the general subject of operating requirements are the installation and arrangement of facilities to achieve a better quality of service, but also a more efficient distribution system and a more economical overall electric system from the generating plant to the consumer's premises.

The operations may be classified into four specific functions and may be listed under simplified headings: Quality of service, Load shedding, Cogeneration and Demand control (or peak suppression)

These are somewhat interrelated, and all involve the distribution system.

5.1 Quality of Service

Operations involving the improvement of quality of service to the consumer measures to:

1. Isolate faults and restore service to the unfaulted portion of the distribution system
2. Transfer loads between phases or between circuits to relieve overloads or potential overloads, and improve voltage conditions
3. Switch on and off capacitors installed out on the distribution feeders (and in the substations) to improve power factor, reducing the value of current flowing and releasing capacity of distribution facilities, with resultant voltage improvement
4. Enable portions of the distribution system, including the substation portion, to be deenergized for construction and maintenance purposes without affecting the remaining portion of the circuit

Designs of distribution systems include provisions for carrying out these operations by means of suitable circuit extensions and switches. With the development of electronic and miniaturized systems of control and communication, many of these operations, generally performed manually and sometimes with a significant lapse of time, may now be performed automatically almost instantaneously.

5.2 Load Shedding

Why

The need for load shedding stems from two general causes, usually unforeseen:

1. Lack of sufficient power supply
2. Lack of sufficient transmission or distribution load-carrying ability

These conditions may come about from:

1. Load growth faster than the construction of new facilities can be accomplished
2. Abnormally high unforeseen demands that are created by unusual seasonal changes or by some special events that cause a significant loss in diversity of consumers' loads
3. Failure or overload in some element or elements of the supply facilities; e.g., transmission line failure, substation transformer failure, etc., for a prolonged period.

How

In this context, load shedding implies decreasing the load on the substation bus, substation transformer, or incoming transmission line. This may be accomplished in two basic ways:

1. Voltage reduction
2. "Brownout," or periodic disconnecting of feeders for relatively short periods of time on a predetermined schedule

In rare instances is resort had to the employment of both of these methods at the same time.

5.2.1 *Voltage* Reduction: Voltage reduction may be accomplished by manipulating voltage regulators at the substation on individual feeders, or on the substation bus, where the substation's voltage is so regulated. Voltages may be reduced by steps according to the amount of load shedding required. In circuits that supply essentially lighting or unity power factor loads, a 1 percent voltage drop results in almost a 1 percent drop in load.

Steps may be 1 or 2 percentage points each to a maximum of about 8 percent; more often, however, voltage is lowered in two steps, (say) 5 percent and 8 percent.

Lowering voltage beyond this 8 percent value may prove self-defeating as light output from incandescent lamps decreases to the point where additional lighting may be turned on. Fluorescent lighting is also affected as maintenance of the electron flow in the fluorescent tube becomes tenuous. Power loads usually continue to operate satisfactorily at the lower voltage, drawing more current, so that they have little effect on load reduction. This increase in current, however, may cause overheating, loss of torque, and other undesirable conditions to take place.

In some instances, the lowering of voltage may take place on the transmission or sub transmission incoming supply circuit or circuits when they are equipped with voltage regulators at the sending ends. In this event, the voltage regulators on the distribution feeders (or on the distribution feeder bus) at the substation may have to be blocked in a fixed or neutral position so as not to negate the effect of the reduced voltage on the incoming supply.

Regulators installed in the field on portions of primary circuits, for practical reasons, are usually left alone and allowed to travel to their maximum position if necessary. The relatively small amounts of load that can be shed by attending to these units is often not worth the effort necessary to adjust them to non automatic operation at the start and to return them to automatic operation at the end of a usually short period of time.

5.2.2 *Distribution System Problems:* Where distribution feeders are deliberately designed to accommodate such lowering of voltage below normal values, it may be necessary to reinforce or provide for some consumers, usually at the ends of primary circuits. These may have a sufficiently low normal voltage that the additional drop may cause damage to some of their connected loads. In most cases, provision involves the shortening of secondary mains and the more closely spaced installation of transformers; also, taps may be set for a lower (or the lowest) ratio of transformation. Sometimes, the installation of a booster transformer in those farthest sections of the primary circuit will accomplish the purpose. In any event, this feature requires investigation and the taking of necessary measures preferably before the need for such voltage reduction to shed load is placed in effect.

Where the need for voltage reduction stems only from some deficiency in the distribution system, that deficiency should be identified and removed as quickly as possible; such a need might occur in the case of overloads in an outgoing underground cable supplying a feeder where the cable carries too great a load under normal conditions, or under contingency conditions where it may be called upon to carry the load of an additional circuit or circuits, or parts of them.

5.2.3 Low-Voltage Network: Where the feeders supply a low-voltage secondary network, extreme care must be exercised in lowering the voltage on the supply primary feeders. Operation of the regulators must be coordinated so that the voltage on each of the feeders is lowered as simultaneously as practical to prevent opening of network protectors on the feeder if its voltage alone is lowered. In turn, the additional load picked up by the feeder or feeders whose voltage is not lowered may cause "hunting" between the protectors of the several feeders, or may cause feeders to trip from overloads in a cascading effect that would shut down the network. In some instances, the overcurrent relays on the feeder circuit breakers may be blocked to prevent feeders from tripping from temporary overloads until all the regulators have been adjusted and locked in at the desired lowered voltage level. If the voltage lowering operation is to be a relatively frequent occurrence, relay settings on the network protectors in the field may be made sufficiently insensitive to keep the protectors from hunting and the feeders from cascading out.

5.2.4 Brownout: Brownout is a procedure in which feeders are taken out of service for a relatively short period of time on a predetermined basis, usually one at a time, to reduce the demand on the substation supply transformers or on the facilities back to the generating station. Critical loads, such as hospitals and military bases, are usually supplied from two sources with double-throw facilities to accomplish a switchover to an energized source, either manually or automatically. Where this arrangement does not exist, it may be necessary to sectionalize that portion of a feeder supplying such critical loads, connecting it to an energized feeder when its normal supply feeder is deenergized. In some instances, where more than one critical load may exist on a feeder, that feeder may be exempt from the brownout procedure. Feeders supplying low-voltage networks are usually exempt as the load dropped by them in such an operation would be picked up by the others supplying the network, and the net reduction in load would be very nearly zero.

5.3 Cogeneration

Why

Basically, cogeneration involves the interconnection of consumer's generation to the utility's distribution system. Changing energy and economic conditions have made such interconnections feasible in many instances, and, in some areas, mandated by law. Large users of steam and hot water have found it economically desirable to generate electricity and use the "waste" heat to meet their steam and hot water requirements. The electricity so produced that they do not use themselves is sold to the utility, usually at an advantageous rate. This is because regulatory guidelines tend to favor a rate paid for power purchased by a utility (the avoidable cost to produce power) to be based on the utility's *least* efficient power plant, whereas the cost of power to a utility consumer is usually based on an *average* cost to produce power .

5.3.1 Paralleling the Systems

Paralleling the consumer's generation facilities with those of the utility requires that additional protection equipment be installed at the cogenerator's facilities. The principal features of this additional protection include:

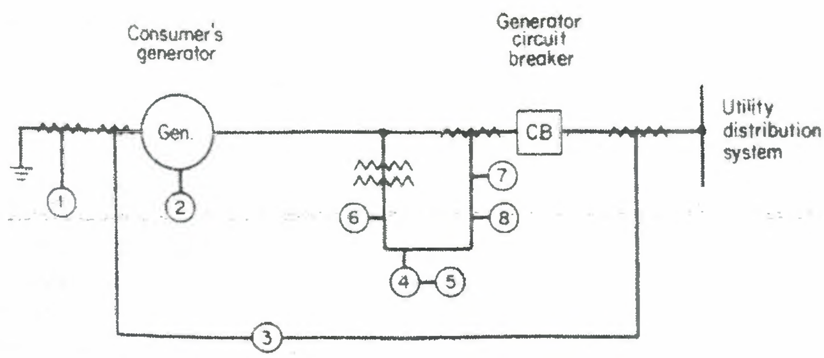
1. Automatic synchronizing of the generator output with the utility
2. Relaying to prevent the closing of the circuit breaker to the utility system until the cogenerator's generator is open, for protection of that generator
3. Relaying to open the circuit breaker to the utility system on loss of power in the utility system

4. Relaying to open the circuit breaker to the utility system on a ground fault on the utility system

5. Relaying to control the cogenerator's generator circuit breaker to provide generator overcurrent protection, phase current balance protection, reverse power protection, under- and over-frequency protection, and under- and overvoltage protection.

6. Control of engine governor equipment for speed, generator phase match, and generator load

The electrical connections and indicated protection are shown on the one-line diagram in Fig. 5-1.



1. Ground relay
2. Generator governor
3. Differential protective relay
4. Frequency meter and relay
5. Synchronizing device
6. Undervoltage relay
7. Time-overcurrent relay
8. Directional power relay

Figure 5-1 One-line diagram showing protection relaying for consumer cogeneration unit.

5.3.2 Modes of Operation

There are several load relationships that may exist between the cogenerator and the utility:

1. The cogenerator always supplying power at a constant rate; i.e., the cogenerator supplying a part of the utility's base load
2. The cogenerator always supplying power in variable amounts, fluctuating with the consumer's needs; i.e., the cogenerator supplying only a marginal part of the utility's load
3. The cogenerator and the utility both supplying the consumer's requirements on a normal or contingency basis
4. The utility supplying all of the consumer's requirements on a contingency basis

5.3.3 The Distribution System

The variation in the modes of operation not only may affect the settings applied to the protective relays, but may influence the design of the utility's distribution system. Obviously, the distribution facilities required will vary with the mode of operation, and the problem of maintaining voltage within acceptable limits as conditions change (e.g., from mode 1 to mode 4 above) may tax the engineer's ingenuity.

The wide variations that may take place in voltage profiles and current distribution in the distribution circuit to which the cogenerator is connected may require rearrangement of the circuit configuration to maintain safe and acceptable standards of electricity supply. These may require the installation of additional switching facilities to achieve desired sectionalization and rearrangement; preferably the switches should be automatically operated. Moreover, as generators are usually under control of one operating group while the distribution system is controlled by a separate group, some difficulties in coordination may arise.

5.4 Demand Control (Or Peak Suppression)

From an economic viewpoint, it is desirable to hold down the peak load or maximum demands on all the parts of the electric system—generation, transmission, and distribution. This has the desirable effects of reducing plant investment and at the same time reducing operating expenses (fuel) because of reduced I^2R losses.

Load shedding as described above is a form of demand control or peak suppression, but is associated with contingencies usually of a temporary nature; demand control applies to a permanent reduction in maximum demands as a normal condition.

For a utility, the most efficient use of its facilities, from an investment point of view, is to use them throughout their lifetimes at maximum loads. By definition, if this were done, the load factor for the facilities would be 100 percent. This does not occur, because some consumer loads are not always required and are turned off. The closer the utility can approach 100 percent load factor, however, the better the investment can be utilized, and the lower a unit of output can be priced.

The load factor concept in supplying a given load applies equally well whether it is applied to the utility itself or to a single consumer. For example, it is not unusual for a utility to have an annual load factor of 50 to 60 percent because of seasonal air-conditioning loads; this implies that a great part of the facilities used to meet summer peak demands will remain idle the rest of the year.

Typical load factors range from less than 20 percent for some residences to over 90 percent for some industrial plants (like some manufacturing plants having large air-filtering installations). In between, office buildings typically may have load factors of 20 to 30 percent and large, three-shift manufacturing plants 70 to 80 percent. Small to medium industries may have load factors ranging from 20 to 70 percent.

5.4.1 Conservation

Demand control is also a conservation measure, as it will substantially reduce losses, in both the utility's and the consumer's facilities. These reductions will be reflected in fuel consumption at the utility's generating plants and in both demand and energy charges (including fuel adjustment charges) in the consumer's bill.

Although the total overall consumption by a consumer may remain the same, the leveling of demands will decrease the *maximum* current flow, though the *reduced* current flow may continue for a longer period of time. As losses $(I^2R]$ vary as the square of the current, the lower current should result in a substantial reduction in the total energy requirements of the consumer.

Experience has also indicated that reviews for reducing demand often discover unnecessary operation of some equipment, and result in elimination of some operations and improved methods of operation all of which result in decreased energy consumption.

5.4.2 Load Management

Basically, to reduce the demand on its facilities, the utility must seek to reduce the individual consumers' demands. Preferably, the individual consumer's demands should also be coordinated so as to achieve a minimum coincident demand. This latter feature is more difficult of attainment than the first, as it involves cooperation not only between the utility and the consumer, but among a number of consumers as well. Methods for reducing demands differ for large consumers, such as industrial plants, and for small consumers, such as residences; both, however, employ rate incentives.

(a) Large Consumers: For large consumers the connection with the demand metering of large consumers and their role in schemes employed for reducing consumer demands has to be discussed. This is important to the consumer, as utility rates include demand charges based on the registered maximum demand. The timing impulses from the demand meter are used in several schemes to hold down demands to predetermined values.

To reduce demand requires that nonessential load peaks be reduced or eliminated. Loads are analyzed into several categories:

1. Those that are essential, that cannot be turned off without affecting safety and operations.
2. Those that may be curtailed or turned off for relatively short periods of time without being noticed (e.g., 10 min out of each hour); they may be programmed to be shut off sequentially for predetermined periods of time.
3. Those that may be deferred put off to some random off-peak time which may differ from day to day (or other period).
4. Those which may be conveniently rescheduled regularly to off-peak periods.

Typical examples of such categories for large industrial consumers are shown in Table 5-1.

TABLE 5-1 TYPICAL CATEGORIES OF LARGE CONSUMER LOADS

Category	Examples
Essential	Lighting (some)
	Elevators
	Production equipment (some)
	Ventilators (some)
	Pumps (some)
Curtailable	Air conditioners
	Heaters
	Ventilators
	Refrigerators
	Water pumps
	Ovens
Deferrable	Coolers
	Air compressors
	Water heaters
	Equipment testing
Reschedulable	Electric furnace
	Process ovens
	Incinerators
	Trash compactors
	Battery chargers

(b)Load Cycling: Cycling involves the turning off and on of individual loads or groups of loads. How long they can be turned off and how often is predetermined, and the off-on times are staggered so that a minimum number of such loads are on at any one time to achieve the smallest practical maximum demand.

Most automatic demand-control systems employ load cycling and involve some technique of demand forecasting to determine when loads should be turned off and on. All are based on the consumer's actual consumption, and its rate compared to some predetermined ideal rate. Several methods of obtaining the comparison have been devised yielding different degrees of accuracy and precision; these will not be further detailed as they are not within the scope of this book. Almost all employ pulses obtained from the utility's demand meter for matching the demand under consideration with that being recorded by the demand meter. Demand-control equipment also acts to control "average" maximum demands, leaving the utility still needing to meet the actual or peak maximum demand.

Demand control usually leads to increased off-on switching of equipment. Care must be taken, therefore, to ensure that thermal overloads and mechanical failure of switching devices do not occur because of short cycling of equipment.

(c) Small Consumers: Most small consumers are residential consumers whose demand is not usually metered. Efforts by the utility to hold down their demands are limited almost to promotional rates which, for practical purposes, cannot be policed. More and more, however, utilities are installing demand meters or clocking devices connected to the larger loads, such as hot water heaters, dish and clothes washers, etc. Consumers are thereby encouraged to install small computer-actuated devices for controlling the turning off and on of such loads; these include supplementary time delays so that the initial inrush currents on the various appliances will not (because of possible loss of diversity) all occur simultaneously, causing service interruption and possible damage to the appliance. Thermal devices have been developed for storing cold and heat during off-peak periods to be used during periods of electrical peaks.

5.4.3 Load Management Control

A number of utilities have assumed control of devices that will switch off loads on their system automatically when undesirable demand levels are being reached. This involves the identification of noncritical loads that can be placed under the control of the utility with agreed-upon constraints regarding maximum time to be left off. Agreements with consumers include favorable "interruptible" rate schedules. These may be controlled by means of signals transmitted by radio, carrier, or telephone communication. (Similar means of communication are also employed in small residential consumers, mentioned earlier.)

Costs for such demand-control installations are sometimes shared with the (large) consumer, where the same equipment is also used to control the consumer's maximum demand. This demands an almost continuous review to ascertain that a target value set up by the consumer will not run afoul of that set up by the utility.

5.5 Utility Problems

The utility generally must meet seasonal and daily load peaks, peaks of relatively short duration. Generation, transmission, and distribution facilities must be provided to meet these demands.

5.5.1 Generation: Utilities generally have three levels of power generation equipment; base-load units, usually the newest and most highly efficient (as well as the most expensive); midrange units, which are less efficient and are perhaps the most recent of older generation facilities; and units generally operated as peak units, the least efficient and usually the oldest, but sometimes new units specifically designed for this short-term purpose. Controlling system demands, therefore, results in lessened need to operate the least efficient units and, in the long term, defers the addition of the most expensive newest units.

5.5.2 Transmission: Transmission lines are the bulk carriers of electrical energy, and fall into the same category as generators as far as investment is concerned. Here, too, the older and less efficient transmission lines, usually those operating at lower voltages than the newest lines, constitute part of the transmission network, including those facilities needed to ensure continuity of adequate service in contingencies. Controlling system demands will not only result in lowered I^2R losses, as indicated previously, but will also defer, if not make unnecessary, the installation of new and expensive transmission lines.

5.5.3 Distribution: The same general observations concerning transmission lines also apply to distribution circuits. Additional distribution facilities (including substations) and conversions or construction at higher voltages can be deferred if the system demands can be controlled.

In the case of distribution facilities, however, a problem arises as to the rating of equipment, particularly transformers. The rating of such equipment, though nominally predicated on its current-carrying ability, is actually based on the allowable temperature at which insulation may be subject to failure. This temperature is a function not only of the heat caused by the losses (copper and iron) developed within the unit, but also of the duration of the developed heat. The control of demands on the distribution system will, on the one hand, reduce the maximum values of heat applied (as noted previously), but on the other, may reduce the thermal margin of safety resulting from the duration of the heating cycles. In some instances, no doubt, the net overall effect may be negligible; in others, especially during periods of prolonged hot ambient temperatures, such as exist in summertime, the net overall effect may be appreciable. Units so affected should, therefore, be closely monitored.

CONCLUSION

The distribution and transmission of electrical energy in daily use of life has unique importance which cannot be falsified. As a general view we have three steps for the transaction of the electrical energy. The main point is the generating stations where electrical energy is generated and after that it is transmitted at high-voltage level, to the substations from where it is distributed further. As a result we have generation, transmission, distribution and utilization. At the generating substations we have step-up transformers which step-up the generated voltage. This generated voltage is raised to a high-voltage level which is transmitted over high-voltage transmission lines. At the transmission substation we have step-down transformers which step-down the high voltage. After the transmission substation we may have several interconnecting substations. From the transmission substation or the interconnecting substation, power is transmitted to the distribution substation. At distribution substation we have got the step-down transformers which further step-down the transmitted voltage. Distribution substations have got several buses connected to the voltage regulators. Buses at the distribution substation further split into primary feeders which link to the distribution transformers. Distribution transformers supply the power to the ultimate consumers.

Substations can be categorized into transmission Substations, distribution Substations and interconnecting Substations. Substations serve to change the line voltage by means of step-up and step-down transformers and to regulate it by means of synchronous Condensers, static var Compensators and transformers with variable taps. Voltage regulators are used at both transmission and distribution level along lines or at substations and loads. They may be connected permanently but as a regulator of voltage they may be switched on and off the system as changes in load demand. Capacitors reduce the line current necessary to supply the load and reduce the voltage drop in the line as the power factor is improved.

We have got several types of systems for the distribution of electrical energy to the consumers. Electrical energy may be distributed over two or more wires. The principal features desired are safety, smooth and even flow of power. The safety factor usually requires a voltage low enough to be safe when the electric energy is utilized by the ordinary consumer. A steady, uniform, nonfluctuating flow of power is highly desirable, both for lighting and for other operation purposes. Although a direct current system fills

these requirements admirably, it is limited in the distance over which it can economically supply power at utilization voltage. Alternating current systems deliver power in a fluctuating manner following the cyclic variations of the voltage generated. Such fluctuations of power are not objectionable for heating, lighting and small motors bit are not entirely satisfactory for the operation of some devices such as large motors, which must deliver mechanical power steadily and therefore require a steady input of electric power.

In the planning of an electrical distribution system as in any other enterprise, it is necessary to know the quantity of the product or service desired, the quality of the product and the location of the market and the individual market. Good engineering requires that probable future growth of loads be considered in planning. This is usually provided for by spare capacity in the present design of the several elements, or by provisions for possible future additions or alternations or both of these. Load growth is rarely uniform throughout an area, so that growths in various parts of a system will be different from each other and from that of the system as a whole. The final design, however, cannot be divorced from mechanical, economic and other considerations.

The need for conservation of investment capital and use of energy resources indicates the desirability of operating practices that no longer separate the distribution system from other parts of electrical system operations.

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