

# **CHAPTER One**

## **Introduction**

### **1.1 Overview :**

Power engineering is the oldest and most traditional of the various areas of electrical engineering, yet no other facet of modern technology continues to undergo a more persistent evolution in technology and industry structure. The use of capacitors in both shunt and series applications demonstrates this quite well. Since the earliest applications of AC systems, engineers have known that tight control of VAR flow and power factor, using capacitors in many cases, is necessary to attain good operating efficiency and stable voltage. But whereas power factor engineering was once based on simple rules-of-thumb, with the capacitors literally sized and assembled plate by plate in the field, today's capacitor engineering is an intricate analytical process that can select from a diverse range of types of capacitor technologies, including power electronic devices that simulate their action.

Power System Capacitors is a well-organized and comprehensive view of the theory behind capacitors and their practical applications to modern electric power systems. At both the introductory and advanced levels, this research provides a solid foundation of theory, fact, nomenclature, and formula, and offers sound insight into the philosophies of power factor engineering techniques and capacitor selection and sizing.

## **1.2 Problem Statement:**

Having poor power factor increases the current flowing in conductor and thus copper loss increases. Further large voltage drop occurs in alternator, electrical transformer and transmission & distribution lines which gives very poor voltage regulation.

## **1.3 Objectives:**

1. To study the Methods of Power Factor Improvement especially the use of capacitors and the voltage distribution in power substations.
2. to develop an ATP Simulation of Shunt Capacitor Switching in an Electrical Distribution System.

## **1.4 Project Layout:**

The project contains four chapters, they are categorized as shown below:

❖ **CHAPTER One:** It's an introduction chapter and it shows the problem statement, objectives and the project layout.

❖ **CHAPTER Two: General Information in Voltage Distribution.**

The electrical energy produced at the generating station is conveyed to the consumers through a network of transmission and distribution systems. It is often difficult to draw a line between the transmission and distribution systems of a large power system. It is impossible to distinguish the two merely by their voltage because what was considered as a high voltage a few years ago is now considered as a low voltage. In general, distribution system is that part of power system which distributes power to the consumers for utilisation.

### ❖ CHAPTER Three: Power Factor Improvement.

Improving power factor means reducing the phase difference between voltage and current. Since majority of loads are of inductive nature, they require some amount of reactive power for them to function.

### ❖ CHAPTER Four : Simulation

The quality of electric power has been a constant topic of study, mainly because inherent problems to it can lead to great economic losses, especially in industrial processes. Among the various factors that affect power quality, those related to transients originating from capacitor bank switching in the primary distribution systems must be highlighted. In this work, the characteristics of transients resulting from the switching of utility capacitor banks are analyzed, as well as factors that influence their intensities. The conditions under which these effects are mitigated can then be investigated. A circuit that represents a real distribution system, 13.8 kV, was simulated through the software ATP (Alternative Transients Program) for purposes of this study.

### ❖ CHAPTER Five : Conclusion And Recommendations

The reasearch's conclusion and it's recomindations.

# **CHAPTER Two**

## **General Information in Voltage Distribution**

### **2.1 Introduction**

Distribution system represents an important part in the electrical grids and for this reason the electrical companies allocate approximately 40% of the capital investment for distribution systems while the remainder is given to generation and transmission (40% generation & 20% transmission). The distribution system is particularly important for an electrical utility for two reasons:

- 1- It's the close part to the Customers and any failure in distribution system affects the customer directly. For example failures in transmission and generation sections may not cause customer service interruptions.
- 2- It's high investment cost.

### **2.2 Distribution System Components:**

According to figure 2.1 which represents one line diagram of typical electrical power system network the main components of distribution system are:

#### **❖ Sub transmission system:**

The sub-transmission system is partly responsible for transmitting the electrical power from the transmission substation (the source of bulk power) into distribution substation. The transmission voltage is laid in the range 12.47-275 kv.

## ❖ Distribution substation:

Its always step-down the sub-transmission voltage to level suitable for the primary feeders (220/33kv, 100/11kv).

## ❖ Primary feeders:

The primary feeders distribute the power from the low bus side of distribution substation into distribution transformer located in load centres. The nominal voltage of this feeders lay in the range 3.3 to 33 kv.

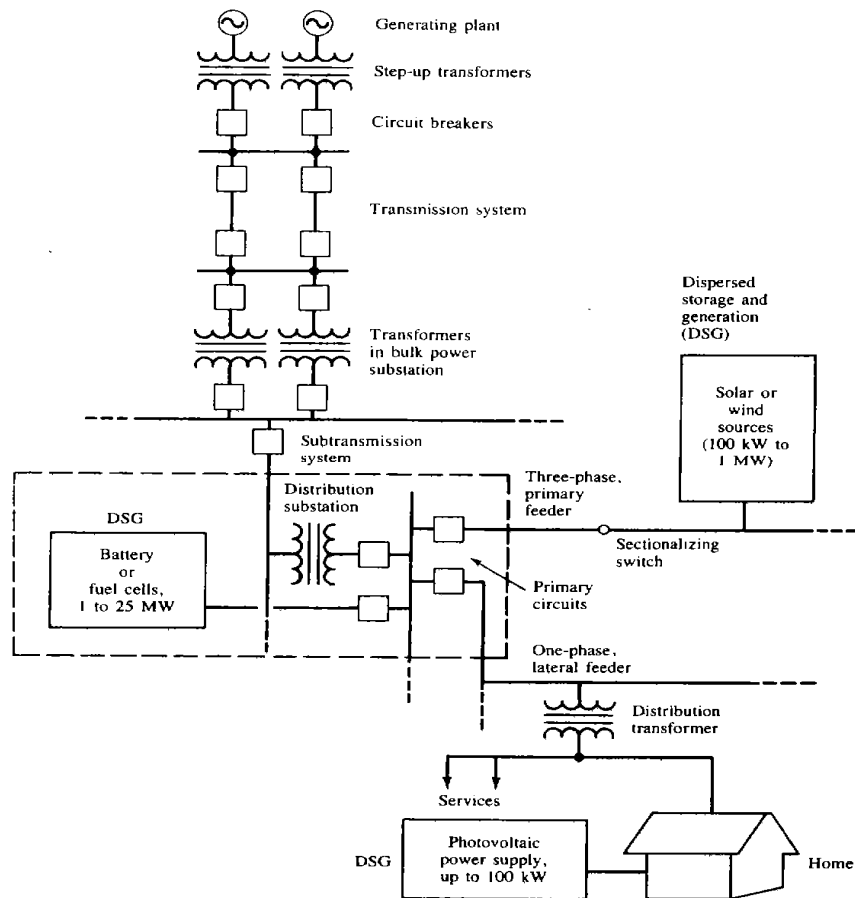


Figure 2.1 one line diagram of typical electrical power system network

### ❖ **Distribution transformers :**

Distribution transformer usually connected to the primary feeders, they reduce the distribution voltage to the utilization voltage. Distribution transformer are rated from 10 to 500 KVA with voltages 3300/415, 11000/415 volts.

### ❖ **Secondary feeders :**

Distribute the power from the secondary side of the distribution transformer into customers services with 415 volt.

### ❖ **Customers services :**

Customer service is a series of activities designed to enhance the level of customer satisfaction – that is, the feeling that a product or service has met the customer expectation.

### ❖ **Dispersed storage and generation (DSG) :**

In the future small and medium dispersed storage and generation units (storage system , solar units, or wind farms) may be attached to customer home, primary feeder or distribution substation to inject power into distribution system and this will require increasing of automation and control of the system.

In general the distribution system may be divided into:

- 1- Primary distribution system : transmits the power from the bulk power source (transmission substation) into distribution transformers.
- 2- Secondary distribution system : distribute the power from distribution transformer into customer service.

## 2.3 Sub-transmission lines:

The sub-transmission system is part responsible for transmission the electrical power from the transmission substation (the source of bulk power) into distribution substation. The sub-transmission circuits may be made of overhead lines or underground cables. The voltage of this circuits varies from 12.47 to 275 kv with the majoriy at 69, 110 and 138 kv levels with general trend in using higher voltages as results of the increasing use of higher transmission voltages. The sub-transmission system designs vary from simple radial system to a complex subtransmisson network and the major conseration affecting the design are cost and reliability. In general there are four types of sub-transmission systems as shown in figure ures below .

- 1- Radial sub-transmission
- 2- Improved radial subtransmission
- 3- Loop subtransmission
- 4- Network subtransmission

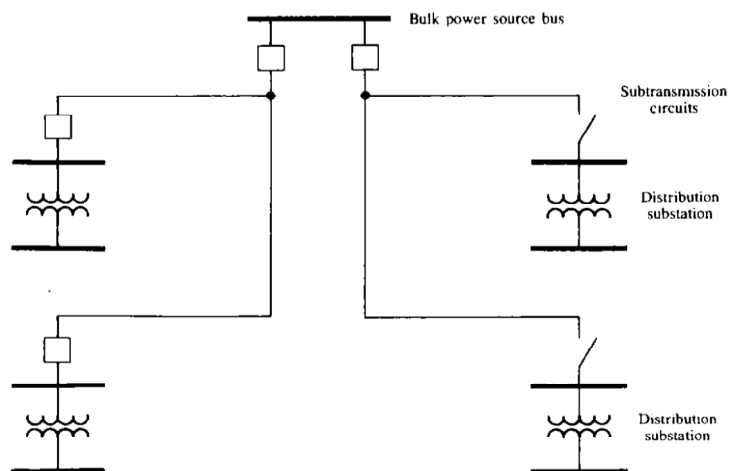


Figure 2.2 Radial sub-transmission system

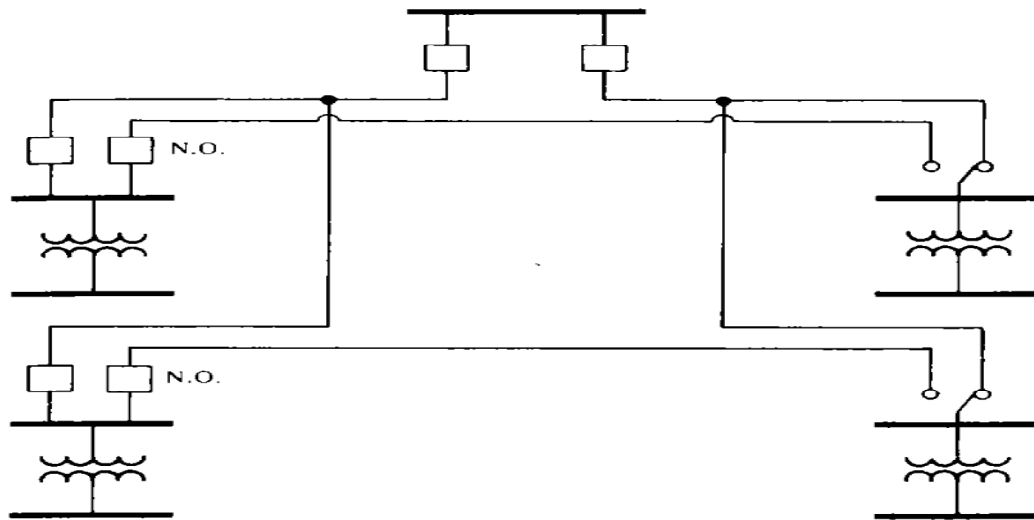


Figure 2.3 Improved Radial sub-transmission system

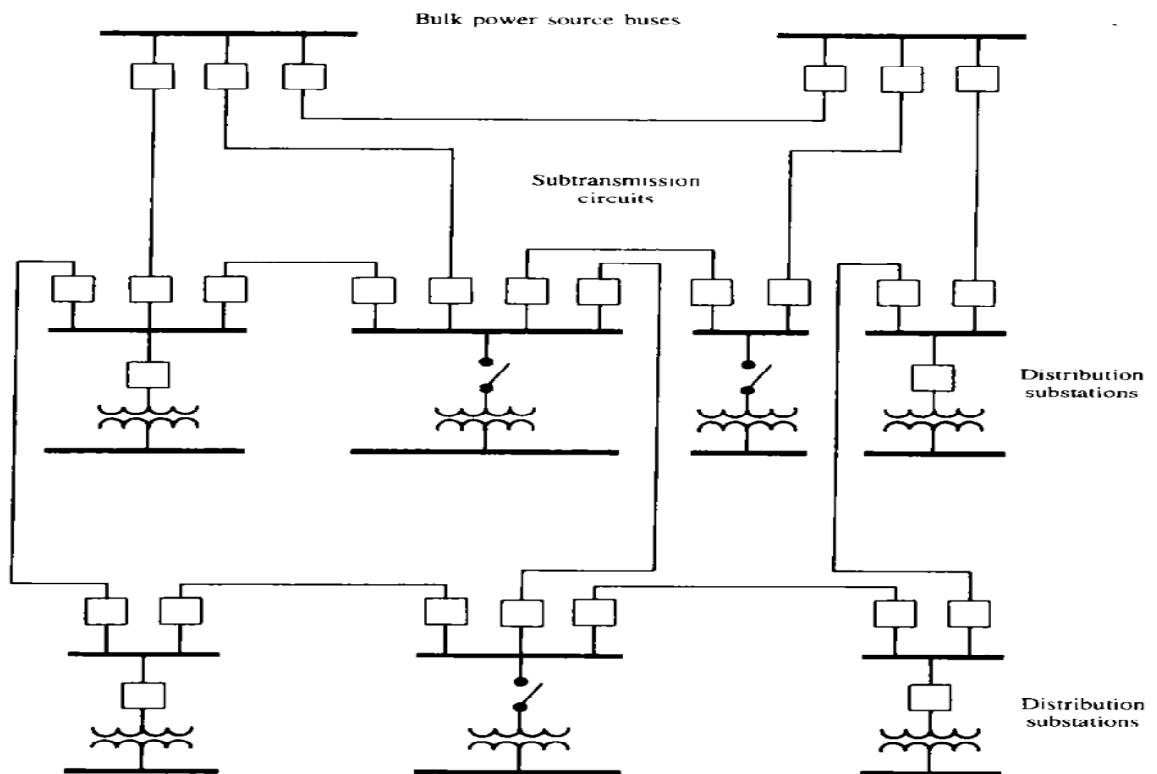


Figure 2.4 Network sub-transmission system



In radial system as the name implies the circuits radiate from the bulk power station to the distribution substation. The radial system is simple and has low first cost but it also has low services continuity, for this reason the radial system is not generally used.

Improved system from radial sub-transmission is introduced as shown in Figure 2.3. In this system additional feeder is incorporated to allow relatively faster service restoration when faults occur on the one of transmission circuits.

Due to higher service reliability the sub-transmission system is designed as loop circuits or multiple circuits forming a sub-transmission grid or network as shown in Figure .2.4. In this design a single circuit origination from a bulk power bus runs through a number of substation and returns to the sane bus.

The network or grid sub-transmission has multiple circuits in order to produce interconnected substations. The design may have more than one bulk power source, therefore it has the greatest service reliability and it requires costly control of power flow and control system. This type is the most commonly used form of sub-transmission.

## **2.4 Distribution Substations:**

Distribution substation is one of the important components of the distribution system. Since the electrical power grid can be consider as simple circuit include power source, its transmission and distribution lines, and finally the load consumers. In this network the substation play an important role by converting the voltages in order to match the transmission and distribution levels.

### **❖ Roles of Substations:**

- 1- Facilitate the regional interconnection for neighbouring electrical grids. This increase system efficiency and reliability.
- 2- Facilitate the connection of different generation station into electrical power grid.
- 3- Step down the high and medium voltages to value suitable for distribution at the customers' level.
- 4- Regulate the power system voltage using the tap changer with the power transformer, capacitors and reactors (the devices lactated at the substation).
- 5- Facilitate the disconnection of some of subsystem (such as transformer, transmission line) to achieve maintenance, programming tests or even extension works using disconnection switches at the substation.

### **❖ Substations Types:**

There are two main types of substations:

- 1- Transmission substations : These substations transform the high transmission voltage into lower high voltage or even medium voltage before delivering the power to distribution centers.

2- Distribution substations : Always step down the medium sub-transmission voltages to low voltage suitable for distribution purposes. In general the substations are divided according to their nature and design into:

- i- Outdoor substation: all the circuits are located in the external space and the circuits are isolated using the air.
- ii- Indoor substation: All the main circuits including the high and low voltages circuits are located inside special building except power transformer. The circuits are isolated using fibre and integrated papers.

### ❖ **Substation components:**

The main components of any substation are:

- 1- Power Transformers: step up/ or down the voltages before distribute the electrical power into load centres.
- 2- Circuit breakers: connect/ or disconnect the power during normal (maintenance, extension ...) or abnormal conditions (faults). These devices have mechanisms for arch extinguish produced during breaking periods. There are many types of circuits' breakers (air blast, oil, vacuum, SF<sub>6</sub>...).
- 3- Isolators: used to provide the visual isolation after already disconnecting the circuit with circuit breakers. There are interlock between the isolator and circuit breaker to guarantee that isolator are opened before the circuit breaker because the isolators are not equipped with arch extinguished mechanisms.
- 4- Bus bars: used to collect the electrical power before distributed it into primary feeders. The bus bars are classified into many types according to substation rating.
- 5- Voltage and current transformers: special transformers uses for measuring and protection purpose. There always step down the current and voltage to values suitable for measuring and protection devices.

- 6- Capacitors and reactors: there can be connected in series or parallel and used for voltage regulation by generation or absorbing the reactive power.
- 7- Lighting arresters: used to protect the substation devices from the high voltage generated due the lighting stroke the substation.
- 8- Earthing system: uses to protect the power system operators from the ground discharge occur in substation devices.
- 9- Earthing switches: this switches use during maintenance to ground the device in order to protect the power system engineers.
- 10- Protection and measurement panels: uses to achieve continuity of supply by safeguard the entire system to maintain, minimize damage and repair costs and to ensure safety of personnel.
- 11- Control panel and communication devices: those are the parts responsible of achieving the logical and soft ware dealing with the electrical devices.
- 12- Batteries to supplies protecting and measuring relays: the batteries act like a reserve source of supplying when the main source is affected or is during fault condition, and the relays are the sensing devices which detect the faults and instantaneously send a signal to its protecting device.
- 13- Current limiting reactors: uses to limit the fault currents, they absorb the fault currents which are expected to cause a complete damage to the isolation system.
- 14- Line trap: uses to protect the substation from high voltages generated due to switching of the breakers.

## 2.5 Substation bus schemes:

The electrical and physical arrangement of the switching and busing at substation are determined by substation type or scheme. The selection of particular substation scheme is based on safety, reliability, economy, simplicity and other consideration. The most commonly used substation bus schemes are shown below.

1-single bus scheme

2-double bus double breaker scheme

3-double bus single breaker scheme

4-main and transfer bus scheme

5-Ring bus scheme

6-breaker and half scheme

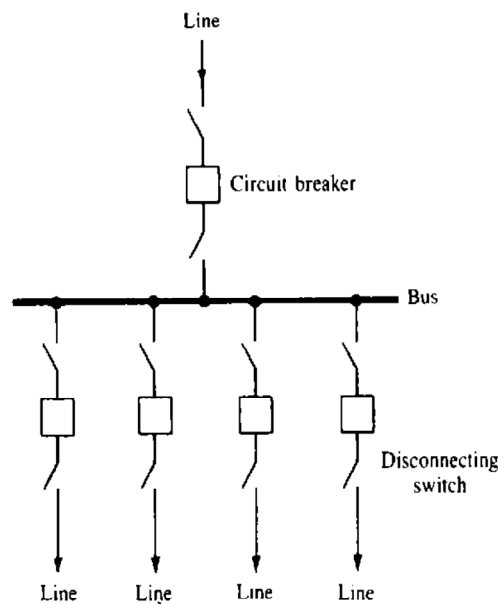


Figure 2.5 single bus scheme

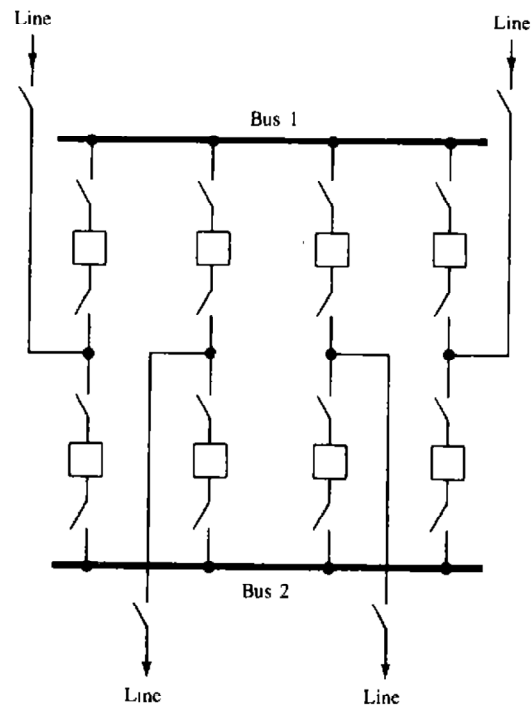


Figure 2.6 double bus double breaker scheme

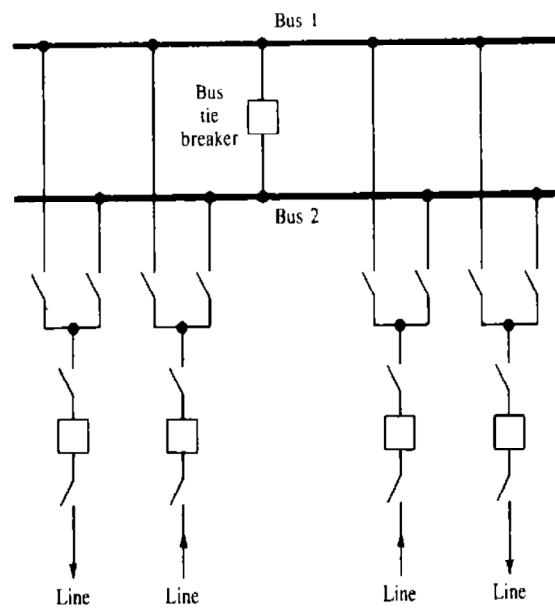


Figure 2.7 double bus single breaker scheme

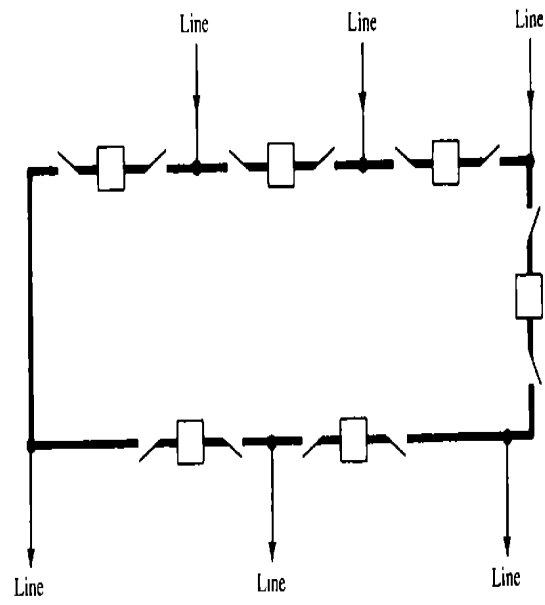


Figure 2.8 Ring bus scheme

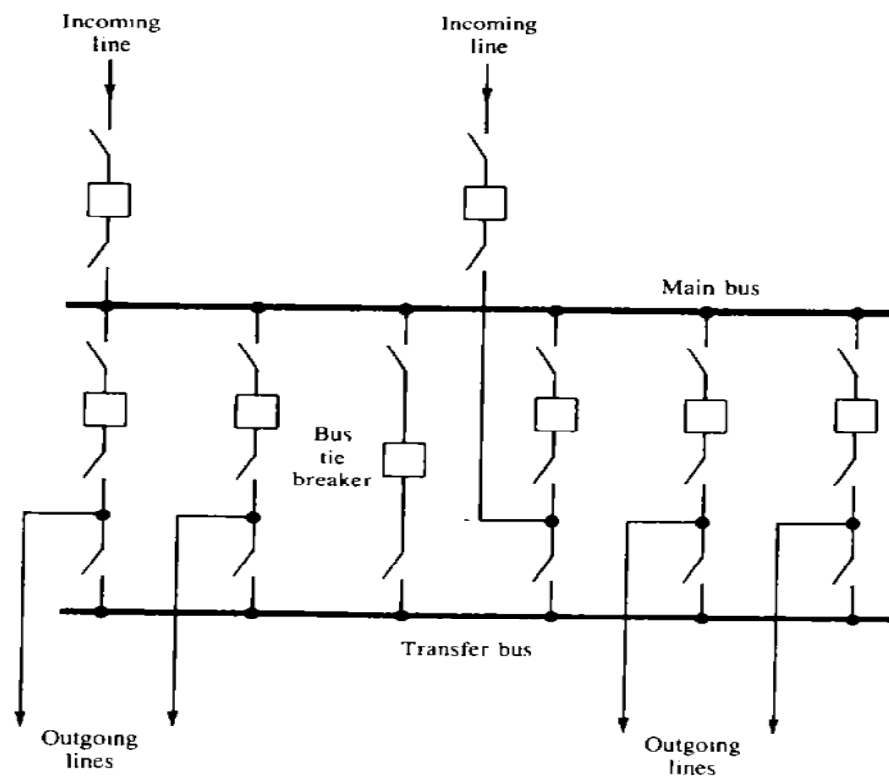


Figure 2.9 main and transfer bus scheme

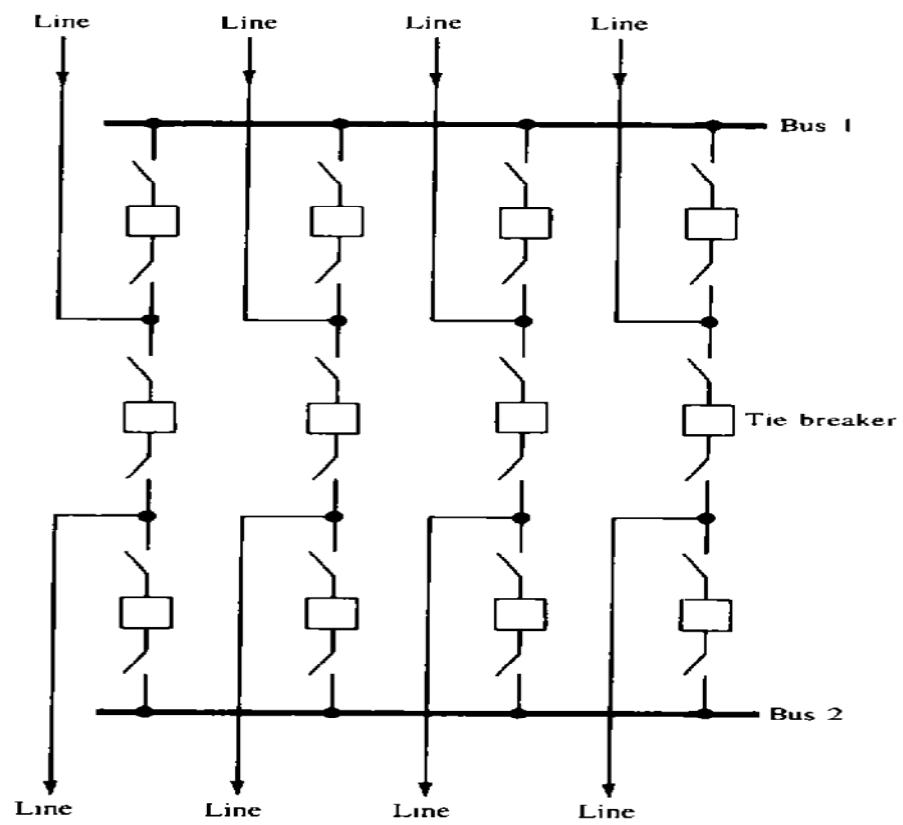


Figure 2.10 breaker and half scheme



## 2.6 Comparison of the bus schemes:

Table 2.1 Comparison of the bus schemes

type	Advantages	disadvantages
single bus	1- Lowest cost	1- Failure of the bus for any reason result in shutdown of the station 2- Difficulties to achieve maintenance or station extension without shutdown the station.
double bus double breaker	1- Each circuit has two dedicated breakers 2-High reliability 3- Any breaker can be taken out for maintenance	1- Most expensive 2- Would lose half the circuits for breaker failure if circuits are not connected to both buses
double bus single breaker	1-Increased flexibility with two buses. 2-Main bus may be isolated for maintenance 3-Circuits could be transferred to other bus using bus tie breakers	1- Extra breaker is required for bus tie 2- Four switches are required per circuit. 3- Line breaker failure take all circuit connected to that bus out of service 4- Bus tie breaker failure takes entire substation out of service
main and transfer bus	1-Low initial cost 2-Any breaker can be taken out for maintenance	1- extra breaker is required for bus tie 2- Failure of the bus or any circuit result in shutdown of the station
Ring bus scheme	1-Low initial cost 2-Flexible operation for breaker maintenance 3- Required only one breaker per circuit 4-Each circuit is fed by two breakers	1- if fault occur during breaker maintenance the ring will separated into two sections 2- If single set of relays is used the circuit must be taken out of service for relay maintenance

breaker and half	1-Most flexible operation 2- High reliability 3- Breaker failure of one side removes only the circuit from service. 4- Bus failure does not remove any feeder circuit from service. 5- Either main bus can be taken out for maintenance.	1- Require 1½ breaker per circuit
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## 2.7 Substation Location

To select ideal location for a substation, the following rules should be observed:

- 1- Locate the substation as much as feasible close to the load centre of its service area.
- 2- Locate the substation such that proper voltage regulation is obtained without extensive measurement.
- 3- Locate the substation such that it provides proper access for incoming sub-transmission lines and outgoing primary feeders.
- 4- The selected substation location should provide enough space for the future substation expansion.
- 5- The selected location should not oppose the land use regulations, local ordinances and neighbours.
- 6- The selected location must help to minimize the number of customers affected by any services discontinuity.

## ❖ Voltage Drop at Substation Main Feeders

The analysis of voltage drop at square shaped service area represents the entire served area of a distribution substation is achieved by assumed:

- 1- The square is fed by four primary feeders from central feed point as shown in Figure 2.12, each feeder and laterals are of three phase.
- 2- Dots represent balanced three phase loads lumped at that location and fed by distribution transformer.
- 3- Uniformly distributed load that mean equal loaded distribution transformers.

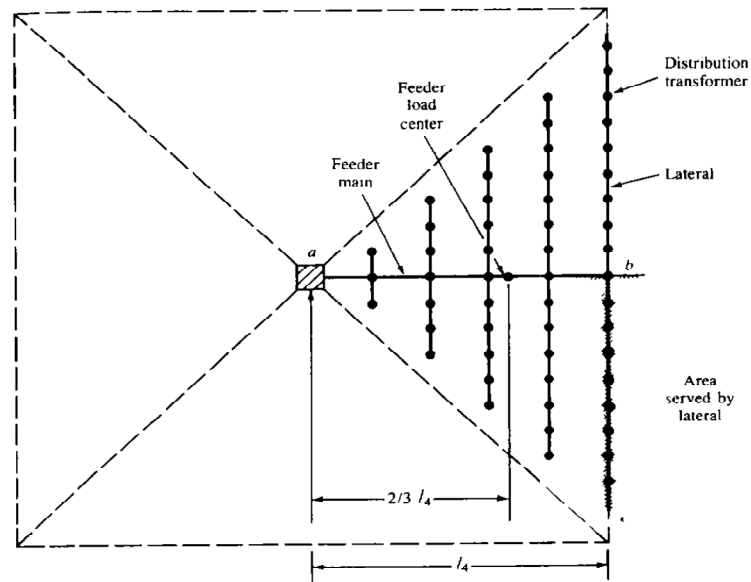


Figure 2.11 square shaped distribution substation service area

In figure 2.12 each feeder serves a total load of

$$S_4 = A_4 \times D \quad KVA \quad (2.1)$$

Where  $S_4$  is kilovolt ampere load served by one of the four feeders emanating from a feed point.  $A_4$  is the area served by one of the four feeders emanating from a feed point ( $m^2$ ). And  $D$  is the load density.

Since :  $A_4 = (l_4)^2$

Where  $l_4$  is the linear dimension of the primary service area in meter.  
Equation (2.1) became:

$$S_4 = (l_4)^2 \times D \quad KVA \quad (2.2)$$

The voltage drop at main primary feeder is:

$$\% VD_{4,main} = \frac{2}{3} \times l_4 \times K \times S_4 \quad (2.3)$$

In this equation the total lumped load is assumed to be located at a distance of  $2/3l$  from central feed point. K onstant is found from conductor voltage drop graph.

Substitution equation (2.2) into (2.3) than:

$$\% VD_{4,main} = 0.667 \times K \times D \times (l_4)^3 \quad (2.4)$$

If the served area is extend to hexagonally shaped served area supplied by six feeders from fed central point as shown in Figure 2.12. each feeder is feed area equal to  $1/6$  of the hexagonally.

$$A_6 = 0.578 \times l_6 \quad (2.5)$$

Where  $l_6$  primary feeder demension. Each feeder serve a total load of

$$S_6 = A_6 \times D \quad (2.6)$$

As before the total lumped load is located at distance of  $2/3l$  from the feed point.therefore the presentage voltage drop is:

$$\% VD_{6,main} = \frac{2}{3} \times l_6 \times K \times S_6 \quad (2.7)$$

$$\% VD_{6,main} = 0.385 \times K \times D \times (l_6)^3 \quad (2.8)$$

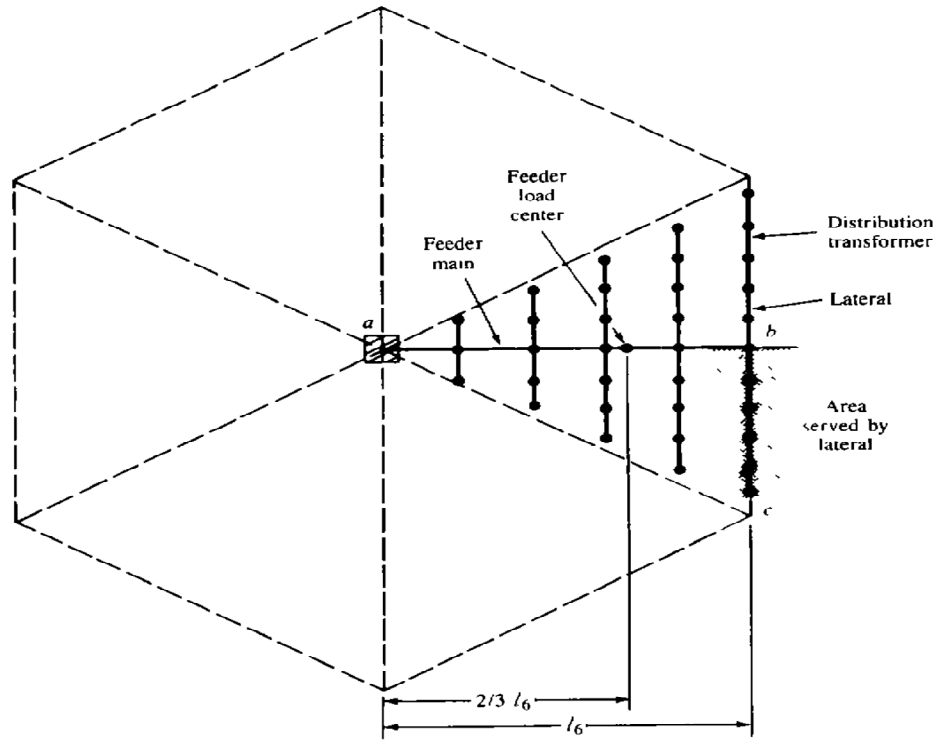


Figure 2.12 hexagonally shaped distribution substation service area

### ❖ Comparison between square and hexagonally:

For square served area, the total area served by all four feeders

$$TA_4 = 4 A_4 = 4(l_4)^2 \quad (2.9)$$

Thus total kilovoltamere served by all four feeders is

$$TS_4 = 4D \times (l_4)^2 \quad (2.10)$$

The percentage voltage drop on the main feeder is

$$\% VD_{4, main} = \frac{2}{3} \times K \times D \times (l_4)^3 \quad (2.11)$$

The load current on the main feeder at feed point a is

$$I_4 = \frac{S_4}{\sqrt{3} \times V_{L-L}} \Rightarrow I_4 = \frac{(l_4)^2 \times D}{\sqrt{3} \times V_{L-L}} \quad A \quad (2.12)$$

For hexagonally served area, the total area served by all four feeders

$$TA_6 = \frac{6}{\sqrt{3}} (l_6)^2 \quad (2.13)$$

Thus total kiovoltamere served by all four feeders is

$$TS_6 = \frac{6}{\sqrt{3}} D \times (l_6)^2 \quad (2.14)$$

The percentage voltage drop on the main feeder is

$$\% VD_{6,main} = \frac{2}{3 \sqrt{3}} K \times D \times (l_6)^3 \quad (2.15)$$

The load current on the main feeder at feed point a is

$$I_6 = \frac{S_6}{\sqrt{3} \times V_{L-L}} \Rightarrow I_6 = \frac{D \times (l_6)^2}{\sqrt{3} \times V_{L-L}} \quad (2.16)$$

The relation between the served areas of four and six feeders can be found under two assumption

- 1- Feeder circuit are thermally limited
- 2- Feeder circuit are voltage drop limited

❖ Thermally limited (That mean  $I_4 = I_6$ )

$$\frac{(l_4)^2 \times D}{\sqrt{3} \times V_{L-L}} = \frac{D \times (l_6)^2}{\sqrt{3} \times V_{L-L}} \quad (2.17)$$

Then

$$\left(\frac{l_6}{l_4}\right)^2 = \sqrt{3} \quad (2.18)$$

By dividing equation (2.13) by (2.10)

$$\frac{TA_6}{TA_4} = \frac{6/\sqrt{3} (l_6)^2}{4(l_4)^2} = \frac{\sqrt{3}}{2} \left(\frac{l_6}{l_4}\right)^2 \quad (2.19)$$

Substituting equation (2.18) on (2.19) then

$$\frac{TA_6}{TA_4} = \frac{3}{2} \quad (2.20)$$

∴ The six feeder area could carry **1.5** time as much as four feeder if they are thermally limited.

❖ Voltage drop limited That mean :

$$\%VD_4 = \%VD_6 \quad (2.21)$$

$$l = 0.833 \times l_6 \quad (2.22)$$

The total area served by all six feeders :

$$TA_6 = \frac{6}{\sqrt{3}} (l_6)^2 \quad (2.23)$$

$$TA_4 = 2.78 \times (l_6)^2 \quad (2.24)$$

Dividing equation (2.23) by (2.24) then:

$$\frac{TA_6}{TA_4} = \frac{5}{4} \quad (2.25)$$

Therefore, the six feeder area could carry **1.25** time as much as four feeder if they are voltage drop limited.

The K constant can be derived using the conductor voltage drop graph (this is graph curve for copper conductors).

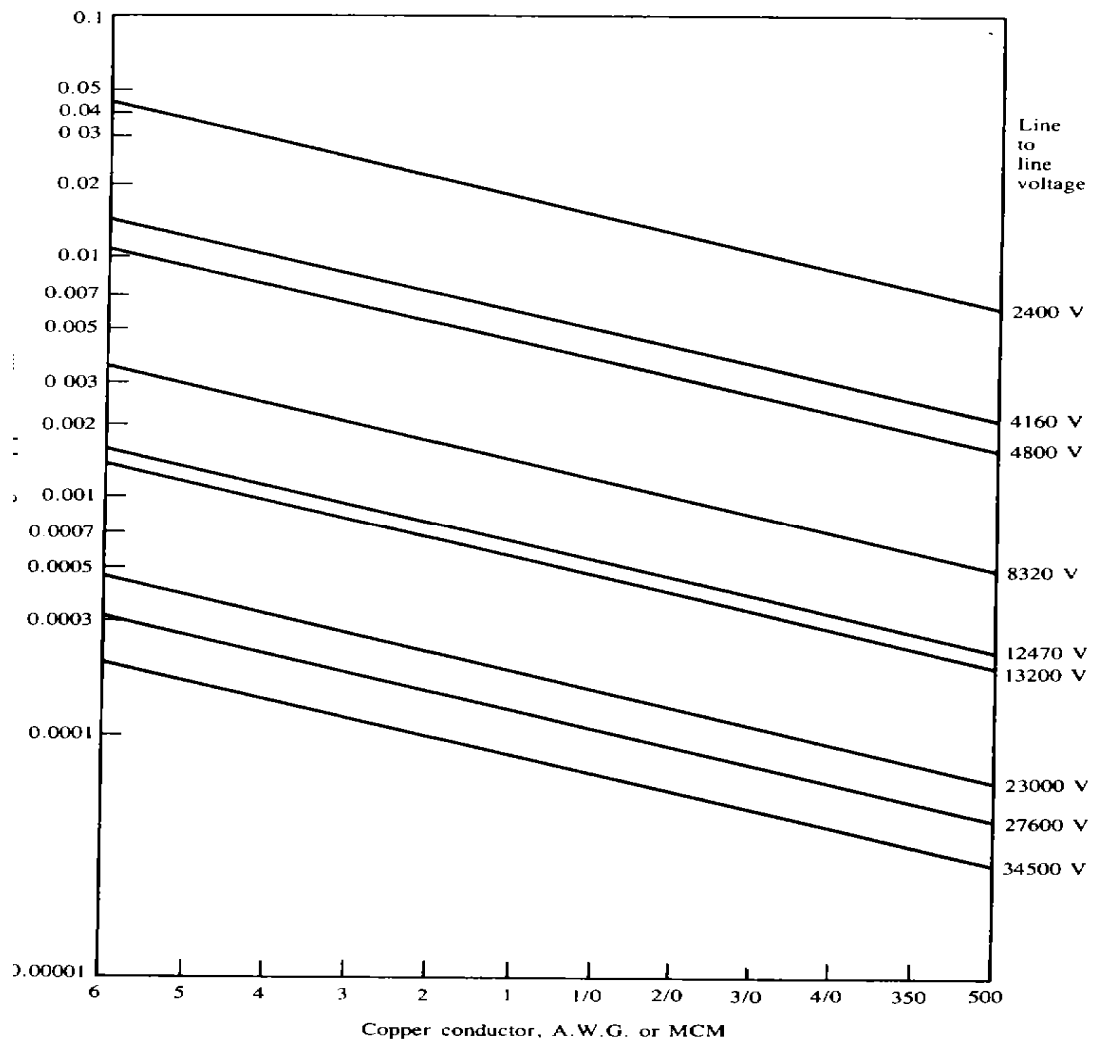


Figure 2.13 K constant for copper conductors



## 2.8 Primary feeder system:

The part of the electric utility system which is between distribution substation and distribution transformers is called the primary system. It is made of circuits known as primary feeders or primary distribution feeders. Figure 2.14 shows one line diagram of typical primary distribution system, the figure includes:

- 1- Main feeder usually three phase, four wire circuit.
- 2- Laterals/ or branches single or three phase circuits tapped of the main, always located at residential and rural areas.
- 3- Sub-lateral single phase circuit consist of line and neutral tapped off the lateral, always located at residential and rural areas.
- 4- Distribution transformers.
- 5- Reclosing devices to sectionalized the feeder in order to as little as possible of the faulted circuits, this can be achieved through coordination of reclosing switches and fuses.
- 6- Shunt capacitors.

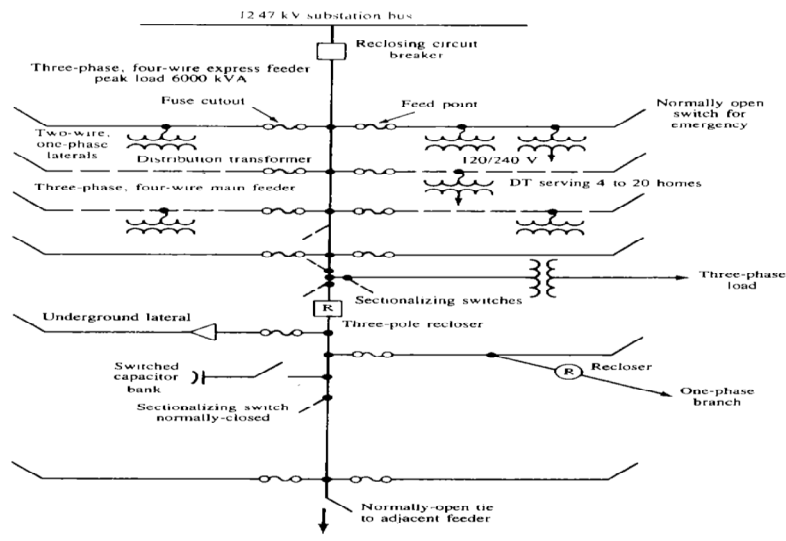


Figure 2.14 one line diagram of typical primary distribution system

There are many factors affecting the selection of primary feeder rating, for example:

- 1- The nature of the load connected.
- 2- The load density.
- 3- The growth rate of the load.
- 4- Cost.
- 5- Capacity of substation.
- 6- Regulation equipment.
- 7- Continuously pf the service.

The voltage condition in distribution systems is improved by using shunt capacitors connected which are connected near the loads to derieved the best benfit. The use of shunt capacitors also improve the power factor and reduce currents and the losses. The voltage condition can be also improved by using series capacitors but they did not reduce the currents and therefore losses in the system.

#### ❖ Radial type primary feeder

The simplest, lowest cost and the most common form of primary feeder is the redial type (see figure. 2.15).

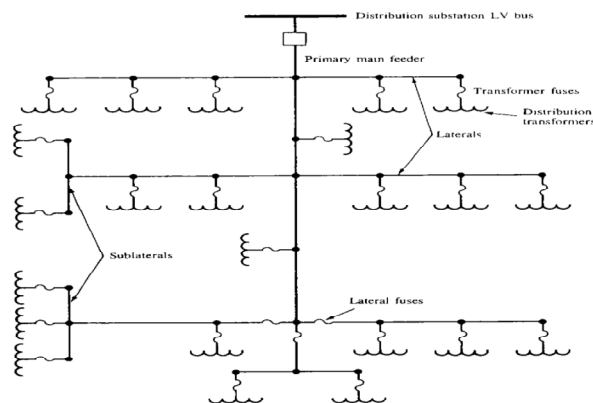


Figure 2.15 : Radial type primary feeder

The main primary feeder branches into various laterals which in turn separated into several sub-lateral to cover all distribution transformers. In general the main feeder is three phase, four wire system and the sub-lateral is single/ or three phase circuit. The current magnitude is the greatest in the feeder conductors leave the substation and continuously lessens out at the end of the feeder as the laterals and sub-laterals are tapped off the feeder. As the current lessens the size of the conductor is also lessens.

The reliability of the service continuity of the radial system is the lowest. Any fault at any location on the main feeder cause a power outage for every consumer on the feeder unless the fault can be isolated from the source by a disconnecting devices such as fuse, sectionalizer, disconnecting switch or recloser.

Figure 2.16 shows a modified radial type primary feeder with tie and sectionalizing switches to provide fast restoration of the service to customers by switching unfaulted section of the feeder. The fault can be isolated by opening the associated disconnection devices on each side of the faulted section.

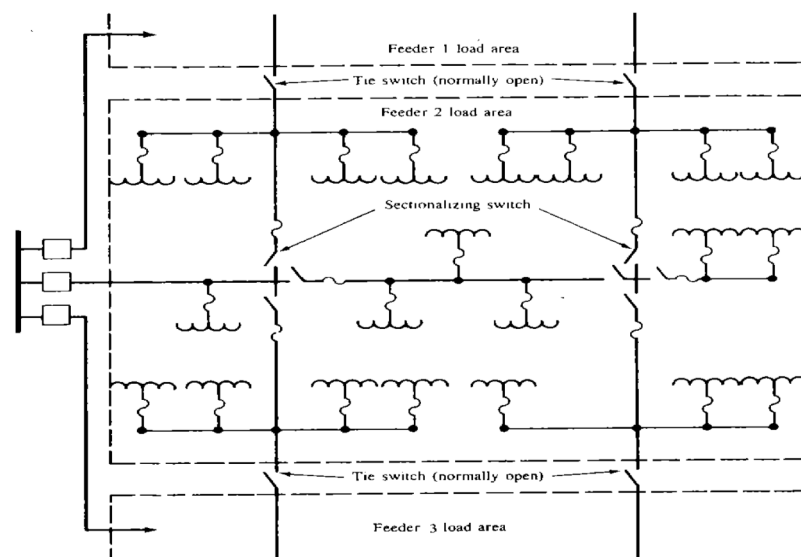


Figure 2.16 Radial type primary feeder with tie and sectionalizing switches

Figure 2.17 show another type of the modified primary feeder with express feeder and backfeed. The section between the substation low voltage bus and the load center of the service area is called an express feeder. No subfeeders or laterals are allowed to be tapped off the express feeder. However a subfeeder is allowed to provide a backfeed toward the substation from the load center.

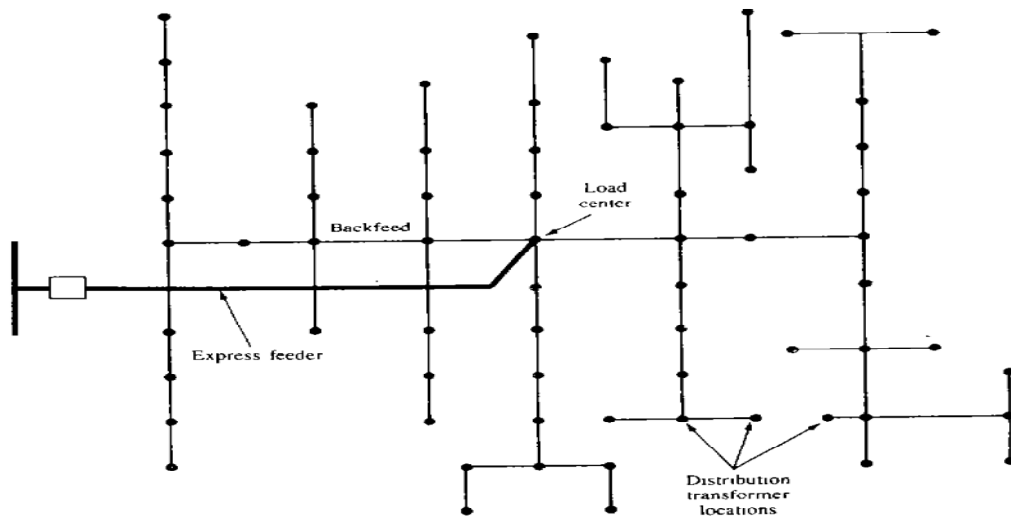


Figure 2.17 Radial type primary feeder with express feeder and backfeed

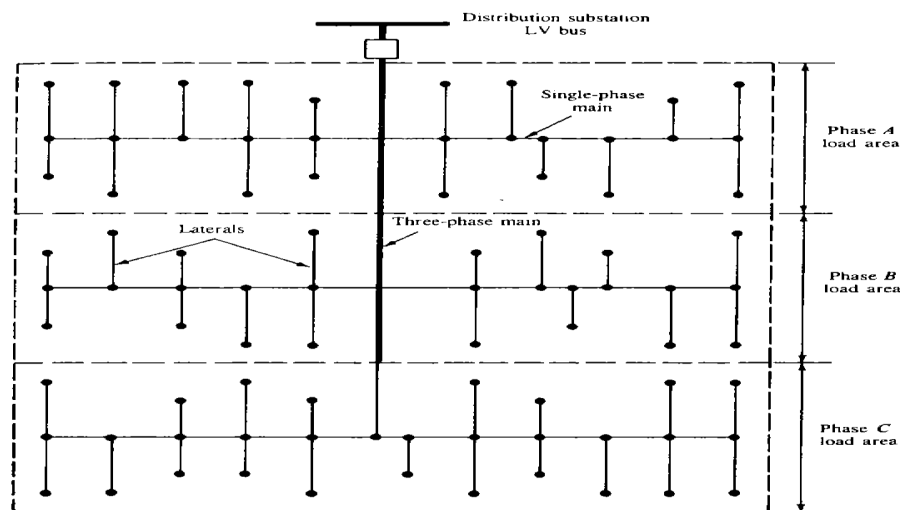


Figure 2.18 Radial type phase area feeder

## ❖ Loop-type primary feeder

Figure 2.19 represent a loop type primary feeder which loop through the feeder load area and return back to the bus. Sometime the loop tie disconnect switch is replaced by a loop tie breaker according to loads conditions.

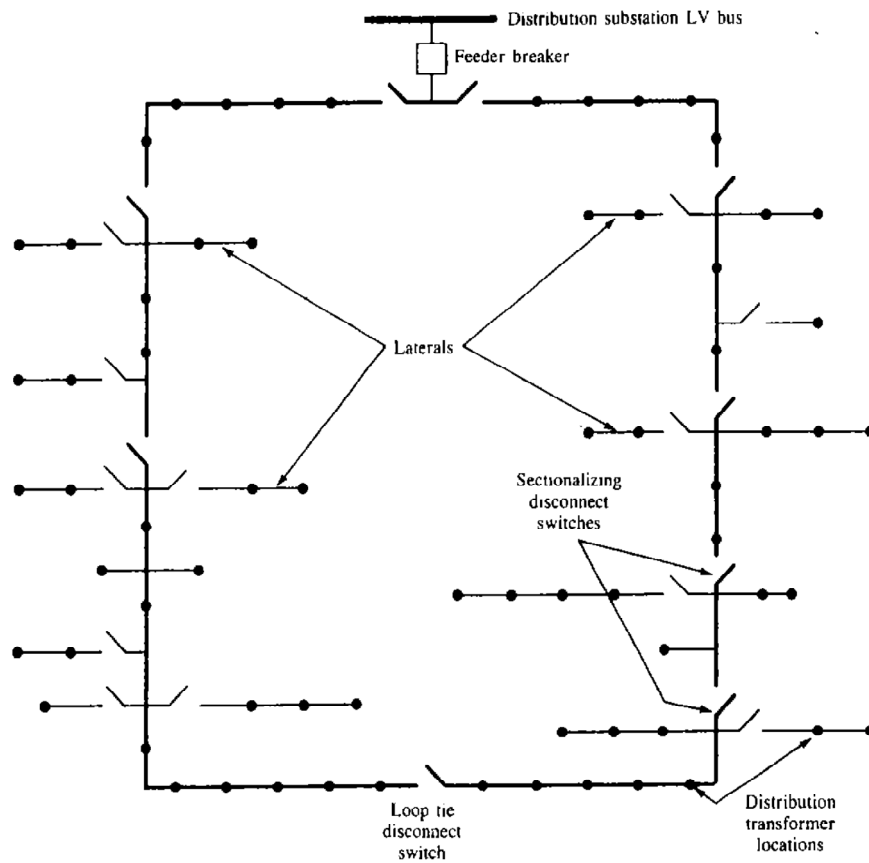


Figure 2.19 loop type primary feeder

The size of the feeder conductor is kept the same throughout the loop, it is selected to carry its rated load plus the load of the other half of the loop. This arrangement provides two parallel paths from the substation to the load when the loop is operated with normally open tie breaker. The loop type feeder is preferred to provide service for loads where high reliability service is required. In general two separated tie breaker is on each end of the loop is preferred although the the cost involved.

### ❖ Network primary feeder

As shown in figure 2.20 a primary network is a system of interconnected feeders supplied by number of substation. Each tie feeder has two associated circuit breakers at each end in order to have less load interrupted due to tie-feeder fault. The primary network system supplies a load from several direction and they have lower power losses compared to to radial and loop system due to load division. The reliabilty and quilty of service of the primary network system is much higher than the other types, however it is more difficult to design and operate than the radial and loop systems.

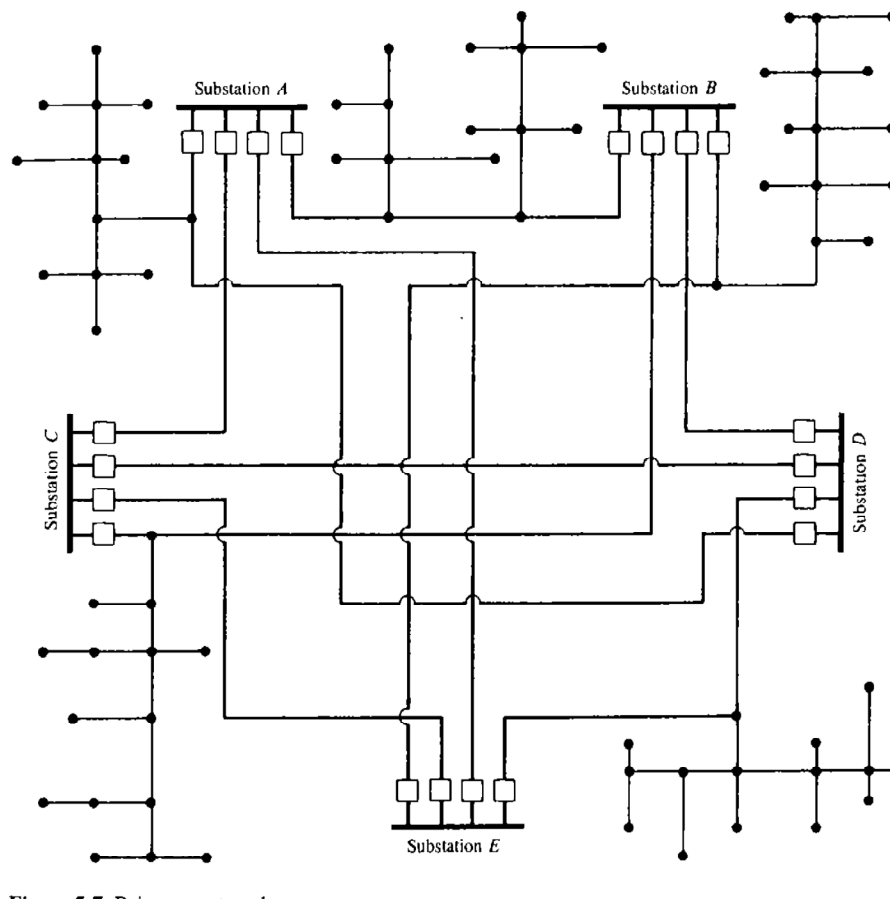


Figure 2.20 Network type primary feeder

## 2.9 Tie line :

A tie line is line connects two supply system to provide emergency service to one system from another as shown in figure 2.21 Usually the tie line provides services for area loads along its route as well as providing emergency services to areas or substation. In general tie line provide either of the following functions:

- 1- To provide emergency service for a adjacent feeder to reduce outage time during emergencies.
- 2- To provide emergency service for adjacent substation systems and eliminating the necessity of having an emergency backup supply at every substation.

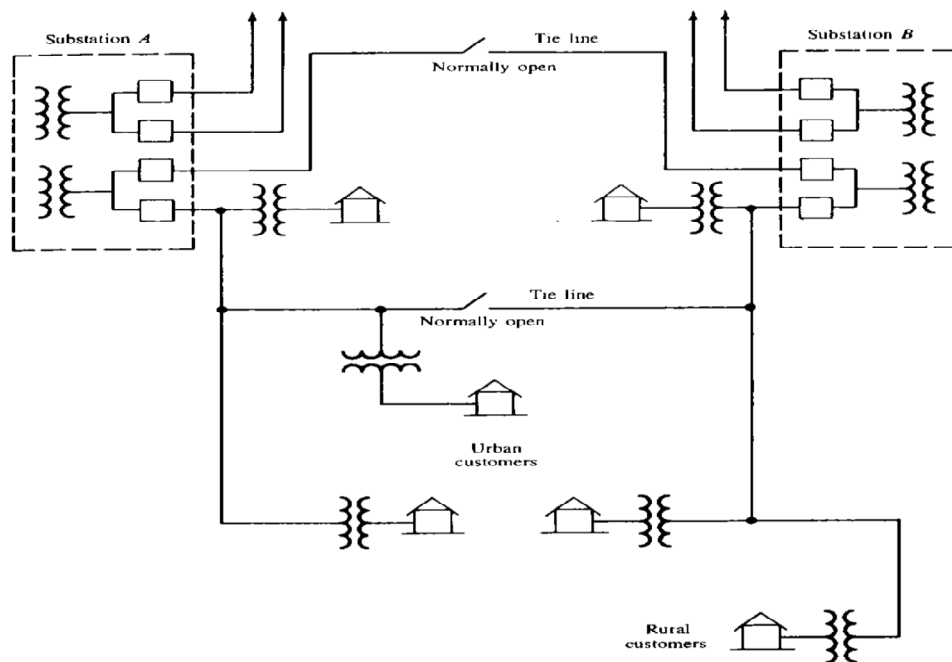


Figure 2.21 one line diagram of typical two substation areas supplied with tie line

## 2.10 The design of radial primary systems

The radial primary system is may be design as overhead lines or underground cables.

### ❖ Over head primaries

Figure 2.22 shows an arrangement for overhead distribution includes main feeder and 10 laterals connected to main feeder with sectionalizing fuses. The distribution area consist of 60 blocks each block contain 24 services.

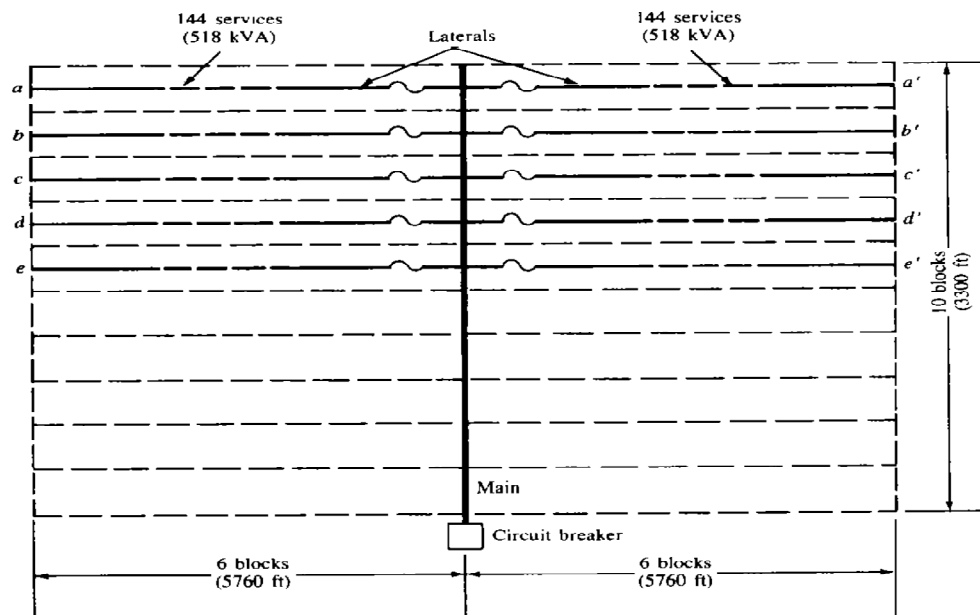


Figure 2.22 an overhead radial distribution system



## ❖ Underground cable primaries

Although the underground cables cost about 1.5 to 10 times the overhead distribution system but they have several advantages:

- 1- Lack of outage due to avormal weather conditions such as ice, snow, rain and lighting.
- 2- Lack of outage cause by accidents, and fire.
- 3- Lack of tree trimming.

Figure 2.23 shows an arrangement for typical overhead and underground cable distribution area. In the figure the four overhead line carry the total load of the area. The distribution area consist of 240 blocks each block contain 24 services. The lateral in made of underground cable.

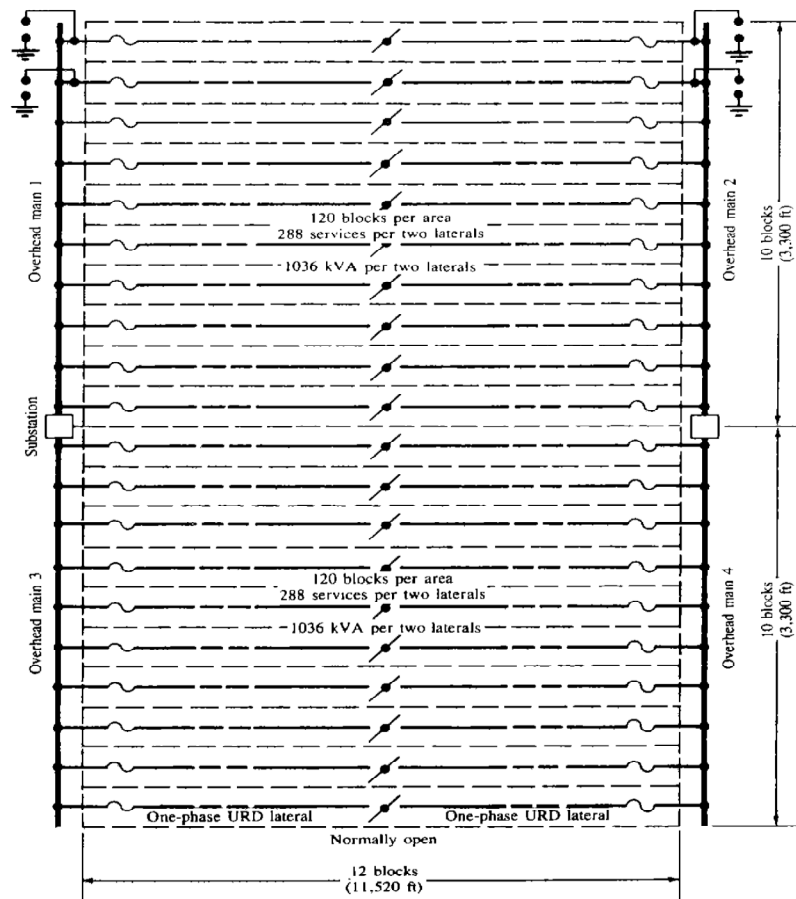


Figure 2.23 two way feed type underground residential distribution system

## **CHAPTER Three**

### **Power Factor Improvement**

#### **3.1 Introduction**

The electrical energy is almost exclusively generated, transmitted and distributed in the form of alternating current. Therefore, the question of power factor immediately comes into picture. Most of the loads (e.g. induction motors, arc lamps) are inductive in nature and hence have low lagging power factor. The low power factor is highly undesirable as it causes an increase in current, resulting in additional losses of active power in all the elements of power system from power station generator down to the utilization devices. In order to ensure most favorable conditions for a supply system from engineering and economical standpoint, it is important to have power factor as close to unity as possible. In this chapter, we shall discuss the various methods of power factor improvement.

#### **3.2 Power Factor**

The cosine of angle between voltage and current in an a.c. circuit is known as power factor. In an a.c. circuit, there is generally a phase difference  $\phi$  between voltage and current. The term  $\cos \phi$  is called the power factor of the circuit.

If the circuit is inductive, the current lags behind the voltage and the power factor is referred to as lagging. However, in a capacitive circuit, current leads the voltage and power factor is said to be leading.

Consider an inductive circuit taking a lagging current (I) from supply voltage (V); the angle of lag being  $\phi$ . The phasor diagram of the circuit is shown

in Figure 3.1. The circuit current ( $I$ ) can be resolved into two perpendicular components, namely;

(a)  $I \cos \phi$  in phase with  $V$

(b)  $I \sin \phi$   $90^\circ$  out of phase with  $V$

The component  $I \cos \phi$  is known as active or wattful component, whereas component  $I \sin \phi$  is called the reactive or wattless component. The reactive component is a measure of the power factor. If the reactive component is small, the phase angle  $\phi$  is small and hence power factor  $\cos \phi$  will be high. Therefore, a circuit having small reactive current (i.e.,  $I \sin \phi$ ) will have high power factor and vice-versa. It may be noted that value of power factor can never be more than unity.

(i) It is a usual practice to attach the word ‘lagging’ or ‘leading’ with the numerical value of power factor to signify whether the current lags or leads the voltage. Thus if the circuit has a p.f. of 0.5 and the current lags the voltage, we generally write p.f. as 0.5 lagging.

(ii) Sometimes power factor is expressed as a percentage. Thus 0.8 lagging power factor may be expressed as 80% lagging.

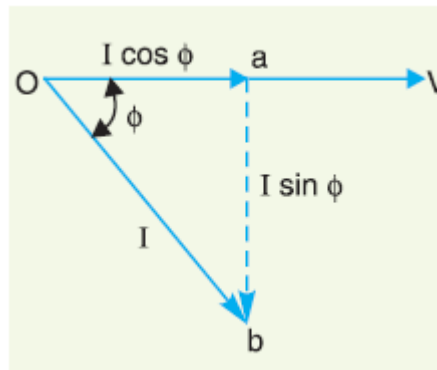


Figure 3.1. The phasor diagram of an inductive circuit

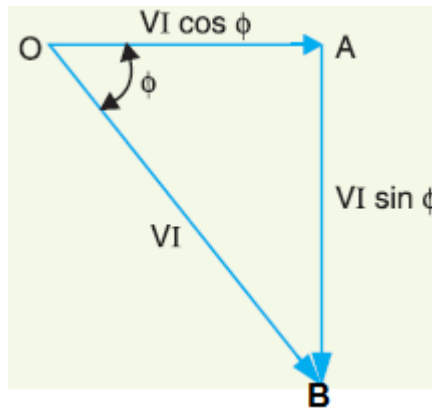


Figure 3.2. The Power Triangle

### 3.3 Power Triangle

The analysis of power factor can also be made in terms of power drawn by the a.c. circuit. If each side of the current triangle oab of Figure 3.1 is multiplied by voltage  $V$ , then we get the power triangle OAB shown in Figure 3.2 where:

$OA = VI \cos \phi$  and represents the active power in watts or kW

$AB = VI \sin \phi$  and represents the reactive power in VAR or kVAR

$OB = VI$  and represents the apparent power in VA or kVA

The following points may be noted from the power triangle:

(i) The apparent power in an a.c. circuit has two components viz., active and reactive power at right angles to each other.

$$OB^2 = OA^2 + AB^2$$

$$\text{Or (apparent power)}^2 = (\text{active power})^2 + (\text{reactive power})^2$$

$$\text{Or (kVA)}^2 = (\text{kW})^2 + (\text{kVAR})^2$$

$$(ii) \text{ Power factor, } \cos \phi = \frac{OA}{OB} = \frac{\text{active power}}{\text{apparent power}} = \frac{kW}{kVA}$$

Thus the power factor of a circuit may also be defined as the ratio of active power to the Apparent power. This is a perfectly general definition and can be applied to all cases, whatever be the waveform.

(iii) The lagging (\*) reactive power is responsible for the low power factor. It is clear from the Power triangle that smaller the reactive power component, the higher is the power factor of the circuit.

$$\text{kVAR} = \text{kVA} \sin \phi = \frac{\text{kW}}{\cos \phi} \sin \phi$$

$$\therefore \text{kVAR} = \text{kW} \tan \phi$$

(iv) For leading currents, the power triangle becomes reversed. This fact provides a key to the power factor improvement. If a device taking leading reactive power (e.g. capacitor) is connected in parallel with the load, then the lagging reactive power of the load will be partly neutralized, thus improving the power factor of the load.

(v) The power factor of a circuit can be defined in one of the following three ways:

(a) Power factor =  $\cos \phi$  = cosine of angle between V and I

$$(b) \text{ Power factor} = \frac{R}{Z} = \frac{\text{Resistance}}{\text{Impedance}}$$

$$(c) \text{ Power factor} = \frac{VI \cos \phi}{VI} = \frac{\text{Active Power}}{\text{Apparent Power}}$$

(vi) The reactive power is neither consumed in the circuit nor it does any useful work. It merely flows back and forth in both directions in the circuit. A wattmeter does not measure reactive power.

**Illustration:** Let us illustrate the power relations in an a.c. circuit with an example. Suppose a circuit draws a current of 10 A at a voltage of 200 V and its p.f. is 0.8 lagging. Then,

$$\text{Apparent power} = VI = 200 \times 10 = 2000 \text{ VA}$$

$$\text{Active power} = VI \cos \phi = 200 \times 10 \times 0.8 = 1600 \text{ W}$$

$$\text{Reactive power} = VI \sin \phi = 200 \times 10 \times 0.6 = 1200 \text{ VAR}$$

---

(\*) If the current lags behind the voltage, the reactive power drawn is known as lagging reactive power. However, if the circuit current leads the voltage, the reactive power is known as leading reactive power.

The circuit receives an apparent power of 2000 VA and is able to convert only 1600 watts into active power. The reactive power is 1200 VAR and does no useful work. It merely flows into and out of the circuit periodically. In fact, reactive power is a liability on the source because the source has to supply the additional current (i.e.,  $I \sin \phi$ ).

### 3.4 Disadvantages of Low Power Factor :

The power factor plays an importance role in a.c. circuits since power consumed depends upon this factor.

$$P = V_L I_L \cos \phi \text{ (For single phase supply)}$$

$$\therefore I_L = \frac{P}{V_L \cos \phi} \quad (3.1)$$

$$P = 3 V_L I_L \cos \phi \text{ (For 3 phase supply)}$$

$$\therefore I_L = \frac{P}{3 V_L \cos \phi} \quad (3.2)$$

It is clear from above that for fixed power and voltage, the load current is inversely proportional to the power factor. Lower the power factor, higher is the load current and vice-versa. A power factor less than unity results in the following disadvantages:

(i) **Large kVA rating of equipment:** The electrical machinery (e.g., alternators, transformers, switchgear) is always rated in <sup>(\*)</sup> kVA. Now,  $\text{kVA} = \frac{\text{kW}}{\cos \phi}$  It is clear that kVA rating of the equipment is inversely proportional to power factor. The smaller the power factor, the larger is the kVA rating. Therefore, at low power factor, the kVA rating of the equipment has to be made more, making the equipment larger and expensive.

(ii) **Greater conductor size:** To transmit or distribute a fixed amount of power at constant voltage, the conductor will have to carry more current at low power

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(\*)The electrical machinery is rated in kVA because the power factor of the load is not known when the machinery is manufactured in the factory.

factor. This necessitates large conductor size. For example, take the case of a single phase a.c. motor having an input of 10 kW on full load, the terminal voltage being 250 V. At unity p.f., the input full load current would be  $10,000/250 = 40$  A. At 0.8 p.f, the kVA input would be  $10/0.8 = 12.5$  and the current input  $12,500/250=50$  A. If the motor is worked at a low power factor of 0.8, the cross-sectional area of the supply cables and motor conductors would have to be based upon a current of 50 A instead of 40 A which would be required at unity power factor.

(iii) Large copper losses: The large current at low power factor causes more  $I^2R$  losses in all the elements of the supply system. This results in poor efficiency.

(iv) Poor voltage regulation: The large current at low lagging power factor causes greater voltage drops in alternators, transformers, transmission lines and distributors. This results in the decreased voltage available at the supply end, thus impairing the performance of utilization devices. In order to keep the receiving end voltage within permissible limits, extra equipment (i.e., voltage regulators) is required.

(v) Reduced handling capacity of system: The lagging power factor reduces the handling capacity of all the elements of the system. It is because the reactive component of current prevents the full utilization of installed capacity.

The above discussion leads to the conclusion that low power factor is an objectionable feature in the supply system.

### **3.5 Causes of Low Power Factor**

Low power factor is undesirable from economic point of view. Normally, the power factor of the whole load on the supply system is lower than 0.8. The following are the causes of low power factor:

(i) Most of the a.c. motors are of induction type (1 $\phi$  and 3 $\phi$  induction motors) which have low lagging power factor. These motors work at a power factor

which is extremely small on light load (0.2 to 0.3) and rises to 0.8 or 0.9 at full load.

(ii) Arc lamps, electric discharge lamps and industrial heating furnaces operate at low lagging power factor.

(iii) The load on the power system is varying; being high during morning and evening and low at other times. During low load period, supply voltage is increased which increases the magnetization current. This results in the decreased power factor.

### 3.6 Power Factor Improvement

The low power factor is mainly due to the fact that most of the power loads are inductive and, therefore, take lagging currents. In order to improve the power factor, some device taking leading power should be connected in parallel with the load. One of such devices can be a capacitor. The capacitor draws a leading current and partly or completely neutralizes the lagging reactive component of load current. This raises the power factor of the load.

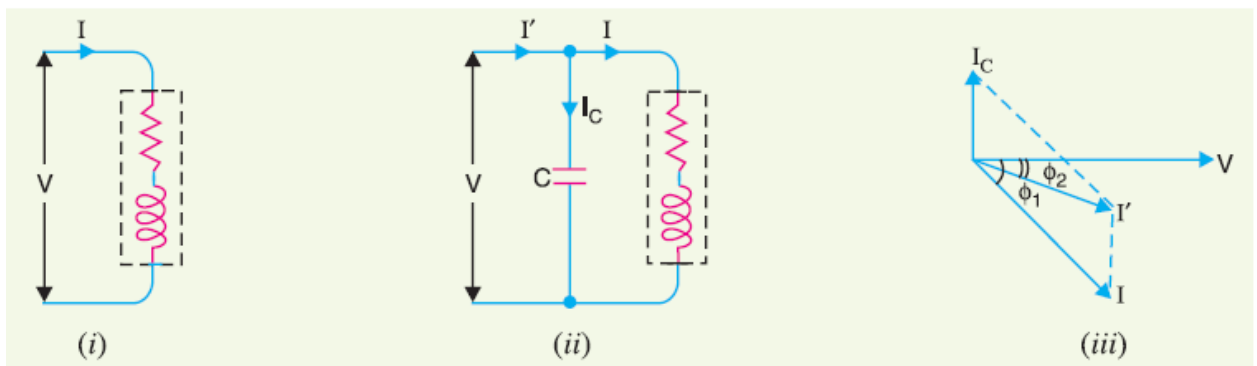


Figure 3.3. power factor improvement by a capacitor



**Illustration.** To illustrate the power factor improvement by a capacitor, consider a single (\*) phase load taking lagging current (I) at a power factor  $\cos \phi_1$  as shown in Figure . 3.3. The capacitor C is connected in parallel with the load. The capacitor draws current  $I_C$  which leads the supply voltage by  $90^\circ$ . The resulting line current  $I'$  is the phasor sum of I and  $I_C$  and its angle of lag is  $\phi_2$  as shown in the phasor diagram of Figure . 3.3. (iii). It is clear that  $\phi_2$  is less than  $\phi_1$ , so that  $\cos \phi_2$  is greater than  $\cos \phi_1$ . Hence, the power factor of the load is improved. The following points are worth noting:

(i) The circuit current  $I'$  after p.f. correction is less than the original circuit current I.

(ii) The active or wattful component remains the same before and after p.f. correction because only the lagging reactive component is reduced by the capacitor.

$$\therefore I \cos \phi_1 = I' \cos \phi_2$$

(iii) The lagging reactive component is reduced after p.f. improvement and is equal to the difference between lagging reactive component of load ( $I \sin \phi_1$ ) and capacitor current ( $I_C$ ) i.e.,  $I' \sin \phi_2 = I \sin \phi_1 - I_C$

$$(iv) \text{ As } I \cos \phi_1 = I' \cos \phi_2$$

$$\therefore VI \cos \phi_1 = VI' \cos \phi_2 \text{ [Multiplying by V]}$$

Therefore, active power (kW) remains unchanged due to power factor improvement.

$$(v) I' \sin \phi_2 = I \sin \phi_1 - I_C$$

$$\therefore VI' \sin \phi_2 = VI \sin \phi_1 - VI_C \text{ [Multiplying by V]}$$

i.e., Net kVAR after p.f. correction = Lagging kVAR before p.f. correction – leading kVAR of equipment

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(\*)The treatment can be used for 3-phase balanced loads e.g., 3- $\phi$  induction motor. In a balanced 3- $\phi$  load, analysis of one phase leads to the desired results.

### 3.7 Power Factor Improvement Equipment:

Normally, the power factor of the whole load on a large generating station is in the region of 0.8 to 0.9. However, sometimes it is lower and in such cases it is generally desirable to take special steps to improve the power factor. This can be achieved by the following equipment:

1. Static capacitors.
2. Synchronous condenser.
3. Phase advancers.

#### 1. Static capacitor:

The power factor can be improved by connecting capacitors in parallel with the equipment operating at lagging power factor. The capacitor (generally known as static) <sup>(\*)</sup> draws a leading current and partly or completely neutralizes the lagging reactive component of load current. This raises the power factor of the load. For three-phase loads, the capacitors can be connected in delta or star as shown in Figure .3.4. Static capacitors are invariably used for power factor improvement in factories.

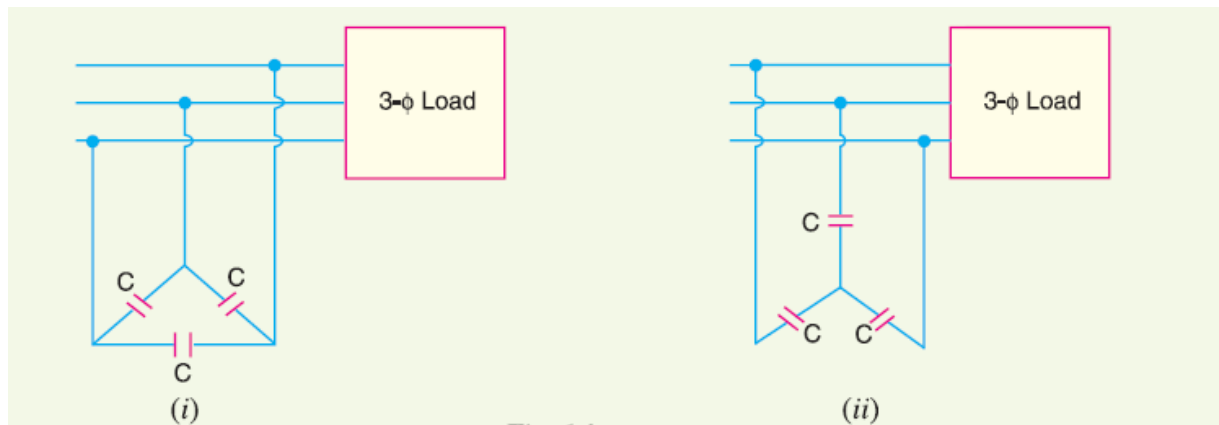


Figure 3.4. Power Factor Improvement Equipment

(\*)To distinguish from the so called synchronous condenser which is a synchronous motor running at no load and taking leading current.

**Advantages:**

- (i) They have low losses.
- (ii) They require little maintenance as there are no rotating parts.
- (iii) They can be easily installed as they are light and require no foundation.
- (iv) They can work under ordinary atmospheric conditions.

**Disadvantages:**

- (i) They have short service life ranging from 8 to 10 years.
- (ii) They are easily damaged if the voltage exceeds the rated value.
- (iii) Once the capacitors are damaged, their repair is uneconomical.

**2. Synchronous condenser:**

A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor. An over-excited synchronous motor running on no load is known as synchronous condenser. When such a machine is connected in parallel with the supply, it takes a leading current which partly neutralizes the lagging reactive component of the load. Thus the power factor is improved. Figure 3.5 shows the power factor improvement by synchronous condenser method. The 3 $\phi$  load takes current  $I_L$  at low lagging power factor  $\cos \phi_L$ . The synchronous condenser takes a current  $I_m$  which leads the voltage by an angle  $\phi_m^{(1)}$ . The resultant current  $I$  is the phasor sum of  $I_m$  and  $I_L$  and lags behind the voltage by an angle  $\phi$ . It is clear that  $\phi$  is less than  $\phi_L$  so that  $\cos \phi$  is greater than  $\cos \phi_L$ . Thus the power factor is increased from  $\cos \phi_L$  to  $\cos \phi$ . Synchronous condensers are generally used at major bulk supply substations for power factor improvement.

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(1) If the motor is ideal i.e., there are no losses, then  $\phi_m = 90^\circ$ . However, in actual practice, losses do occur in the motor even at no load. Therefore, the currents  $I_m$  leads the voltage by an angle less than  $90^\circ$ .

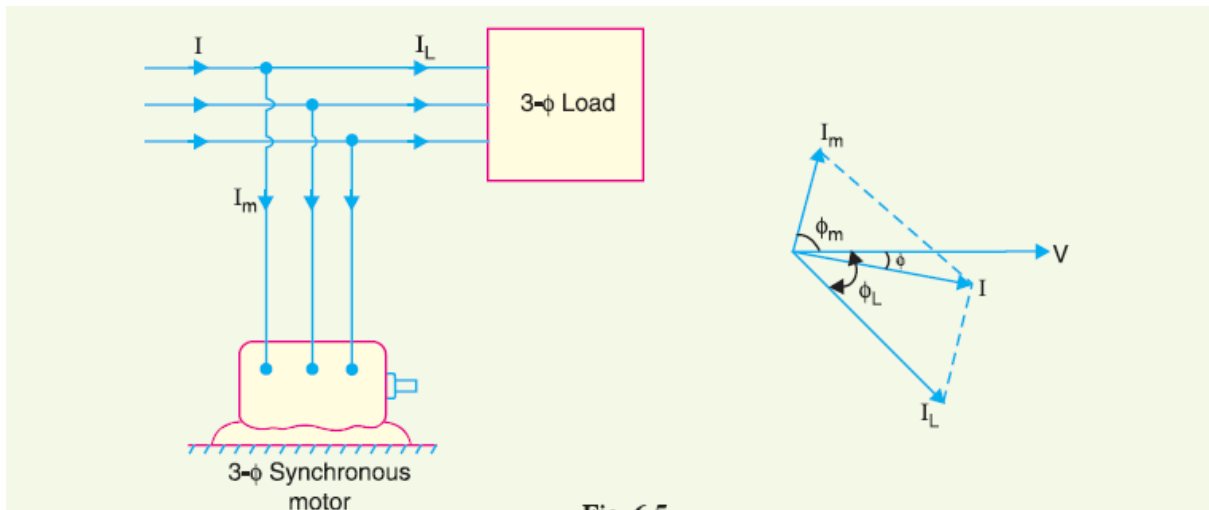


Figure 3.5. the power factor improvement by synchronous condenser method

### Advantages:

- (i) By varying the field excitation, the magnitude of current drawn by the motor can be changed by any amount. This helps in achieving stepless <sup>(1)</sup> control of power factor.
- (ii) The motor windings have high thermal stability to short circuit currents.
- (iii) The faults can be removed easily.

### Disadvantages

- (i) There are considerable losses in the motor.
- (ii) The maintenance cost is high.
- (iii) It produces noise.
- (iv) Except in sizes above 500 kVA, the cost is greater than that of static capacitors of the same rating.
- (v) As a synchronous motor has no self-starting torque, therefore, an auxiliary equipment has to be provided for this purpose.

**Note.** The reactive power taken by a synchronous motor depends upon two factors, the d.c. field excitation and the mechanical load delivered by the motor.

---

(1) The p.f. improvement with capacitors can only be done in steps by switching on the capacitors in various groupings. However, with synchronous motor, any amount of capacitive reactance can be provided by changing the field excitation.

Maximum leading power is taken by a synchronous motor with maximum excitation and zero load.

### **3. Phase advancers:**

Phase advancers are used to improve the power factor of induction motors. The low power factor of an induction motor is due to the fact that its stator winding draws exciting current which lags behind the supply voltage by  $90^\circ$ . If the exciting ampere turns can be provided from some other a.c. source, then the stator winding will be relieved of exciting current and the power factor of the motor can be improved. This job is accomplished by the phase advancer which is simply an a.c. exciter. The phase advancer is mounted on the same shaft as the main motor and is connected in the rotor circuit of the motor. It provides exciting ampere turns to the rotor circuit at slip frequency. By providing more ampere turns than required, the induction motor can be made to operate on leading power factor like an over-excited synchronous motor. Phase advancers have two principal advantages. Firstly, as the exciting ampere turns are supplied at slip frequency, therefore, lagging kVAR drawn by the motor are considerably reduced. Secondly,

Phase advancer can be conveniently used where the use of synchronous motors is unadmissible. However, the major disadvantage of phase advancers is that they are not economical for motors

below 200 H.P.

### 3.8 Calculations of Power Factor Correction:

Consider an inductive load taking a lagging current ( $I$ ) at a power factor  $\cos \phi_1$ . In order to improve the power factor of this circuit, the remedy is to connect such an equipment in parallel with the load which takes a leading reactive component and partly cancels the lagging reactive component of the load. Figure 3.6 (i) shows a capacitor connected across the load. The capacitor takes a current  $I_C$  which leads the supply voltage  $V$  by  $90^\circ$ . The current  $I_C$  partly cancels the lagging reactive component of the load current as shown in the phasor diagram in Figure 3.6 (ii). The resultant circuit current becomes  $I'$  and its angle of lag is  $\phi_2$ . It is clear that  $\phi_2$  is less than  $\phi_1$  so that new p.f.  $\cos \phi_2$  is more than the previous p.f.  $\cos \phi_1$ .

From the phasor diagram, it is clear that after p.f. correction, the lagging reactive component of the load is reduced to  $I' \sin \phi_2$ .

Obviously,  $I' \sin \phi_2 = I \sin \phi_1 - I_C$

Or  $I_C = I \sin \phi_1 - I' \sin \phi_2$

$$\therefore \text{Capacitance of capacitor to improve p.f. from } \cos \phi_1 \text{ to } \cos \phi_2 = \frac{V}{I_C} = \frac{I_C}{\omega V}$$

$$\therefore X_C = \frac{V}{I_C} = \frac{1}{\omega C}$$

**Power triangle.** The power factor correction can also be illustrated from power triangle. Thus referring to Figure 3.7, the power triangle OAB is for the power factor  $\cos \phi_1$ , whereas power triangle OAC is for the improved power factor  $\cos \phi_2$ . It may be seen that active power (OA) does not change with power factor improvement. However, the lagging kVAR of the load is reduced by the p.f. correction equipment, thus improving the p.f. to  $\cos \phi_2$ .

Leading kVAR supplied by p.f. correction equipment

$$= BC = AB - AC$$

$$= \text{kVAR}_1 - \text{kVAR}_2$$

$$= OA (\tan \phi_1 - \tan \phi_2)$$

$$= \text{kW} (\tan \phi_1 - \tan \phi_2)$$

Knowing the leading kVAR supplied by the p.f. correction equipment, the desired results can be obtained.

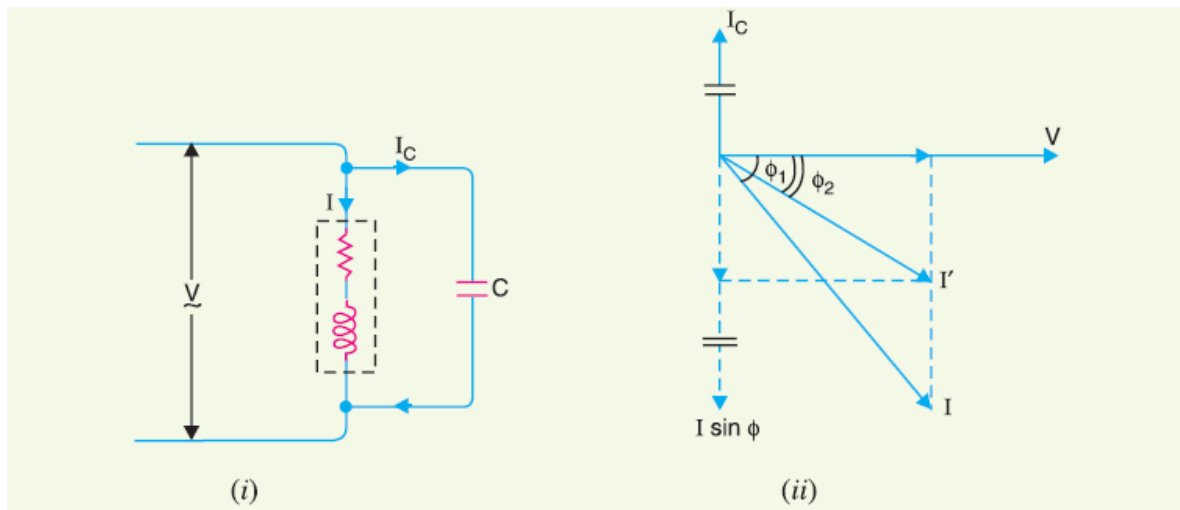


Figure 3.6 (i) shows a capacitor connected across the load.

Figure 3.6 (ii). The lagging reactive component of the load current

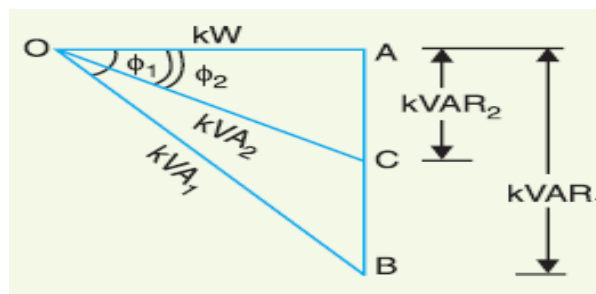


Figure 3.7 Power triangle

### 3.9 Importance of Power Factor Improvement:

The improvement of power factor is very important for both consumers and generating stations as discussed below:

(i) For consumers. A consumer <sup>(1)</sup> has to pay electricity charges for his maximum demand in kVA plus the units consumed. If the consumer improves the power factor, then there is a reduction <sup>(2)</sup> in his maximum kVA demand and consequently there will be annual saving due to maximum demand charges. Although power factor improvement involves extra annual expenditure on account of p.f. correction equipment, yet improvement of p.f. to a proper value results in the net annual saving for the consumer.

(ii) For generating stations. A generating station is as much concerned with power factor improvement as the consumer. The generators in a power station are rated in kVA but the useful output depends upon kW output. As station output is  $\text{kW} = \text{kVA} \times \cos \phi$ , therefore, number of units supplied by it depends upon the power factor. The greater the power factor of the generating station, the higher is the kWh it delivers to the system. This leads to the conclusion that improved power factor increases the earning capacity of the power station.

### 3.10 Most Economical Power Factor:

If a consumer improves the power factor, there is reduction in his maximum kVA demand and hence there will be annual saving over the maximum demand charges. However, when power factor is improved, it involves capital investment on the power factor correction equipment. The consumer will incur expenditure every year in the shape of annual interest and depreciation on the investment made over the p.f. correction equipment. Therefore, the net annual saving will be equal to the annual saving in maximum

---

(1) This is not applicable to domestic consumers because the domestic load (e.g., lighting load) has a p.f. very close to unity. Here, consumer means industrial and other big consumers.

(2) Max. Demand in kVA =  $\frac{\text{Peak kW}}{\cos \phi}$  If  $\cos \phi$  is more, maximum kVA demand will be less and vice-versa.



demand charges minus annual expenditure incurred on p.f. correction equipment.

The value to which the power factor should be improved so as to have maximum net annual saving is known as **the most economical power factor**.

Consider a consumer taking a peak load of  $P$  kW at a power factor of  $\cos \phi_1$  and charged at a rate of  $R_s$  x per kVA of maximum demand per annum. Suppose the consumer improves the power factor to  $\cos \phi_2$  by installing p.f. correction equipment. Let expenditure incurred on the p.f. correction equipment be  $R_s$  y per kVAR per annum. The power triangle at the original p.f.  $\cos \phi_1$  is OAB and for the improved p.f.  $\cos \phi_2$ , it is OAC [See Figure .3.8].

kVA max. demand at  $\cos \phi_1$ ,  $kVA_1 = P/\cos \phi_1 = P \sec \phi_1$

kVA max. demand at  $\cos \phi_2$ ,  $kVA_2 = P/\cos \phi_2 = P \sec \phi_2$

Annual saving in maximum demand charges

$$\begin{aligned} &= R_s \times (kVA_1 - kVA_2) \\ &= R_s \times (P \sec \phi_1 - P \sec \phi_2) \\ &= R_s \times P (\sec \phi_1 - \sec \phi_2) \end{aligned} \quad (2.3)$$

Reactive power at  $\cos \phi_1$ ,  $kVAR_1 = P \tan \phi_1$

Reactive power at  $\cos \phi_2$ ,  $kVAR_2 = P \tan \phi_2$

Leading kVAR taken by p.f. correction equipment

$$= P (\tan \phi_1 - \tan \phi_2)$$

Annual cost of p.f. correction equipment

$$= R_s P_y (\tan \phi_1 - \tan \phi_2) \quad (2.4)$$

Net annual saving,  $S = \text{exp. (i)} - \text{exp. (ii)}$

$$= xP (\sec \phi_1 - \sec \phi_2) - yP (\tan \phi_1 - \tan \phi_2)$$

In this expression, only  $\phi_2$  is variable while all other quantities are fixed. Therefore, the net annual saving will be maximum if differentiation of above expression w.r.t.  $\phi_2$  is zero i.e.

$$\frac{d}{d\phi_2}(S) = 0$$

$$\text{or } \frac{d}{d\phi_2}(S) [xP (\sec \phi_1 - \sec \phi_2) - yP (\tan \phi_1 - \tan \phi_2)] = 0$$

$$\text{or } 0 - (xP \sec \phi_1) - \frac{d}{d\phi_2}(xP \sec \phi_2) - \frac{d}{d\phi_2} (yP \tan \phi_1) + yP \frac{d}{d\phi_2} (\tan \phi_2) = 0$$

$$\text{or } 0 - xP \sec \phi_2 \tan \phi_2 - 0 + yP \sec^2 \phi_2 = 0$$

$$\text{or } -x \tan \phi_2 + y \sec \phi_2 = 0$$

$$\text{or } \tan \phi_2 = \frac{y}{x} \sec \phi_2$$

$$\text{or } \sin \phi_2 = y/x$$

$$\therefore \text{Most economical power factor, } \cos \phi_2 = \sqrt{1 - \sin^2 \phi_2} = \sqrt{1 - (y/x)^2}$$

It may be noted that the most economical power factor ( $\cos \phi_2$ ) depends upon the relative costs of supply and p.f. correction equipment but is independent of the original p.f.  $\cos \phi_1$ .

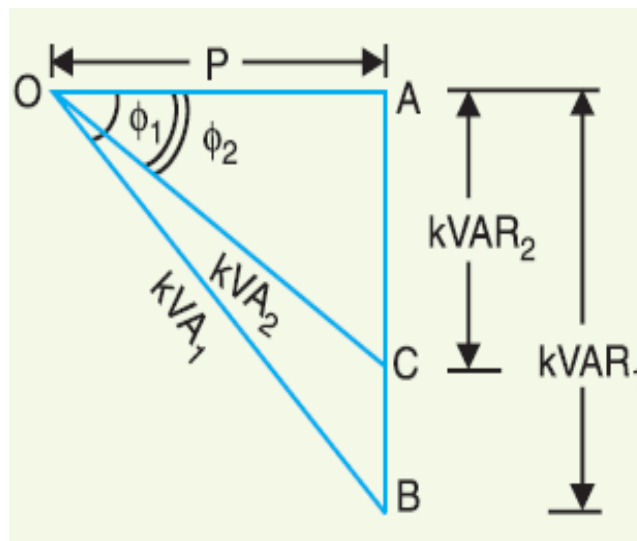


Figure 3.8 Power triangle

### 3.11 Meeting the Increased kW Demand on Power Stations

The useful output of a power station is the kW output delivered by it to the supply system. Sometimes, a power station is required to deliver more kW to meet the increase in power demand. This can be achieved by either of the following two methods :

- (i) By increasing the kVA capacity of the power station at the same power factor (say  $\cos \phi_1$ ). Obviously, extra cost will be incurred to increase the kVA capacity of the station.
- (ii) By improving the power factor of the station from  $\cos \phi_1$  to  $\cos \phi_2$  without increasing the kVA capacity of the station. This will also involve extra cost on account of power factor correction equipment. Economical comparison of two methods. It is clear that each method of increasing kW capacity of the station involves extra cost. It is, therefore, desirable to make economical comparison of the two methods. Suppose a power station of rating  $P$  kVA is supplying load at p.f. of  $\cos \phi_1$ . Let us suppose that the new power demand can be met either by increasing the p.f. to  $\cos \phi_2$  at  $P$  kVA or by increasing the kVA rating of the station at the original p.f.  $\cos \phi_1$ . The power<sup>(\*)</sup> triangles for the whole situation are shown in Figure 3.9.

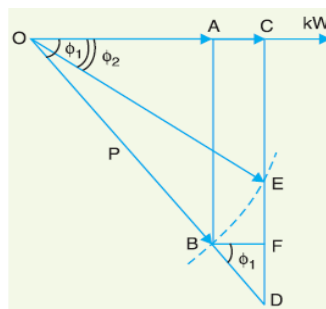


Figure 3.9 The power triangles for the whole situation

(\*) Note the construction. Here  $\Delta OAB$  is the power triangle for the station supplying  $P$  kVA at  $\cos \phi_1$ . The demand on the station is  $OA$  kW. The new demand is  $OC$  kW. This can be met :

(i) either by increasing the kVA demand of the station to  $OD$  at the same p.f.  $\cos \phi_1$ . Obviously,  $\Delta OCD$  is the power triangle when the station is supplying  $OC$  kW at  $\cos \phi_1$ .

(ii) or by increasing the p.f. from  $\cos \phi_1$  to  $\cos \phi_2$  at same kVA i.e.,  $P$  kVA. Obviously,  $OB = OE$ .

Therefore,  $\Delta OCE$  is the power triangle when the station is supplying  $OC$  kW at improved p.f.  $\cos \phi_2$ .

## **CHAPTER Four**

### **Simulation**

#### **“An ATP Simulation of Shunt Capacitor Switching in an Electrical Distribution System”**

##### **4.1 Introduction:**

ATPDraw is a graphical, mouse-driven preprocessor to the ATP version of the Electromagnetic Transients Program (EMTP) on the MS-Windows platform. In ATPDraw the user can construct an electrical circuit using the mouse and selecting components from menus, then ATPDraw generates the ATP input file in the appropriate format based on "what you see is what you get". The simulation program ATP and plotting programs can be integrated with ATPDraw. A license is required to use the solver ATP.

Power quality has been a topic of constant study as problems inherent to it can lead to economical losses, mainly in industrial processes. Although other factors influence power quality, the work presented here focuses on transients originating from shunt capacitor bank switching in primary distribution systems. The privatization of electric companies requires a regulation which, among other aspects, focuses on the quality of electric power, imposing patterns and limits that guarantee customers a clean and reliable supply of energy. This procedure avoids losses to the customers related to the presence of transients as well as interruptions. Research has been carried out in order to evaluate the costs related to interruptions of power supply and power quality (short duration interruptions and voltage sags).

Electric Power Systems have predominantly inductive loads, so that the systems themselves must supply the reactive power consumed. The most practical and efficient way for the utility to supply the reactive power demanded is through the installation of Capacitor Banks (C.B.) in the system. The installation of shunt C.B. brings benefits concerning the reduction of system charging and electrical losses, system capacity release, and also improvements in the power factor. The use of such banks in distribution systems is intense where two types (either fixed or switchable) are utilized depending on the technical criteria adopted by the utility. One of the types of control regarding capacitor switching, which is mostly used nowadays in electrical distribution systems, employing a current relay in order to monitor the load current magnitude. The load variations where the capacitor banks are installed can cause frequent switching when the banks are operated by current relays. Customers are often motivated to install capacitor banks in order to avoid the penalties related to the low power factors imposed by utilities.

## **4.2 Basic Concepts Concerning Energization of Capacitors:**

The capacitor switching phenomenon is shown in Figure 4.1, where resistances were omitted by simplification.

In systems where the natural frequencies of the LC loop are higher than the fundamental frequency (60 Hz), the overvoltage's should continuously increase as the ratio of the natural frequencies approach unity since the fundamental voltage will be essentially constant. The equations for the current and voltage in the capacitor C1 during the closing of the switch S1 in Figure 4.1, with switch S2 open, are given respectively by:

$$VC1(t) = V - [V - VC1(0)] \cos \omega_1 t \quad (4.1)$$

$$I1(t) = \frac{V}{Z_1} \sin \omega_1 t \quad (4.2)$$

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \quad \Rightarrow \text{natural frequency}$$

$$VC1(0) \quad \Rightarrow \text{initial voltage at C1}$$

$$V \quad \Rightarrow \text{Switch Voltage at S1 closing.}$$

$$Z1 = \frac{L_1}{C_1} \quad \Rightarrow \text{Surge Impedance}$$

In Figure 4.1, the closing of switch S2, with switch S1 already shut, is considered. In this case, any potential difference between the two banks is eliminated by a redistribution of charge. The equalizing current that flows in the inductance L2, is given by:

$$I2(t) = \frac{V1 - VC2(0)}{\sqrt{L_2 \frac{(C_1 + C_2)}{C_1 C_2}}} \sin \omega_2 t \quad (4.3)$$

$$\omega_2 = \frac{1}{L_2 \frac{(C_1 + C_2)}{C_1 C_2}} \quad (4.4)$$

$$V1 \quad \Rightarrow \text{C1 voltage at S2 closing}$$

$$VC2(0) \quad \Rightarrow \text{initial voltage at C2}$$

$$\omega_2 \quad \Rightarrow \text{transient frequency}$$

### 4.3 Case Study

This simulation focuses on the effects of the C.B. switching in the utility primary distribution system, at the customer's plant (industry). The circuit shown in Figure 4.2 was used for the purpose of this study. It consists of a primary distribution system with a feeder that exclusively supplies one single industry whose demand was approximately 9.0 MVA, at 13.8 kV. The substation transformer was modeled considering its saturation curve. Two C.B.

(900 and 1,200 kVAr) were installed along the feeder in order to simulate the real life case. This feeder consists of a CA-477 MCM bare cable in conventional overhead structure, and it was represented by coupled RL elements. The industry's load basically comprises induction motors whose power varies from 0.25 to 600 HP, which corresponds to 10,750 kW of installed power.

The effects of the C.B. switching in the distribution system were simulated using ATP software. The industry's load shown in Figure 4.2 was represented by two elements: one represents the R-L loop with constant impedance and the other represents the capacitor used for power factor correction. The ordinary C.B. installation pattern is consists of a structure with only two oil switches, with a nominal capacity of 200 A, installed at the external phases, with the internal phase permanently energized. Several load conditions required by the industry were considered for the utility C.B. energization (900 kVAr and 1,200 kVAr), which are summarized in Table4.1. It was assumed that the power factor of the industry was corrected from 0.80 to 0.92, according to their needs.

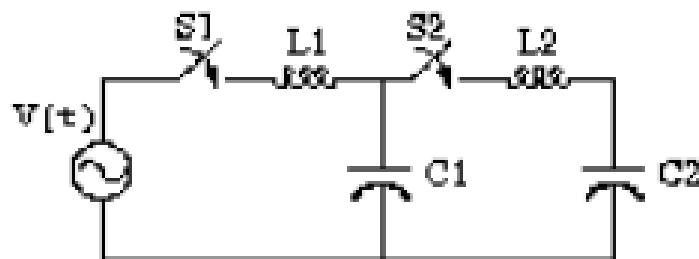


Figure 4.1 Circuit with two L-C loops

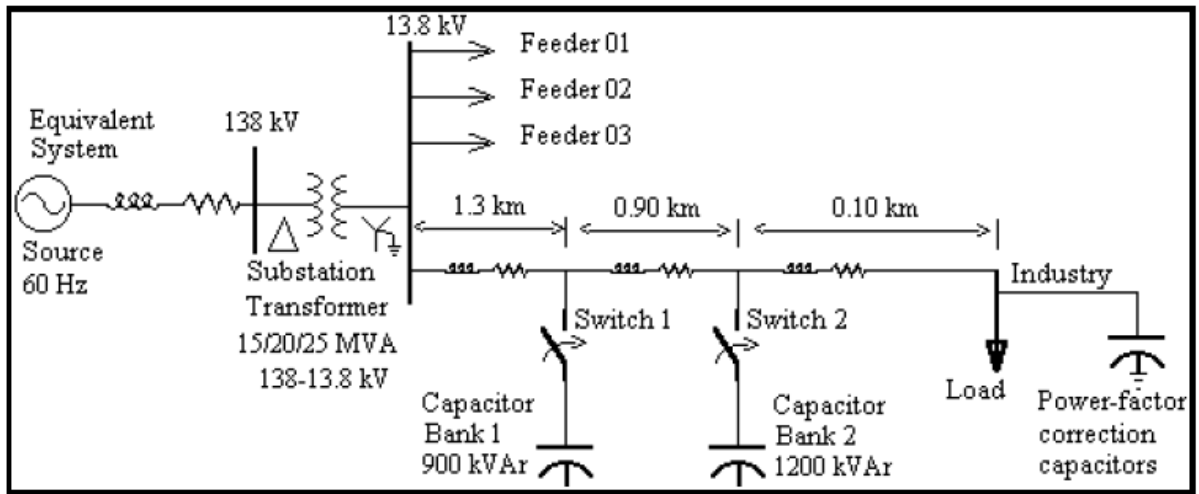


Figure 4.2 One-phase diagram of the distribution system studied

Several load conditions required by the industry were considered for the utility C.B. energization (900 kVAr and 1,200 kVAr), which are summarized in Table 4.1. It was assumed that the power factor of the industry was corrected from 0.80 to 0.92, according to their needs.

Table 4.1- Load impedances related to load currents

		C.B. - 900 kVAr			C.B. - 1200		
	load	90	120	150	168	224	280
Load with pf.= 0.92 (per phase)	R ( $\Omega$ )	61.58	46.18	36.94	32.99	24.73	19.79
	Xl ( $\Omega$ )	46.19	34.64	27.71	24.74	18.55	14.84
	L (mH)	122.5	91.89	73.50	65.64	49.19	39.38
Industry C.B. (per phase)	KVAr	214	285	356	399	532	665
	Xc ( $\Omega$ )	296.6	222.7	178.3	159.1	119.2	95.46
	$\mu$ F	8.94	11.91	14.88	16.67	22.25	27.79



Table 4.2 - Maximum transient overvoltage

C.B. energization – 900 kVAr Load 90 (A)	Maximum voltage (p.u.)		
	at the bank	at substation	at load
Original situation	1.77	1.49	2.06
C.B. at substation	1.80	1.80	2.00
5 ms pole spread	1.77	1.51	2.08
Load without capacitors	1.92	1.60	1.91
1995 kVAr at the load	1.80	1.50	1.44
Synchronized closing	1.34	1.21	1.35

### ❖ Transient Voltages

Several cases were simulated using ATP software in order to evaluate the conditions that affect the associated C.B. energization transient intensity. The case in which the 900 kVAr C.B. is energized during a 90 A load current was used as a reference for several simulations where other variables were modified. In Table 4.2 some of the obtained maximum overvoltage values of the distribution system are presented. The peak voltage at different locations of the distribution system for the switching of the 900 kVAr C.B. is shown. Apart from the specified cases, simultaneous closing was adopted.

For the first three cases, amplification of the transient overvoltage at the industry was experienced. The largest value of 2.08 p.u. was obtained when the pole spread was considered, with phase A closing 5 ms after the other and near the voltage peak. For the last three cases, the transient overvoltage at the industry was attenuated. As noticed in the literature, the synchronous switch closing is very efficient in the mitigation of the transient overvoltage.

When the industry's load is modeled without the power factor correction capacitors, a low transient overvoltage is noticed. This situation is also observed for the case in which the industry has all his capacitors switched on ( 1995 kVAr).

Figure 4.3 illustrates the voltage waves at the load for the 900 kVAr C.B. switching (reference case). Transients in the voltage waves can be observed up to four cycles after the bank switching.

Figure .4.4 shows the voltage waves for the case where the 1,200 kVAr C.B. is switched at the 168 A load current, with the 900 kVAr C.B. already switched on and in a steady state. In this case, high frequency components are intensified due to the interaction of the L-C loop formed in the circuit.

Figure 4.5 illustrates the maximum overvoltage peak with relation to the load current for the 900 kVAr and 1,200 kVAr C.B. respectively. It can be observed that the overvoltage transients are mitigated when the C.B. are switched at higher load currents.

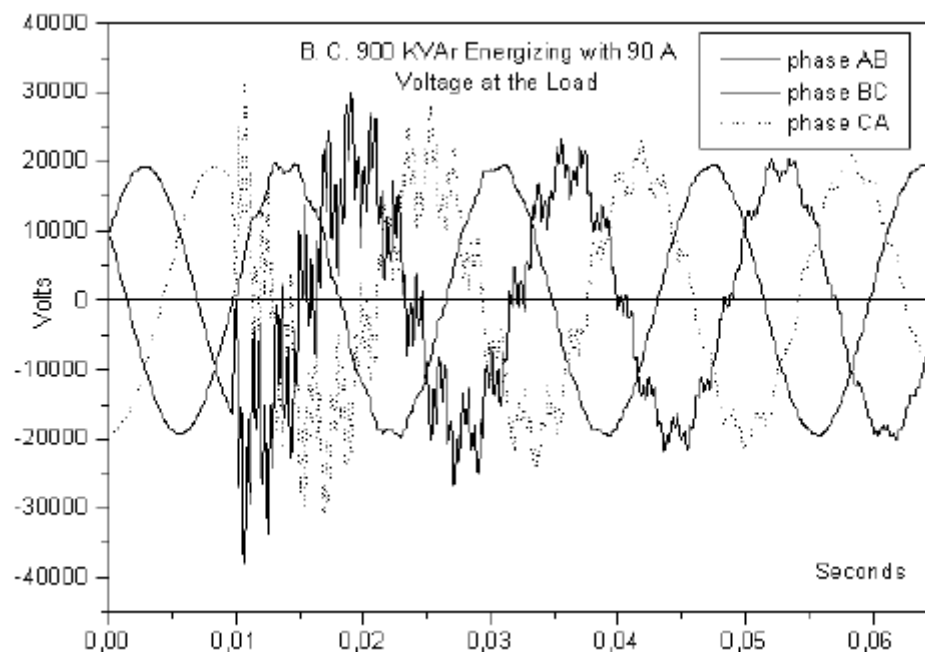


Figure 4.3. 900 kVAr bank energization - load voltage

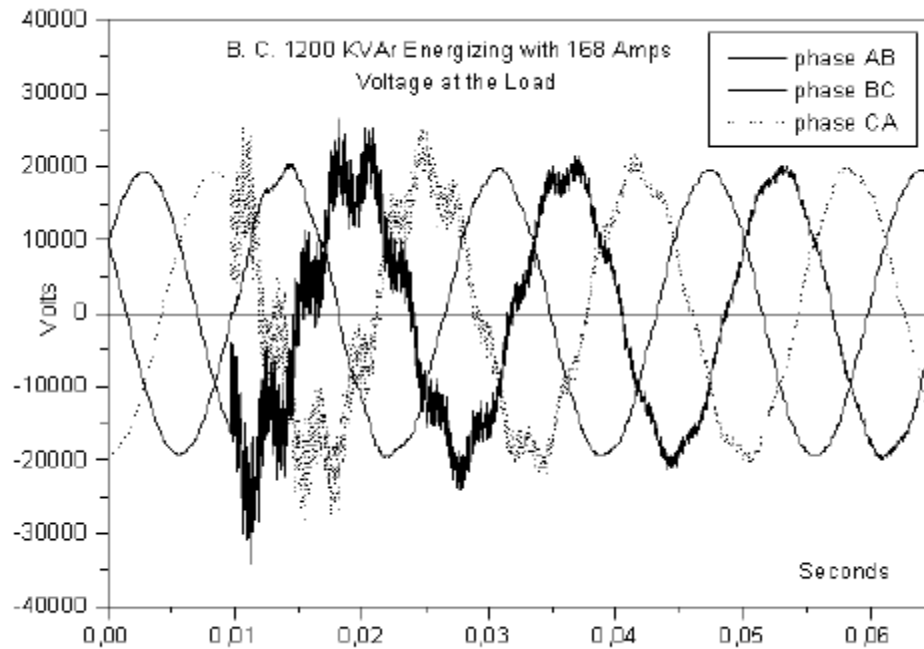


Figure 4.4 1,200 kVAr bank energization - load voltage

#### ❖ Transient Currents

High current values can appear in the industry's plant due to C.B. switching and they can last various cycles. For the 900 kVAr C.B. switching with load currents of 90 and 150 A, the maximum current peaks at the industry's plant were 1,051 and 1,231 A, respectively. At the substation, peaks of 615 and 670 A were observed. Special attention should be given to the currents observed at the industry's plant, especially because of its protection and control equipment.

Figure s. 6 and 7 show the current waves which appear at the industry's plant resulting from the switching of 900 kVAr and 1,200 kVAr C.B., respectively. As for the voltage cases, high frequency components can be observed for various milliseconds.

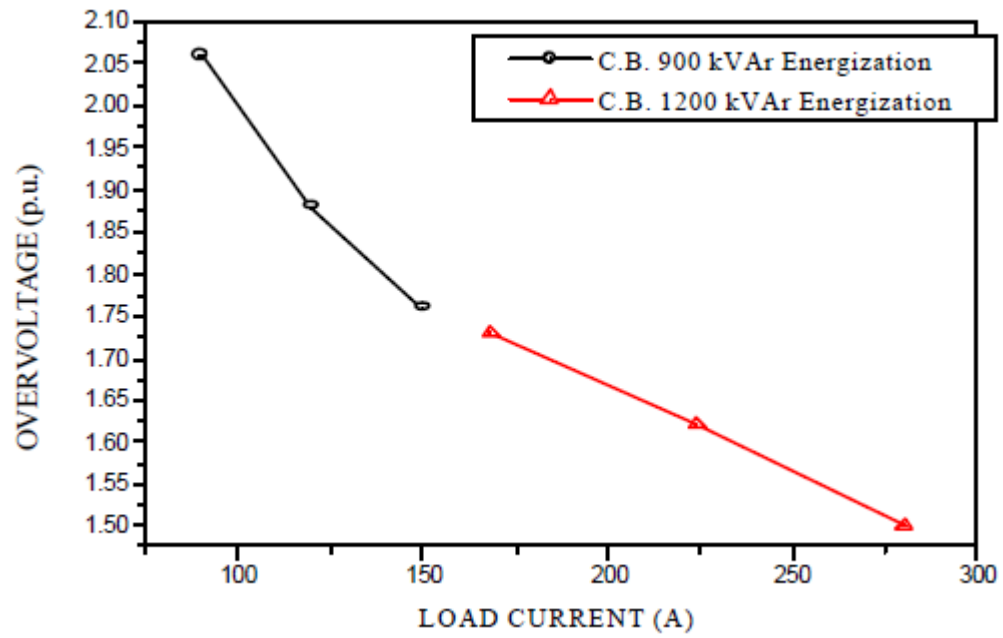


Figure 4.5. Load current variation effect for the maximum overvoltage values

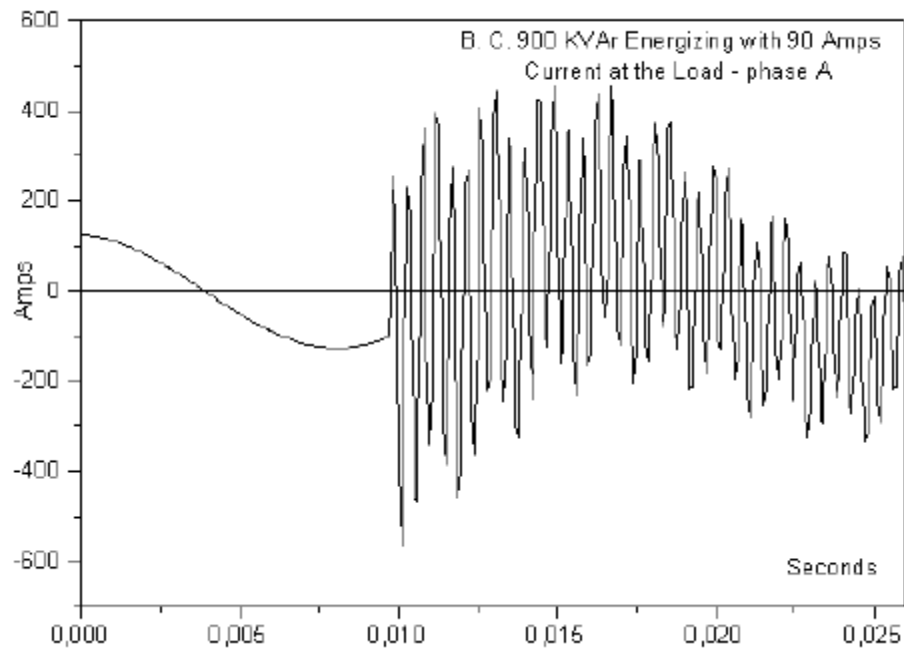


Figure 4.6 900 kVAr bank energization - load current

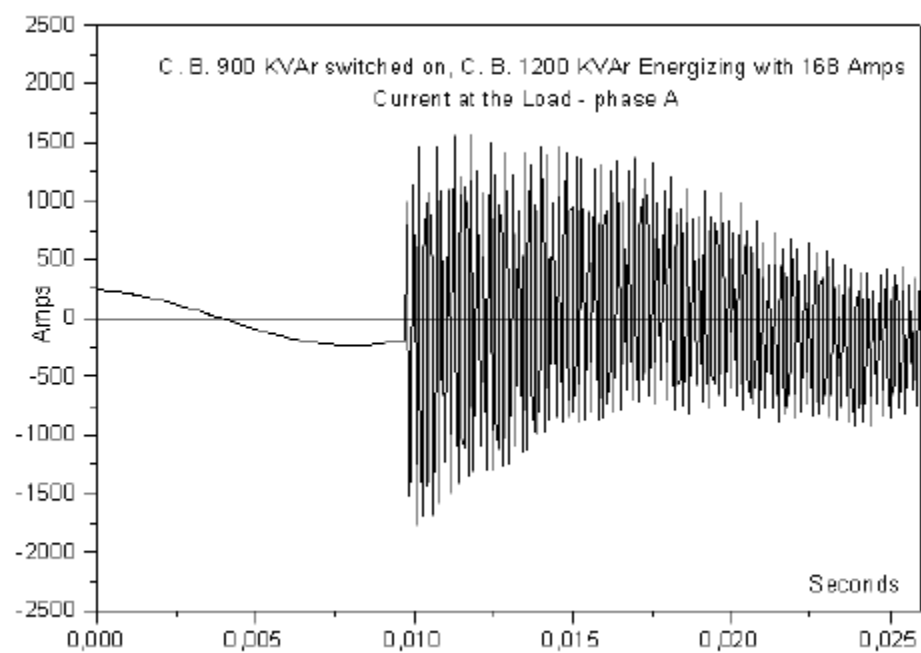


Figure 4.7 1,200 kVAr bank energization - load current

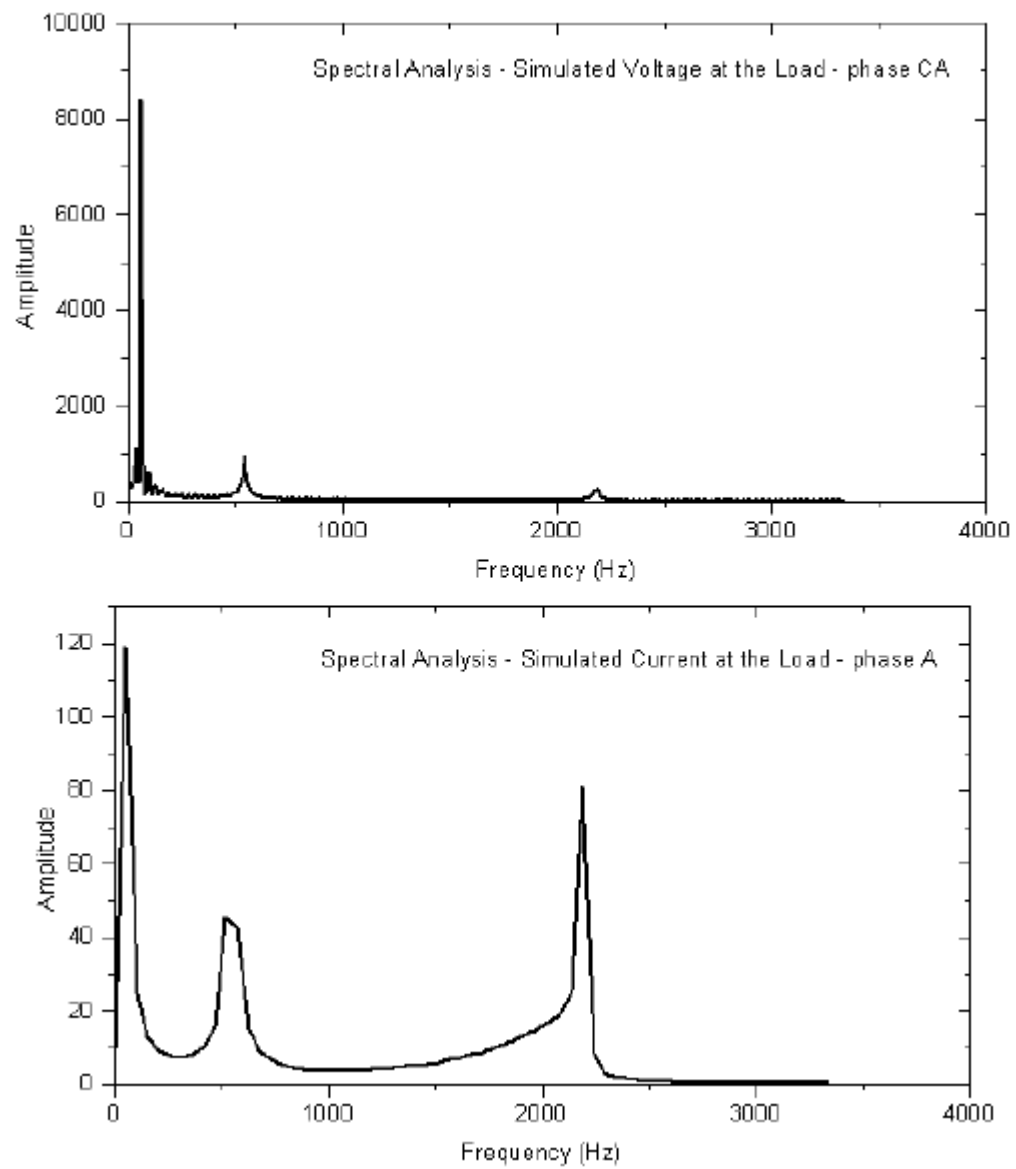


Figure 4.8. Simulated voltage and current frequency spectrum at the load

## 4.4 Conclusion

In this simulation characteristics of transients, which originated from utility capacitor bank switching, were studied. Moreover, factors that influence the intensity of such transients were investigated in order to identify the conditions in which these effects can be undermined. It should be pointed out that a circuit representing a real-life feeder of a primary distribution system, 13.8 kV was simulated. The software ATP (Alternative Transients Program) was utilized for such purposes. A comparison with real life data recorded at the distribution system was performed in order to validate the simulation. The following aspects regarding factors that influence the intensity of the transients were observed:

- Regarding the industry's load current value during utility bank switching, it was observed that the overvoltage transients were mitigated when the banks were inserted at a higher load current condition.
- Regarding synchronous closing, it was observed that transient voltages were reduced when switches were closed at zero voltage, as expected. Pole spread can intensify the magnitude of transients.
- Transient overvoltages can be additionally amplified or mitigated depending on the industry capacitor bank size.
- Transient overvoltages and over currents observed during the switching of the 1200 kVAr capacitor bank were higher in frequency when compared to the transients related to the switching of the 900 kVAr capacitor bank.

## **CHAPTER Five**

### **Conclusion And Recommendations**

#### **Conclusion:**

- 1- Several approaches to improving power factor to acceptable levels while preventing a leading power factor are available.
- 2- One method is to design improvement to some level below unity. Improving power factor to 0.95, for example, would ensure some tolerance for fluctuating load levels, but would not necessarily prevent leading power factor during times of light system loading.
- 3- Alternatively, automatically switched capacitor banks can be used to control capacitive reactive power connected to the system. Depending upon the levels of capacitance that are switched, automatic capacitor banks can introduce voltage transients into the distribution system. Depending upon the presence of harmonic load currents, automatic capacitor banks can also introduce a resonant condition.
- 4- Synchronous motors can be connected to the distribution system with automatic controls for its operation as a reactive power compensator. Synchronous condensers provide an excellent method for "seamless" power factor improvement and harmonic power control, as no switching occurs. Synchronous motors, however, are relatively large and are not practical for use on smaller distribution systems.
- 5- Installing static capacitors directly at and switched on and off with the offending load is another solution, but can be costly simply from the number of locations that may be required.
- 6- Finally, harmonic filters may be required if low power factor is contributable in whole or in part to significant harmonic loads. Caution must be exercised when capacitors designed for 60 Hz operation are installed on a system with significant harmonic load currents to prevent harmonic resonance.



## ❖ **Recommendations :**

- 1- The amount of automatically switched capacitive reactance required to improve power factor is determined by the maximum reactive power requirements of the system, minus the minimum reactive power requirements, and minus the harmonic reactive power requirements of the system.
- 2- Automatically switched capacitance may take one of several forms outlined above, including one or more static capacitor banks switched by the controller of a large motor, one or more automatically switched capacitor banks connected to a common bus, or a synchronous condenser.
- 3- The location and configuration of capacitive reactance is governed by technical concerns and economics. It is more economically feasible to group the capacitance required for several small motors at the common point of connection, namely a motor control center or distribution panel, than to install individual power factor capacitors at each motor.
- 4- Because economics frequently dictate that a combination of static and automatically switched .capacitance be installed at the same location, capacitor manufacturers typically offer this combination as a standard product.
- 5- Every electrical distribution system is unique in composition and in operation. Using a cookbook approach to power factor improvement that neglects the inherent characteristics of the distribution system equipment and loads can result in more significant problems than low power factor.

The historical database available from utility bills can be used to determine the peak magnitude of reactive power consumed by the electrical system. The system one-line diagram can be used to identify large or numerous low-power factor loads for further study. A systematic method of measuring actual power requirements of feeders and loads can be used to establish the

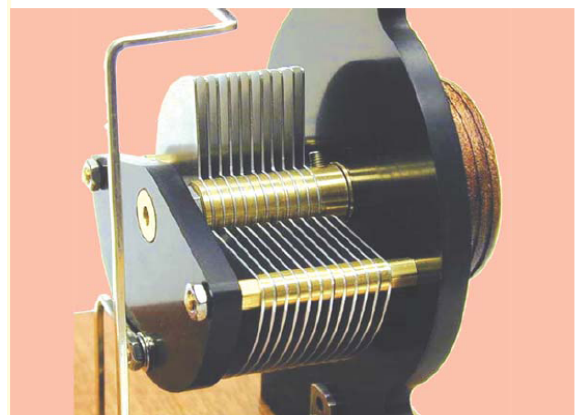
framework for understanding the quantities calculated base upon the utility database.

6- Placing the measured power requirements of the individual loads into the context of the system one-line diagram brings the project scope of work into focus. The nature and location of significant reactive power consuming loads will help to determine the optimal engineering solution.

7- The power requirements of any non-linear loads as determined from measured data will provide the basis for establishing the amount, configuration and location of harmonic filters to install on the system. Typical locations are at any large non-linear loads, or at any common points of connection for non-linear loads. Whether any harmonic filters are switched or are static will be determined by the operational nature of the nonlinear loads.

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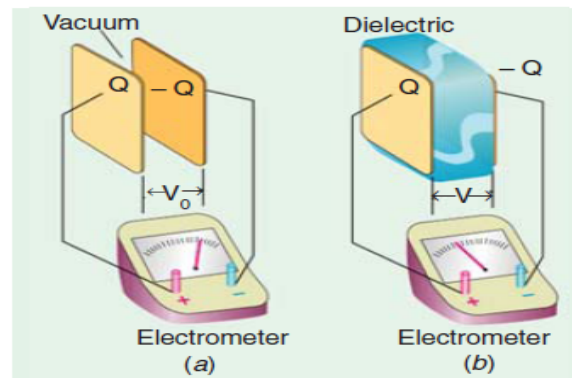
## Appendices:



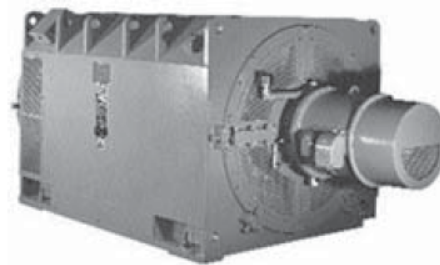
The above figure shows a variable capacitor. A capacitor stores electric charge and acts a small reservoir of energy



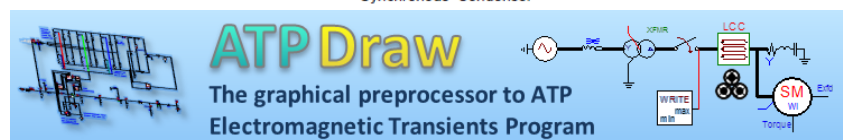
A capacitor stores electricity



The figure shows how the capacitance changes when dielectric constant is changed



Synchronous Condenser



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