1

Introduction to Electric Power Systems

The main parameters in electrical systems are voltage and current. The product of voltage and current gives a third parameter called power, and power consumed over some time duration is called energy [1]. The electric power system consists of power generation, transmission and distribution system [2]. Power is generated from two main sources, namely conventional energy sources and non-conventional energy sources. The conventional energy sources are non-renewable which gets depleted over a period of time, while non-conventional energy sources are non-depleting sources [3, 10, 30]. Most large-scale power plants are located in areas where the raw materials are available locally and generated power is transmitted over long distances for distribution. An electrical conducting medium is required in order to transfer the power from generating station to load center. This conducting medium is called as transmission system. Transformers and transmission lines are the main components of the transmission system; they are used to transfer the power from generating station to consumers (customers) at various operating voltage levels. Generation voltage of the conventional power plant typically ranges from 6.6 kV to 22 kV, and transmission voltage typically ranges from 110 kV to 765 kV. High voltage is stepped down to various voltage levels for different consumers depending upon the requirements and installed capacity.

1.1 Introduction

In general, electrical power used for commercial and residential purpose is mostly Alternating Current (AC). An AC voltage or current has the magnitude and direction which changes periodically with respect to time, unlike the Direct Current (DC) supply, which has constant magnitude with respect to time. Figure 1.1 shows the waveform of AC (voltage and current) and Figure 1.2 shows the waveform of DC (voltage and current).

P. Sivaraman, C. Sharmeela, A. Thaiyal Nayagi, and R. Mahendran. Basic Electrical and Instrumentation Engineering, (1–78) © 2021 Scrivener Publishing LLC

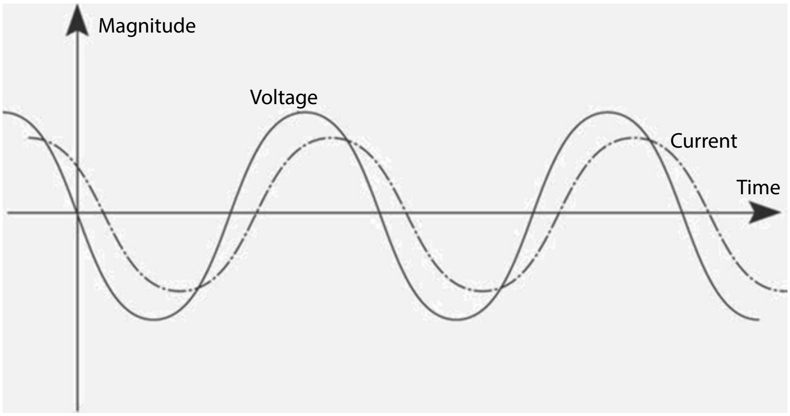


Figure 1.1 Waveform of AC.

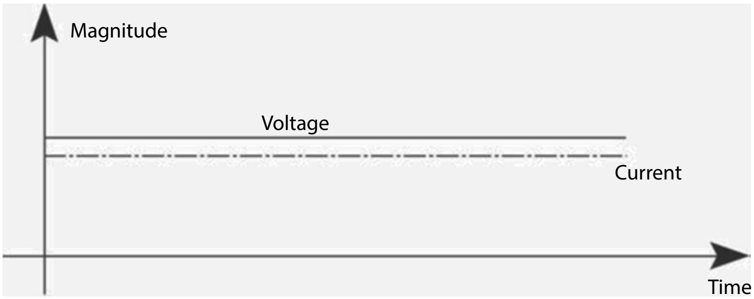


Figure 1.2 Waveform of DC.

Types of AC supply system:
The AC supply system is classified into two types based on the number of phases:

- Single-phase power supply
- Three-phase power supply

A. The single phase supply

The single-phase power supply is used to power all the single-phase loads in the systems. Generally, single-phase power supply is derived from a three-phase, four-wire circuit. The single-phase voltage level varies from country to country. The general single-phase supply voltage is 220 V, 230 V, 240 V in low voltage systems (in Asian countries). Most of the single-phase supply systems are 2W systems as shown in Figure 1.11.

B. Three-Phase Power Supply

The three-phase power supply is used to power certain loads which need the poly-phase supply for their operation. Here phase means branch circuits or winding and poly means many. Such loads in any applications need a power supply which has a poly-phase supply system. For example, three-phase power supply is also called poly-phase power supply. In order to develop poly-phase supply, the armature winding of an alternator is divided into the number of phases as required. In each winding section, voltage gets induced with 120° displacement. These windings are arranged in such a way that the magnitude and frequency is the same for all the phases with definite phase difference with respect to the other phases. That means, in a three-phase power supply system, there are three voltages with equal magnitude and frequency having a phase difference of 360°/3 = 120° between them.

Advantages of three-phase supply systems are

- Single-phase power supply are obtained from three-phase power supply and in reverse three-phase power supply is not obtained from single-phase power supply
- Three-phase induction motors are self-starting motors where single-phase induction motors are not self-starting motors
- For transmission and distribution, a three-phase system needs smaller size conductor material as compared with single-phase system for same volt amperes

1.1.1 Electrical Parameters

The main parameters in an electrical system are voltage and current. The product of voltage and current gives a third parameter called power, and power consumed over some duration is called energy.

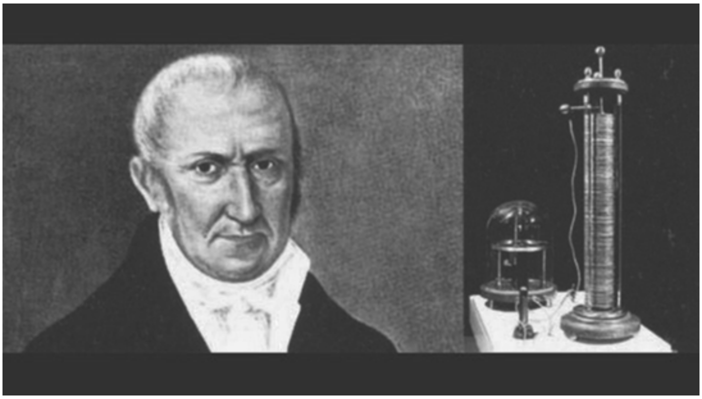
AC systems: Voltage, Current, Frequency and Phase angle

DC systems: Voltage and Current

1.1.1.1 Voltage

Potential difference between any two points in an electrical circuit is called voltage. The SI unit of voltage is Volts (V) [1]. Higher values of voltage are mentioned as kV. The other name of voltage is Electro Motive Force (EMF). The representation of voltage is two types: peak to peak voltage (instantaneous voltage) and RMS voltage.

Alessandro Volta (18th Feb 1745 – 5th March 1827): An Italian scientist who invented the first battery cell. In order to honour him, SI unit of electric potential is named Volt.



Alessandro Volta. Courtesy: Google image.

RMS voltage:

The peak to peak voltage of phase to phase is shown in Figure 1.3. Average voltage of positive half cycle to negative half cycle is zero. As the absolute voltage is not zero, average voltage cannot be used as a measuring scale for AC. In order to perform the analysis and calculation, a new term called RMS is considered for measurement. Theoretically, RMS voltage in AC is equivalent to the amount of heat produced if the DC of some magnitude produces the same heat on the same resistance.

Generally, most of voltage referred in specification is RMS voltage unless specified.

Example 1.1: A 40 W incandescent lamp is connected across 1ϕ, 230 V, 50 Hz AC supply.

Here the voltage 230 V is RMS voltage.

Note: When using the multi meter for voltage measurements, first check the meter is RMS rated or peak rated in order to avoid confusion. For an example, if RMS rated meter read the voltage as 230 V, the peak rated meter will read the same voltage as 325.2 V.

RMS voltage from peak voltage:

RMS voltage can be calculated if peak voltage is known. The expression for RMS voltage is given in eqn. 1.1.

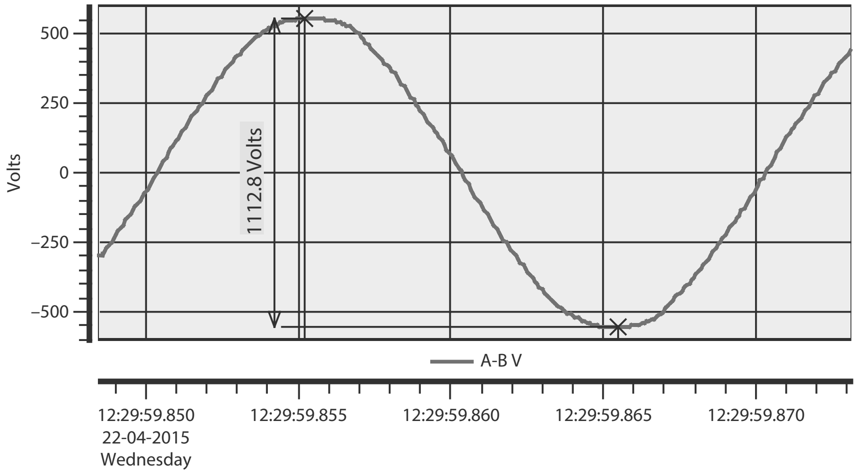


Figure 1.3 Peak to peak voltage of R phase to Y phase. Note: This figure is captured using Dranetz Power Quality analyser.

$$\text{Voltage (RMS)} = \frac{\text{Voltage (Peak)}}{\text{Crest Factor}} \tag{1.1}$$

For sinusoidal wave shape, the value of crest factor is $\sqrt{2}$.

Example 1.2: A sinusoidal supply voltage is 340 V peak. Calculate equivalent RMS voltage.

Solution:

$$\text{Voltage (RMS)} = \frac{\text{Voltage (Peak)}}{\sqrt{2}} = \frac{340}{\sqrt{2}}$$

Voltage (RMS) = 240.5 V is ~241 V.

Example 1.3: A sinusoidal supply voltage is 565 V peak. Calculate equivalent RMS voltage.

Solution:

$$\text{Voltage (RMS)} = \frac{\text{Voltage (Peak)}}{\sqrt{2}} = \frac{565}{\sqrt{2}}$$

Voltage (RMS) = 399.6 V is ~400 V.

Peak voltage from RMS voltage:

Peak voltage can be calculated if RMS voltage is known. The expression for peak voltage is given in eqn 1.2.

$$\text{Voltage (Peak)} = \text{Voltage (RMS) X Crest Factor} \tag{1.2}$$

Example 1.4: A sinusoidal supply voltage is 240 V (RMS). Calculate equivalent peak voltage.

Solution:

$$\text{Voltage (Peak)} = \text{Voltage (RMS)} * \sqrt{2} = 240 * \sqrt{2}$$

$$\text{Voltage (Peak)} = 339.3 \text{ V is} \sim 339 \text{ V}$$

Example 1.5: A sinusoidal supply voltage is 415 V RMS. Calculate equivalent peak voltage.

Answer:

$$\text{Voltage (Peak)} = \text{Voltage (RMS)} * \sqrt{2} = 415 * \sqrt{2}$$

$$\text{Voltage (Peak)} = 586.8 \text{ V is} \sim 587 \text{ V.}$$

Peak to peak voltage:

Voltage measured between the maximum value of the positive half cycle and the minimum value of the negative half cycle is known as peak to peak voltage. This voltage is generally measured in individual voltage cycle, unlike the peak voltage which is the product of RMS voltage and crest factor measured in voltage trend. Peak to peak voltage of R to Y phase is shown in Figure 1.3.

The maximum voltage of positive half cycle of above waveform is 556.4 V and minimum voltage of negative half cycle of the waveform is 556.4 V. Voltage between positive half cycle to negative half cycle is +556.4 to -556.4 V is called peak to peak voltage. It is 1112.8 V in the above Figure 1.3. Figure 1.4 shows the peak voltage trend, which is different from peak to peak voltage.

From Figure 1.4, the peak voltage is between 555 V to 560 V for the time duration 70 minutes between 12:40 hours to 13:50 hours.

Voltage in three-phase circuit:

Voltage in a three-phase circuit is determined based on the system configuration. The determination of voltage in a circuit is based on whether the circuit is in star or delta configuration.

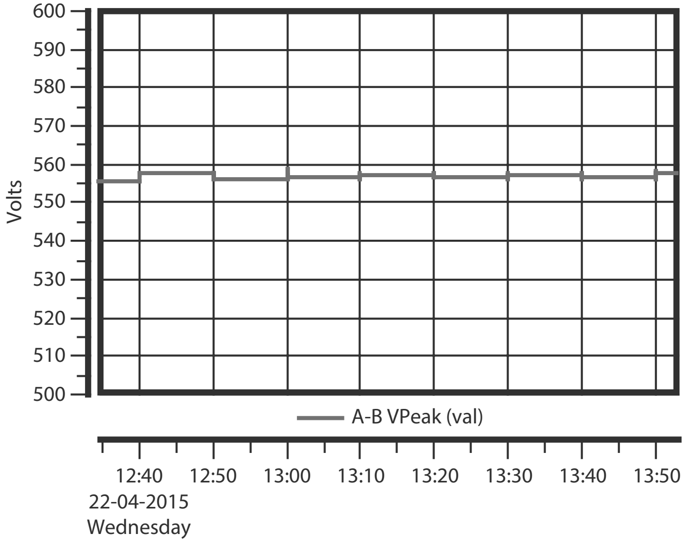


Figure 1.4 Peak voltage trend. Note: This figure is captured using Dranetz Power Quality analyser.

1. Phase to phase voltage – For delta circuits
2. Phase to neutral voltage – For star circuits

The relationship between the above two voltage determinations is expressed in the equation (1.3) and (1.4).

In delta circuit, the phase voltage is determined by

$$\text{Voltage}_{\text{Ph}} = \frac{\text{Voltage}_{\text{Line}}}{\sqrt{3}} \tag{1.3}$$

In star circuit, the line voltage is determined by

$$\text{Voltage}_{\text{Line}} = \sqrt{3} \text{ x } \text{Voltage}_{\text{Ph}} \tag{1.4}$$

Where

$\text{Voltage}_{\text{Line}}$ is line voltage
$\text{Voltage}_{\text{Ph}}$ is phase voltage

In delta circuit, line current in delta circuit is greater than line current in star circuit. Similarly, the line voltage in star circuit is greater than line voltage in delta circuit.

Example 1.6: A distribution transformer of 2 MVA power rating Dyn11 configuration is having ratio of 11 kV/433 V. How do we understand this voltage?

Answer:

A distribution transformer is generally used to cater single-phase loads connected on three-phase distribution. This is the reason the secondary side of the transformer is star with neutral in the circuit. The primary side of the transformer is delta. 11 kV at primary side means phase to phase voltage across RY, YB and BR. 433 V secondary corresponds to 250 V between RN, YN and BN while 433 V could be recorded between RY, YB and BR.

The phase to phase voltage is voltage between any of two phases (R to Y, Y to B or R to B). It can either be RMS voltage or peak voltage and it is applicable to three-phase 3wire and three-phase 4wire circuits. The three-phase 4wire, 415 V, 50 Hz AC circuit is shown in Figure 1.5.

Example 1.7: What is the voltage between R to Y phase in Figure 1.5?

Answer: 415 V.

The three-phase 3W, 11 kV, 50 Hz AC circuit is shown in Figure 1.6.

Example 1.8: What is the voltage between Y to B phase in Figure 1.6?

Answer: 11 kV.

In India, the transmission voltages are 11 kV, 22 kV, 33 kV, 66 kV, 110 kV, 132 kV, 220 kV, 230 kV, 400 kV and 765 kV and the distribution voltage is

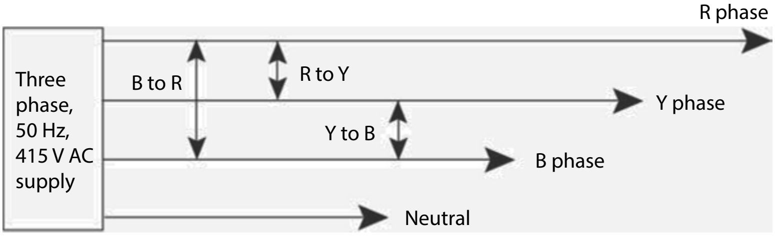


Figure 1.5 Three-phase, Four-wire circuit configuration.

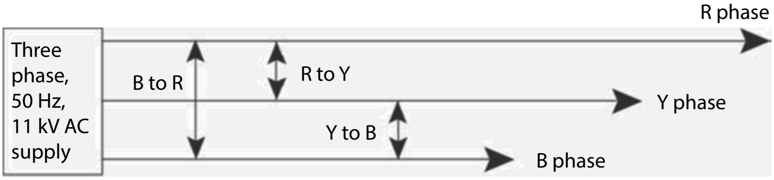


Figure 1.6 Three-phase, Three-wire circuit configuration.

415 V. All the above-mentioned voltages are phase to phase voltage only. Similar voltage levels are used in other countries in the world.

The three-phase power supply system has three voltages with equal magnitude, frequency and displaced by 120° each other. That means, the phase angle difference between three phases is 120 electrical degrees. The vector displacement of three-phase voltage is shown in Figure 1.7.

The three-phase voltages are denoted as e_R, e_Y e_B, and their expression are given below

$$e_R = E_m \sin(\omega t)$$
$$e_Y = E_m \sin(\omega t - 120°)$$
$$e_B = E_m \sin(\omega t + 120°) = E_m \sin(\omega t - 240°)$$

As Phasor rotates in anti-clockwise direction, voltage e_Y lags e_R by 120° and e_B lags e_R by 240°.

The phase angle displacement of three-phase voltage wave shape is shown in Figure 1.8.

The voltage displacement between the phases should be 120 electrical degrees. 360 electrical degrees equal to 20.066 milli seconds from Figure 1.8. Corresponding electrical degree for 6.793 milli seconds is worked out as 121.8 electrical degrees. Figure 1.9 shows the angular separation between three phases. Y phase voltage lags R phase by 120.938° similarly B phase lags Y phase 120.938°. Figure 1.8 and Figure 1.9 represent the phase angle displacement in time domain and angular domain form, respectively.

Line to neutral voltage is voltage between any one of the line to neutral. This voltage is applicable where neutral conductor is also a return current carrying conductor in the circuit like in three-phase four-wire circuit and single-phase two-wire circuit. Low voltage distribution system uses the

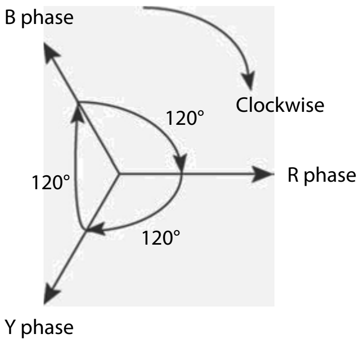


Figure 1.7 Vector displacement of three phases.

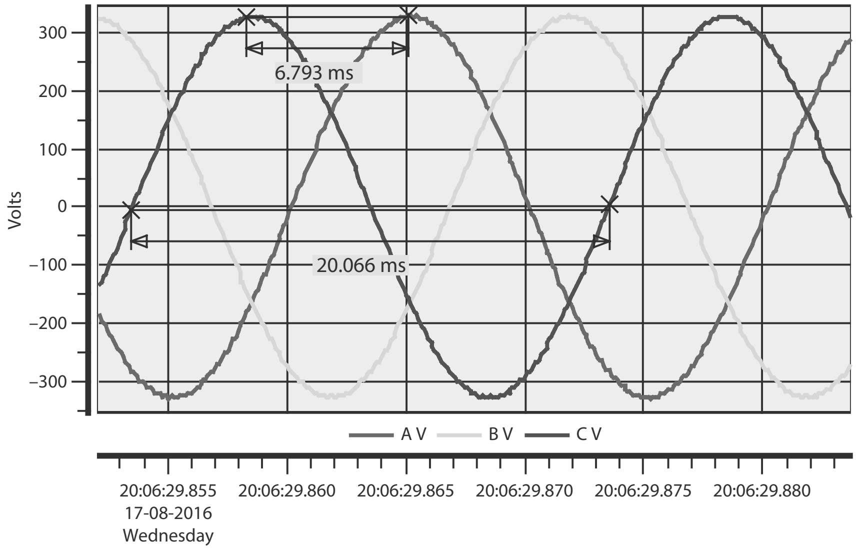


Figure 1.8 Phase angle displacement of three-phase voltage waveform in time domain.
Note: This figure is captured using Dranetz Power Quality analyser.

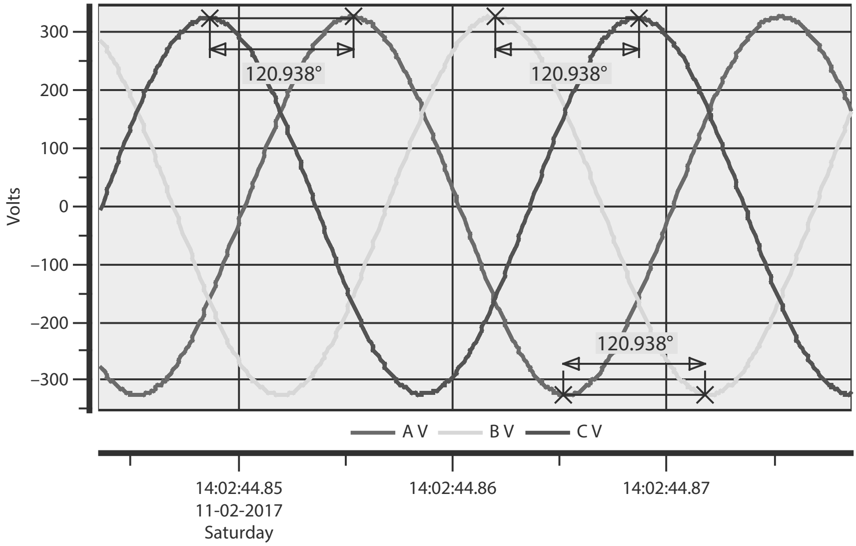


Figure 1.9 Phase angle displacement of three-phase voltage waveform in angular form.
Note: This figure is captured using Dranetz Power Quality analyser.

neutral for single-phase loads. The three-phase, four-wire, 415 V, 50 Hz AC circuit is shown in Figure 1.10.

Example 1.9: What is the voltage between R phase and neutral in Figure 1.10?
Answer: from eqn. 1.4, R phase and neutral voltage is 240 V.

The single-phase, two-wire AC circuit is shown in Figure 1.11.

Example 1.10: What is the voltage between R phase and neutral in Figure 1.11?
Answer: 240 V.

1.1.1.2 Current

Current is rate of flow of electric charge across the potential difference in a closed electric circuit. The current flows from high voltage to low voltage in the closed circuit [1]. The SI unit of current is Ampere (A). Higher values of current are mentioned as kA.

Andre Marie Ampere (20th Jan 1775 – 10th Jun 1836): A French scientist discovered the science of classical electromagnetism and electrodynamics. In order to honour him, SI unit of electric current is his name, Ampere.

Andre Marie Ampere. Courtesy: Google image.

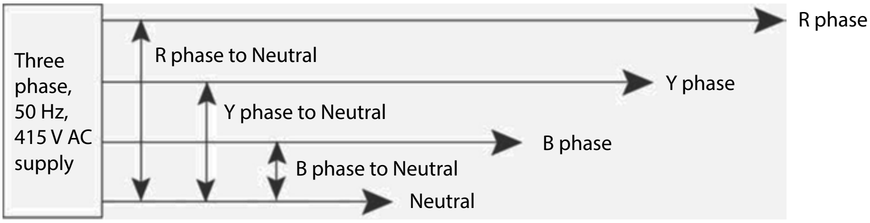


Figure 1.10 Three-phase, four-wire circuit configuration.

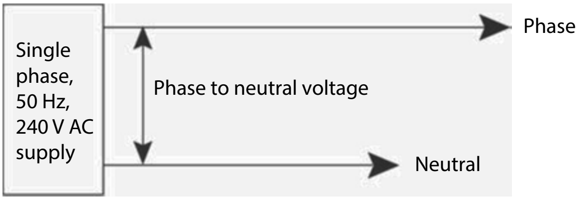


Figure 1.11 Single-phase, two-wire system.

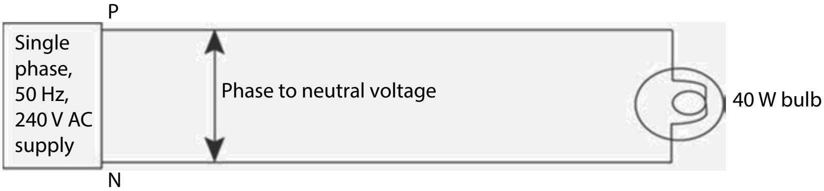


Figure 1.12 40 W bulb connected across 240 V supply.

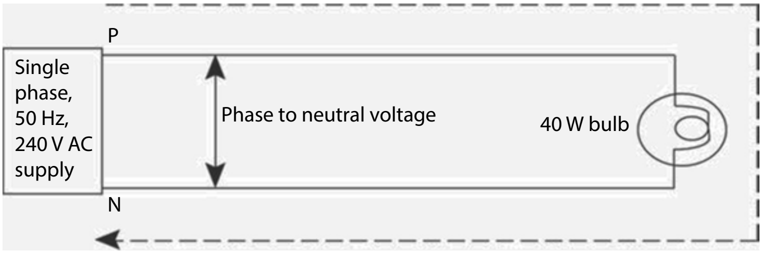


Figure 1.13 Direction of current flow for positive half cycle.

A single-phase, two-wire AC circuit is shown in Figure 1.12.

The current flow direction for positive half cycle is represented as dotted line in Figure 1.13.

The current flow direction for negative half cycle is represented as dotted line in Figure 1.14.

The factor which decides the value of current flow in the circuit is load impedance.

Example 1.11: A 5 Ω resistance (load) is connected across a single-phase 230 V, 50 Hz AC supply is shown in Figure 1.15. Calculate the current drawn by 5Ω resistance.

Solution:

Theoretical calculation: Current drawn by the load resistance of 5 Ω is theoretically calculated by Ohms law [31].

$$V = IR \tag{1.5}$$

$$I = \frac{V}{R} \tag{1.6}$$

$$I = 230/5$$

$$I = 46\ \text{A}$$

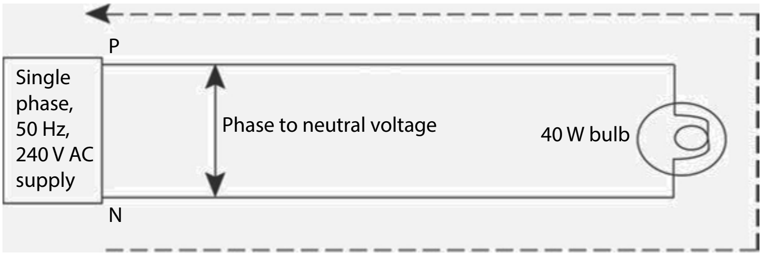


Figure 1.14 Direction of current flow for negative half cycle.

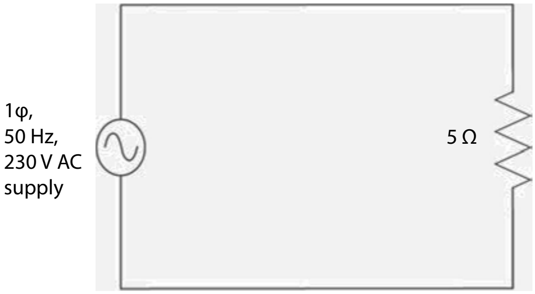


Figure 1.15 Circuit diagram of single-phase AC supply feeding R Load.

Simulation result:

The instantaneous current (IL) wave shape drawn by the load and RMS current trend are shown in Figure 1.16 and Figure 1.17, respectively.

The current in RMS value of a Sine wave from simulation is 0.046 kA or 46 A. i.e,

$$I_{RMS} = \frac{I_{instantaneous}}{\sqrt{2}} = 46\ \text{A}$$

George Simon Ohm (16th March 1789 – 6th July 1854): A German scientist discovered direct proportionality between the potential difference applied across a conductor and the resultant electric current. This relationship is called Ohm's law. In order to honour him, SI unit of electric resistance is in his name. Ohm.

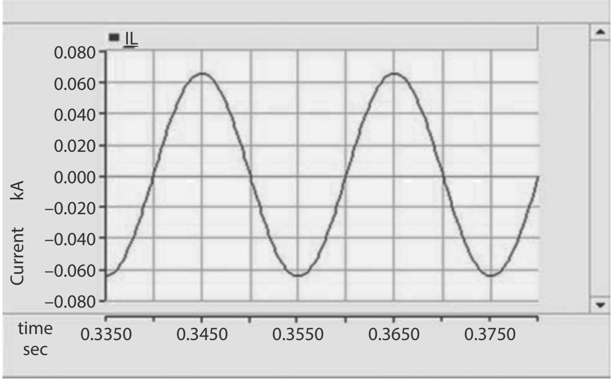


Figure 1.16 Current wave shape in kA.

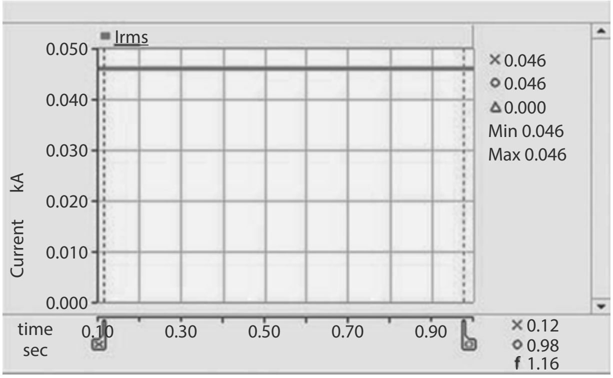


Figure 1.17 RMS current trend in kA.

1.1.1.3 Time Period and Frequency

Time period is the duration of one full cycle equalling one positive half cycle and one negative half cycle for a span of 360°. Frequency is the physical count of positive and negative half cycles appearing in one second. In India, the power supply frequency is 50 Hz. The 50 Hz frequency has 50 numbers of positive half cycle and 50 numbers of negative half cycle in one second. In the United States, the power supply frequency is 60 Hz. The 60 Hz frequency has 60 numbers of positive half cycle and 60 numbers of negative half cycle in one second. Conversely, one upon frequency is the time period. The time period of one cycle is 20 milli second for 50 Hz frequency.

$$F = \frac{1}{T} \tag{1.7}$$

$$T = \frac{1}{F} \tag{1.8}$$

Figure 1.18 shows the wavelength of 19.994 milli seconds which corresponds to one cycle. Figure 1.19 shows 50.02 cycles appear in one second.

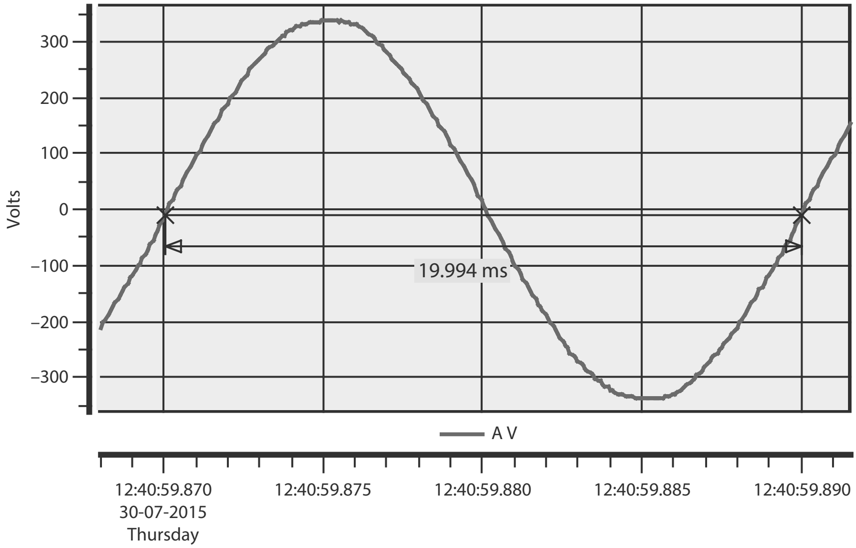


Figure 1.18 Time period. Note: This figure is captured using Dranetz Power Quality analyser.

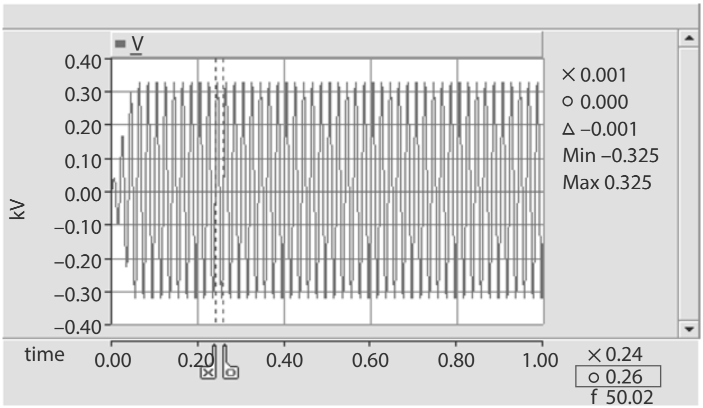


Figure 1.19 Voltage frequency.

In other words, one upon 19.994 in Figure 1.18 equals 50.02 which is reflected in Figure 1.19.

1.1.1.4 Phase Angle (ϕ)

The angular displacement between the voltage and current wave shapes determine whether current leads the voltage or current lags the voltage

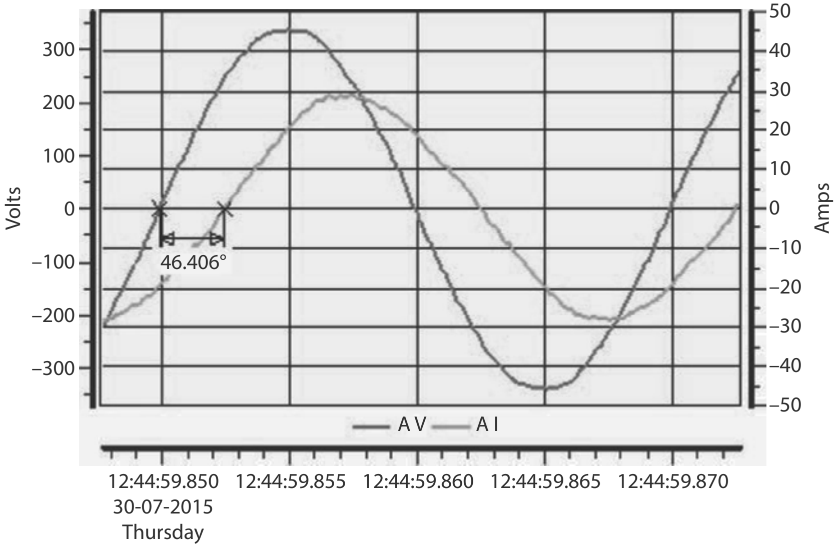


Figure 1.20 Phase angle between voltage and current. Note: This figure is captured using Dranetz Power Quality analyser.

or both are in phase. This factor is vital in AC system as this will decide whether the product of voltage and current is positive or negative. The phase displacement in angular degrees between voltage and current wave shape is 46.406° as shown in Figure 1.20

The cosine value of the phase angle displacement is called as displacement power factor without presence of multiple frequencies (harmonics) introduced by modern power electronics devices explained in detail in section 1.1.4.

1.2 Three-Phase Supply Connections

In a single-phase system, two wires (line and neutral) are functionally sufficient for transferring the power to the load. The three-phase system, three wires (R, Y, B) or four wires (R, Y, B, N) are functionally required for transferring the power to the loads. Three wires are required for powering the three-phase loads without neutral like motor loads and four wires required for three-phase loads with neutral like UPS systems [22]. The three-phase power supply connections are classified into two types.

1) Star connection or wye connection
2) Delta connection

1.2.1 Star Connection

The star connection is formed by connecting starting or terminating ends of all the three windings of transformer or generator together as shown in Figure 1.21. The one ends of the winding $R_2 - Y_2 - B_2$ are connected together and formed as star connection. Other ends of the winding $R_1 - Y_1 - B_1$ are connected to the loads. The common point N is called Neutral point. The phases

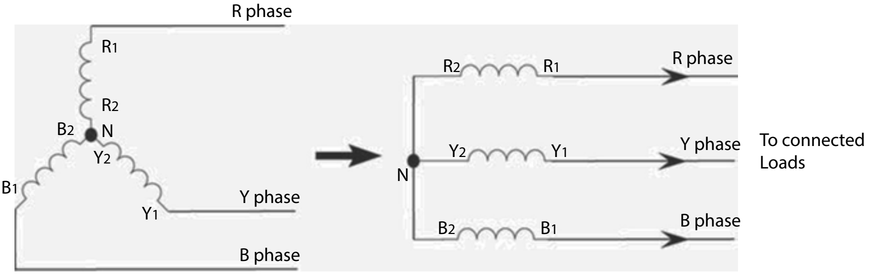
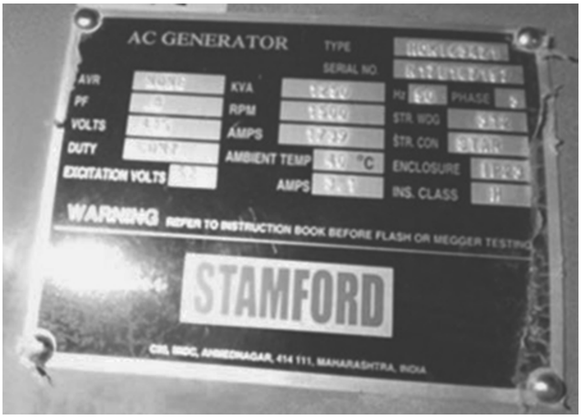


Figure 1.21 Star circuit connection.

$R_1 - Y_1 - B_1$ and common point N as neutral is extended to the connection points where the different loads are getting connected. The star circuit is suitable for six numbers of possible loads combination such as RY, YB, BR, RN, YN and BN.

The star connection is used in three-phase AC generator and transformers [6]. The name plate details of three-phase AC generator and transformer are shown in Figure 1.22 and Figure 1.23, respectively.

The terminal connection of transformer star winding in actual site installation is shown in Figure 1.24.



AC GENERATOR

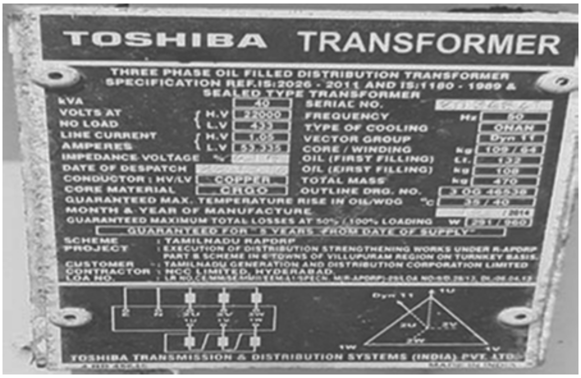
TYPE [illegible]
SERIAL NO. [illegible]
AVR NONE
PF [illegible]
VOLTS [illegible]
DUTY [illegible]
EXCITATION VOLTS [illegible]
KVA [illegible]
RPM [illegible]
AMPS [illegible]
AMBIENT TEMP 40 °C
AMPS [illegible]
Hz 60 PHASE [illegible]
STR. WDG [illegible]
STR. CON STAR
ENCLOSURE [illegible]
INS. CLASS [illegible]

WARNING REFER TO INSTRUCTION BOOK BEFORE FLASH OR MEGGER TESTING

STAMFORD

CG, MIDC, AHMEDNAGAR, 414 111, MAHARASHTRA, INDIA

Figure 1.22 Name plate details of AC generator (Courtesy: Stamford).



TOSHIBA TRANSFORMER

THREE PHASE OIL FILLED DISTRIBUTION TRANSFORMER
SPECIFICATION REF.IS:2026 - 2011 AND IS:1180 - 1989 &
SEALED TYPE TRANSFORMER

kVA 40
VOLTS AT NO LOAD H.V 22000
L.V 433
LINE CURRENT AMPERES H.V 1.05
L.V 53.335
IMPEDANCE VOLTAGE % [illegible]
DATE OF DESPATCH [illegible]
CONDUCTOR : HV/LV COPPER
CORE MATERIAL CRGO
SERIAL NO. [illegible]
FREQUENCY Hz 50
TYPE OF COOLING ONAN
VECTOR GROUP Dyn 11
CORE / WINDING kg 109 / 64
OIL (FIRST FILLING) Lt. 132
OIL (FIRST FILLING) kg 108
TOTAL MASS kg 470
OUTLINE DRG. NO. 3 00 46538
GUARANTEED MAX. TEMPERATURE RISE IN OIL/WDG °C 35 / 40
MONTH & YEAR OF MANUFACTURE [illegible] / 2014
GUARANTEED MAXIMUM TOTAL LOSSES AT 50% / 100% LOADING W 291 / 960
GUARANTEED FOR "5 YEARS FROM DATE OF SUPPLY"
SCHEME : TAMILNADU RAPDRP
PROJECT : EXECUTION OF DISTRIBUTION STRENGTHENING WORKS UNDER R-APDRP PART B SCHEME IN 6 TOWNS OF VILLUPURAM REGION ON TURNKEY BASIS.
CUSTOMER : TAMILNADU GENERATION AND DISTRIBUTION CORPORATION LIMITED
CONTRACTOR : NCC LIMITED, HYDERABAD.
LOA NO. : [illegible]

TOSHIBA TRANSMISSION & DISTRIBUTION SYSTEMS (INDIA) PVT. LTD.

Figure 1.23 Name plate details of transformer (Courtesy: Toshiba).

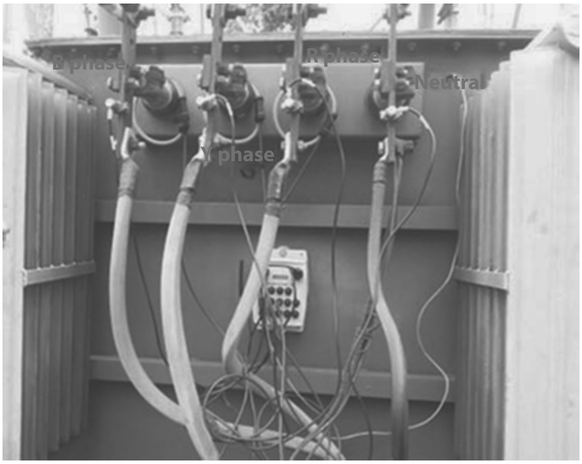


Figure 1.24 Terminal connection of transformer secondary side - star winding.

Advantages of star circuit:
The star circuit has the following advantages over delta circuits:

1) The line voltage in star circuit is phase voltage multiplied by $\sqrt{3}$ and current drawn by star circuit is less as compared with current drawn by delta circuit. Hence, required conductor size for star circuit is lesser for same rating.
2) Star circuit has the neutral point, hence three-phase, four-wire system can be developed.
3) It provides the two different voltage levels for the load connection. For an example, 415 **V** between line to line and 240 **V** between line to neutral.
4) Both single-phase and three-phase loads can be connected in single star circuits.

Disadvantages of star circuit:
The star circuit has the following disadvantages over delta circuits:

1) Higher size neutral conductor is required for highly unbalanced and harmonic producing loads.

1.2.2 Delta Connection

The delta connection is formed by connecting one end of the winding to starting point of other winding to form a closed loop as shown in Figure 1.25.

The winding end R_2 is connected with starting point of another winding Y_1, winding end Y_2 is connected with starting point of another winding B_1 and winding end B_2 is connected with starting point of another winding R_1. The output connections are taken at mid of the two windings such as $B_2 - R_1$, $R_2 - Y_1$ and $Y_2 - B_1$. Delta circuits are suitable for three numbers of loads combination such as RY, YB and BR.

The practical connection or forming delta circuit in transformer is shown in Figure 1.26 and Figure 1.27. In Figure 1.26, winding end $R_2 - Y_1$ is combined and output is taken at the combined point. This transformer

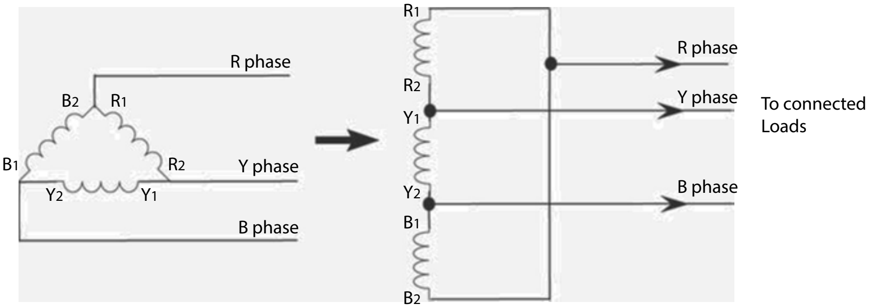


Figure 1.25 Delta circuit connection.

Figure 1.26 Practical connection or forming delta circuit in transformer.

Figure 1.27 Practical connection or forming delta circuit in transformer.

(1:1 ratio transformer) used at output side of the UPS system for providing the isolation in the circuit (415 V level).

In Figure 1.27, winding end $B_2 - R_1$ is combined and output is taken at the combined point is R phase (Red color), winding end $R_2 - Y_1$ is combined and output is taken at the combined point is Y phase (Yellow color) and winding end $Y_2 - B_1$ is combined and output is taken at the combined point is B phase (Blue color).

Advantages of delta circuit:
The delta circuit has the following advantages over star circuits:

1) More suitable for three-phase loads like induction motors
2) Unbalancing is avoided

Disadvantages of delta circuit:
The delta circuit has the following disadvantages over star circuits:

1) Suitable for three-phase loads only; connection of single-phase loads are not possible.

1.2.3 Balanced Load

The loads are called balanced loads when drawing the balanced or equal current magnitude in all the three phases from the power supply [7]. In other words, impedance connected across the supply is equal for all the three phases. The delta circuit having the impedances Z_{RY}, Z_{RB} and Z_{YB} connected across the RY, YB and RB phases respectively i.e $Z_{RY} = Z_{RB} = Z_{YB}$. If the impedance of Z_{RY}, Z_{RB} and Z_{YB} is equal/same, then the circuit is called as balanced delta circuit shown in Figure 1.28.

The star circuit having the impedances Z_R, Z_Y and Z_B connected across the RY, YB and RB phases respectively and RN, YN and BN line to neutral respectively, i.e., $Z_R = Z_Y = Z_B$. If the impedance of Z_R, Z_Y and Z_B is same, then the circuit is called as balanced star circuit and shown in Figure 1.29.

Practically most of the three-phase induction motors have equal impedances in all three phases. The magnitude of current flowing to the motor is almost equal in all the three phases. These three-phase motor loads are called balanced loads.

Example 1.12: A three-phase, 11 kW induction motor name plate details is shown in Figure 1.30.

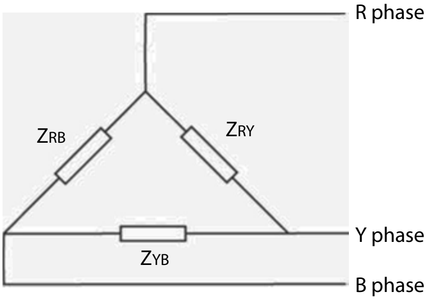


Figure 1.28 Balanced delta circuit.

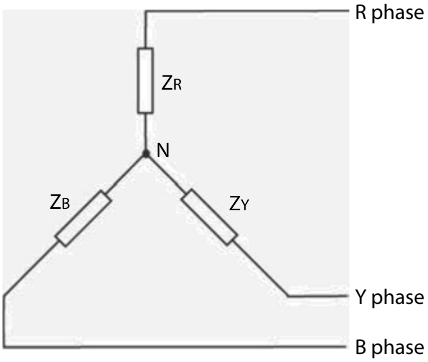


Figure 1.29 Balanced star circuit.

Figure 1.30 Name plate details of three phase induction motor (Courtesy: TECO).

When the motor is operating at 415V, 50Hz frequency at 0.88 power factor, it draws the 20.5A current/phase in delta connection and 11.8A current/phase in star connection. The same motor, when operating at 380V, 60Hz frequency at 0.85 power factor, draws the 21A current/phase in delta circuit and 11.6A current/phase in star circuit.

1.2.4 Unbalanced Load

Loads are called unbalanced loads when drawing the unbalanced or unequal current magnitude in all the three phases from the supply [7]. In other words, impedance connected across the supply is not equal in all the three phases, i.e., $Z_{RY} \neq Z_{YB} \neq Z_{BR}$. If the impedance of Z_{RY}, Z_{YB} and Z_{RB} is not equal, then the circuit is called as unbalanced circuit.

1.2.5 Star – Delta Conversion

The Star-Delta conversion is used to convert the impedances in star circuit to equivalent impedance in delta circuit. The star-delta conversion is shown in Figure 1.31.

In general, resistance of delta circuit is calculated from eqn 1.9.

$$R_\Delta = \frac{R_P}{R_{\text{opposite}}} \tag{1.9}$$

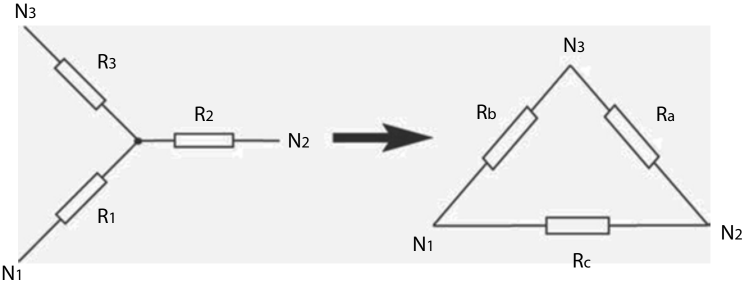


Figure 1.31 Star to delta conversion.

Where

$R_P = R_1R_2 + R_2R_3 + R_3R_1$

From eqn (1.9), the resistance R_a, R_b. R_c is calculated as

$$R_a = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_1}$$

$$R_b = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_2}$$

$$R_c = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_3}$$

R_a, R_b and R_c is delta circuit impedances

R_1, R_2 and R_3 is star circuit impedances

1.2.6 Delta to Star Conversion

The Delta-Star conversion is used to convert the impedances in delta circuit to equivalent impedance of star circuit. The delta-star conversion is shown in Figure 1.32.

$$R_1 = \frac{R_bR_c}{R_a + R_b + R_c}$$

$$R_2 = \frac{R_aR_c}{R_a + R_b + R_c}$$

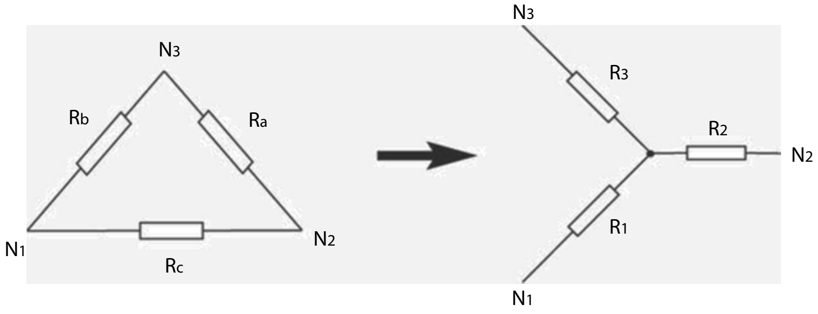


Figure 1.32 Delta to star conversion.

$$R_3 = \frac{R_a R_b}{R_a + R_b + R_c}$$

Where

R_a, R_b and R_c is delta circuit impedances
R_1, R_2 and R_3 is star circuit impedances

1.3 Power

Electricity is fed to devices which in turn do the work for us. For example, an electric heater delivers thermal power (heat) and a motor delivers mechanical power. Both the devices consume electrical power and deliver different forms of output which are utilized directly. Electrical power is a product of voltage and current. Depending upon the type of circuit, electrical power is classified into three forms:

1) Real power (W)
2) Reactive power (VAr)
3) Apparent power (VA)

1.3.1 Real Power or Active Power (P)

Real power is the power that gets consumed by the load to deliver useful output. The SI unit of real power is expressed in Watts (W). Higher values of real power are mentioned as kW, MW and GW.

Example 1.13: A 40 W incandescent lamp is connected across single-phase, 240 V AC supply.

Answer:

40 W is the power consumed by the incandescent lamp and it converts 40 W of electrical power to illumination and heat.

The equation to calculate the real power in 1ϕ circuit is given in eqn 1.10.

$$P = VI\cos(\phi) \tag{1.10}$$

Where

P is real power in W
V is line to neutral voltage in V
I is current in A
Cos ϕ is power factor

Example 1.14: A 5Ω resistive load is connected across single-phase, 240 V AC supply as shown in Figure 1.33. Power factor is unity. Calculate the real power consumed by the resistive load.

Answer:

Load resistance is 5Ω
Power factor is unity
Current flow from eqn 1.6, 240/5 = 48 A
Real power consumed by the load from eqn 1.10, 240 x 48 x 1 = 11520 W
Real power consumed by the resistive load is 11520 W or 11.52 kW.

The equation to calculate the real power in 3ϕ balanced circuit is

$$P = \sqrt{3}VI\cos(\phi) \tag{1.11}$$

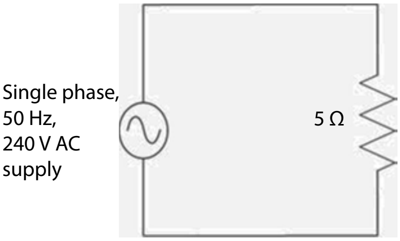


Figure 1.33 Single phase, 240V circuit powering resistive (5 Ω) load.

Where

P is real power in W
V is phase to phase voltage in V
I is per phase current in A
Cos ϕ is power factor

Example 1.15: A 5Ω resistive load is connected across the all phases as shown in Figure 1.34. Circuit is assumed to be balanced and power factor is unity. Calculate the real power consumed by the resistive load.

Answer:
Voltage is 415 V
Load resistance is 5Ω/ph
Power factor is unity
From eqn. 1.4, line to neutral voltage is 240 V.

Current flow per phase from eqn 1.6, 240/5 = 48 A
Real power consumed by the load from eqn 1.11, = 1.732 x 415 x 48
Total power consumed by the load is 34501 W or 34.5 kW.

For an unbalanced circuit, real power in eqn 1.11 is not applicable and the expression to calculate the real power in 3ϕ unbalanced circuit is given in 1.12.

$$P = V_r I_r \cos(\phi_r) + V_y I_y \cos(\phi_y) + V_b I_b \cos(\phi_b) \tag{1.12}$$

Where

P is real power in W
V_r, V_y, V_b are the respective line to neutral voltages in V
I_r, I_y, I_b are the respective phase currents in A
Cos ϕ_r, Cos ϕ_y, Cos ϕ_b are the respective power factors

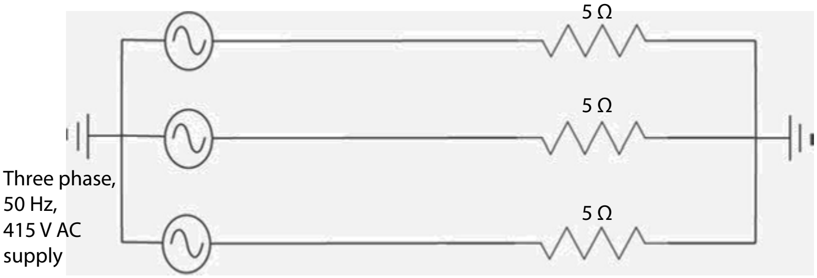


Figure 1.34 Three-phase, 415V balanced circuit powering the resistive load (5 Ω/phase).

Example 1.16: A 415 V distribution system has unbalanced loads across the three phases. Calculate the real power for phase R has 50A at 0.8 lagging power factor, phase Y has 70A at 0.9 lagging power factor and phase B has 80A at unity power factor as shown in Figure 1.35.

Answer:

From eqn 1.4, $V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{415}{\sqrt{3}} = 240V$ (line to neutral voltage is 240 V).

$V_r = V_y = V_b = 240$ V.

$I_r = 50A$, $I_y = 70A$, $I_b = 80A$

$Cos\phi_r = 0.8$, $Cos\phi_y = 0.9$, $Cos\phi_b = 1$

Real power consumed by the load from eqn 1.12,

P = (240x50x0.8) + (240x70x0.9) + (240x80x1)

P = 9600 + 15120 + 19200 = 43920 W or 43.92 kW.

1.3.2 Reactive Power (Q)

When an AC circuit is energized, a magnetic field is created across the conductor due to reactance offered by the path. The magnetising current drawn by the reactive load to produce the magnetic field helps in consuming active power. The product of applied voltage and magnetising current is the power which is required to consume the active power. This power is known as reactive power, which is essential for active power consumption [8]. In other words the power drawn by the reactive component of the load is reactive power.

The reactive power is expressed as Voltage Ampere reactive (VAr). Higher values of reactive power are mentioned as kVAR and MVAR.

The equation for calculate the reactive power in single-phase circuit is

$$Q= VI \sin(\phi) \tag{1.13}$$

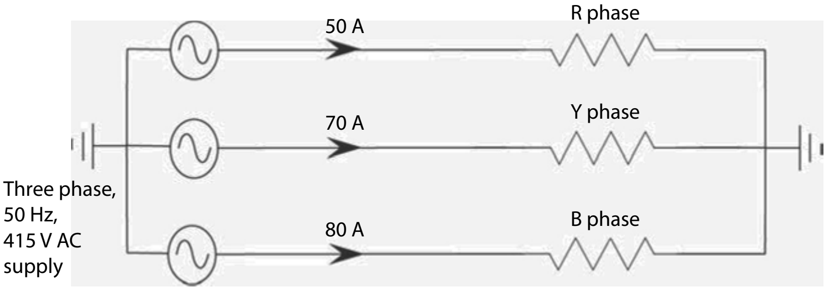


Figure 1.35 Three-phase, 415V unbalanced circuit.

Where

Q is reactive power in VAR
V is line to neutral voltage in V
I is phase current in A
ϕ is angle between voltage and current

Example 1.17: A 5Ω load at 0.8 PF connected across single phase, 240 V AC supply as shown in Figure 1.36. Calculate the reactive power drawn by the load.

Answer:

Load is 5Ω
Power factor is 0.8
From eqn 1.6, 240/5 = 48 A
$\phi = \text{Cos}^{-1}(0.8) = 36.87°$
Reactive power drawn by the load from eqn 1.13,
$Q = 240 \times 48 \times \text{Sin}(36.87°)$
$= 6912\text{VAr}$ or 6.91 kVAr

The equation for calculate the reactive power in three-phase balanced circuit is

$$Q = \sqrt{3}VI\sin(\phi) \tag{1.14}$$

Where

Q is reactive power in VAr
V is phase to phase voltage in V
I is per phase current in A
ϕ is angle between voltage and current

Figure 1.36 Single phase, 240V circuit.

Example 1.18: A three-phase, 415V, system has 10Ω impedance with 0.85 lagging power factor in each phase as shown in Figure 1.37. Calculate the reactive power drawn by the load.

Answer:

Voltage is 415 V

Load resistance is 10 Ω/ph

Power factor is 0.85

From eqn 1.6, current flow is 240/10 = 24 A

$\phi = \text{Cos}^{-1}(0.85) = 31.79°$

Reactive power drawn by the load from eqn 1.14,

$$Q = \sqrt{3} \text{ x } 415 \text{ x } 24 \text{ x Sin } (31.79°)$$

$$= 9087.8 \text{ VAr or } 9.09 \text{ kVAr.}$$

The equation to calculate the reactive power in three phase, unbalanced circuit is

$$Q = V_r I_r \sin(\phi_r) + V_y I_y \sin(\phi_y) + V_b I_b \sin(\phi_b) \qquad (1.15)$$

Where

Q is reactive power in VAr

V_r, V_y, V_b are the respective line to neutral voltages in V

I_r, I_y, I_b are the respective phase currents in A

ϕ_r, ϕ_y, ϕ_b are the angular displacement between voltage and current for the respective phases

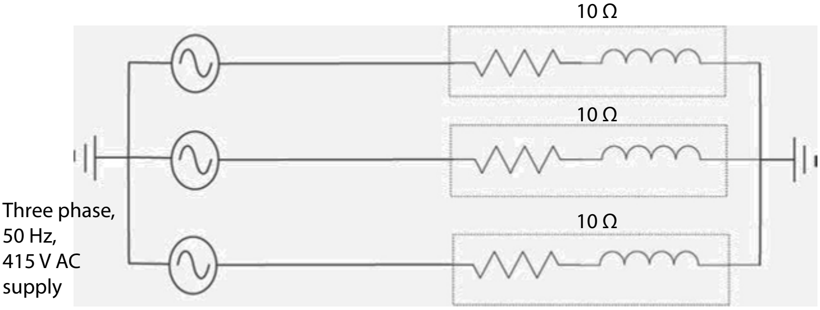


Figure 1.37 Three-phase, 415V balanced circuit.

Example 1.19: A 415 V distribution system has unbalanced loads across the three phases. Calculate the reactive power for phase R has 80A at 0.85 lagging power factor, phase Y has 90A at 0.7 lagging power factor and phase B has 75A at unity power factor as shown in Figure 1.38.

Answer:

From eqn. 1.6, line to neutral voltage is 240 V.

$V_r = V_y = V_b = 240$ V.

$I_r = 80A$, $I_y = 90A$, $I_b = 75A$

$\text{Cos } \phi_r = 0.85$, $\text{Cos } \phi_y = 0.7$, $\text{Cos } \phi_b = 1$

$\phi_r = 31.79°$, $\phi_y = 45.57°$, $\phi_b = 0°$,

Reactive power drawn by the load from eqn 1.15,

$Q = (240 \text{ x } 80\text{x } \sin(31.79°)) + (240 \text{ x } 90 \text{ x } \sin(45.57°)) + (240 \text{ x } 75 \text{ x } \sin(0°))$

$Q = 10114.7 + 15424.7 + 0 = 25539.4$ VAr or 25.53 kVAr.

1.3.3 Apparent Power (S)

Apparent power is the vector sum of real and reactive power. The apparent power is expressed in Volt Amperes (VA). Vector addition technically means taking the square root of the sum of the square of real power and the square of reactive power. The expression for apparent power is given in equation (1.16).

$$VA = \sqrt{W^2 + VAr^2} \tag{1.16}$$

All the three forms of power are represented using power triangle where real power is represented along the abscissa, reactive power along the ordinate and apparent along the hypotenuse. The power triangle is shown in Figure 1.39.

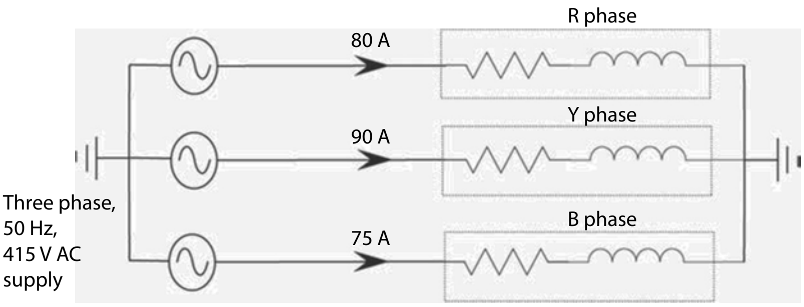


Figure 1.38 Three phase, 415V unbalanced circuit.

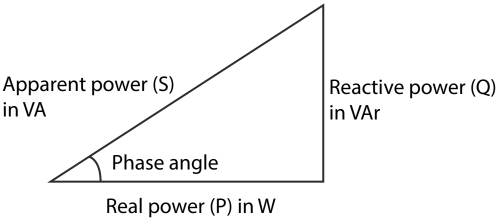


Figure 1.39 Power triangle.

The equation 1.17 is used for calculating the apparent power in single-phase circuit when voltage and current are known.

$$S = V \text{ x } I \tag{1.17}$$

Where

S is apparent power in VA
V is line to neutral voltage in V
I is current in A

Example 1.20: A single-phase, 1000W focus lamp draws 4.6A current in a 240 V AC supply as shown in Figure 1.40. Calculate the apparent power.

Answer:

From eqn. 1.17, S = 240 x 4.6 = 1104 VA or 1.1 kVA.

The equation 1.18 is used for calculating the apparent power in three-phase, balanced circuit when voltage and current are known.

$$S = \sqrt{3}Vl \tag{1.18}$$

Figure 1.40 Single-phase circuit powering 1000 W focus lamp.

Where

S is apparent power in VA
V is phase to phase voltage in V
I is per phase current in A

Example 1.21: A three-phase, 415V system has 10Ω load impedance with 0.85 lagging power factor in each phase as shown in Figure 1.41. Calculate the apparent power in the circuit.

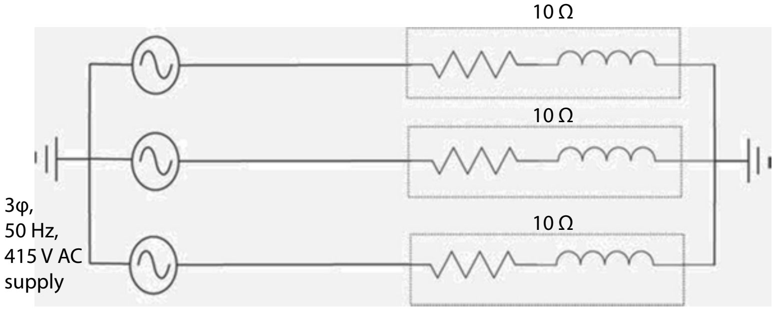


Figure 1.41 Three-phase, balanced circuit.

Answer:

From eqn. 1.4, line to neutral voltage is 240 V.
Per phase current from eqn 1.6, 240/10 = 24 A
$S = \sqrt{3} \text{ x } 415 \text{ x } 24$
S = 17251.23 VA or 17.25 kVA

The expression for calculating the apparent power from real power and reactive power is given in eqn. 1.19.

$$VA = \sqrt{W^2 + VAr^2} \tag{1.19}$$

Where

VA is apparent power
W is real power
VAr is reactive power

Example 1.22: A load draws 2.3 kVAr reactive power to consume 5.59 kW of real power. Calculate the apparent power.

Answer:

kW = 5.59
kVAr = 2.3
From eqn 1.19, $kVA = \sqrt{kW^2 + kVAr^2}$
$kVA = \sqrt{5.59^2 + 2.3^2}$
$= 6.04$ kVA

The expression for calculation of apparent power from real power and power factor is given in eqn 1.20.

$$VA = \frac{W}{PF} \tag{1.20}$$

Where

VA is apparent power

W is real power

PF is power factor

Example 1.23: A three-phase, 415 V induction motor is consuming the 5.59 kW power from the supply and operating at 0.8 lag power factor. Calculate the apparent power flowing in the circuit.

Answer:

From the eqn 1.20, $kVA = \frac{kW}{PF}$

$$kVA = \frac{5.59}{0.8}$$

Apparent power = 6.99 kVA

The expression for calculating the apparent power in three-phase, unbalanced circuit is given in eqn 1.21.

$$S = V_r I_r + V_y I_y + V_b I_b \tag{1.21}$$

Where

S is apparent power in VA

V_r, V_y, V_b are the respective line to neutral voltages of R, Y and B phases respectively and expressed in Volts

I_r, I_y, I_b are the respective phase currents of R, Y and B phases respectively and expressed in Amps

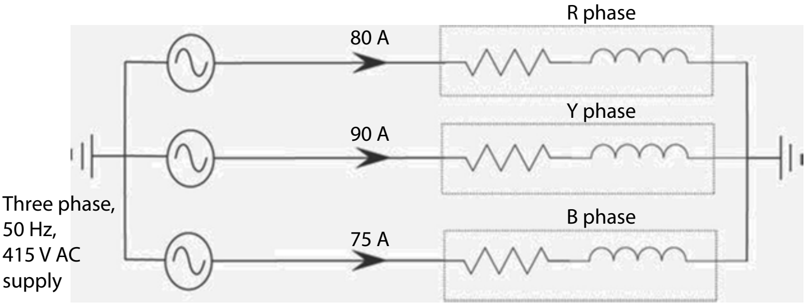


Figure 1.42 Three phase, 415V unbalanced circuit.

Example 1.24: A 415 V distribution system has unbalanced loads across three phases. Phase current of 80A, 90A and 75A flow in R, Y and B phases, respectively, as shown in Figure 1.42. Calculate the real power when R phase was at 0.85 power factor, Y phase was at 0.7 PF and B phase at unity power factor.

Answer:

From eqn. 1.4, line to neutral voltage is 240 V.

$V_r = V_y = V_b = 240$ V.

$I_r = 80A, I_y = 90A, I_b = 75A$

$S = (240 \times 80) + (240 \times 90) + (240 \times 75)$

Apparent power = 19200 + 21600 + 18000 = 58800 VA or 58.8 kVA.

1.4 Power Factor (PF)

Power factor is the effective usage of real power converted into useful work from apparent power. PF is a load dependent parameter and it comes into the picture for inductive and capacitive loads. When current flows in inductive circuit, reactive power is used for magnetization. Utilization of more reactive power to consume active power reduces the power factor [8, 11]. In other words, power factor determines how effectively real power is consumed in the electric circuit. The expression for true power factor is given in eqn. 1.22.

$$PF = \frac{\text{Real Power (W)}}{\text{Apparent Power (VA)}} \tag{1.22}$$

The power factor is generally classified into two types

i) Classification based on R, L and C through load characteristics

ii) Classification based on harmonics producing loads

1.4.1 Classification Based on Load Characteristics

Power factor is defined as the ratio of real power (W or kW) to apparent power (VA or kVA) and expression for power factor is given in eqn 1.22. The power factor is unity when phase angle difference between voltage and current is 0°. The power factor is zero when phase angle difference between voltage and current is 90°. Hence, the value of power factor lies between 0 and 1.

Where

1 is highest power factor when real power equals apparent power or angular displacement between voltage and current is 0°

0 is lowest power factor when real power is zero and reactive power equals apparent power or angular displacement between voltage and current is 90°.

The power factors are classified into three types based on linear relation between voltage and current characteristics:

- Unity power factor
- Lagging power factor
- Leading power factor

The relation between voltage and current for pure resistive, inductive and capacitive loads are listed in Table 1.1.

Unity power factor (Power factor value is 1):

The unity power factor is where the current follows the voltage in phase or angular displacement between voltage and current is zero. The following loads are resistive in nature and draw unity power factor from the supply:

- Incandescent lamp
- Water heater
- Soldering iron
- Iron box

Example 1.25: Unity PF representation using PSCAD simulation

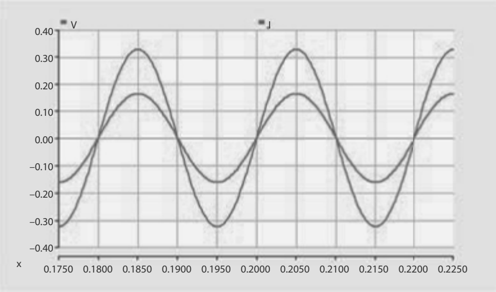
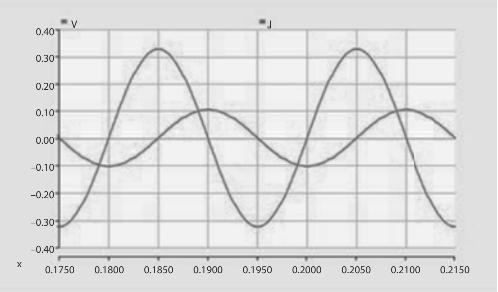
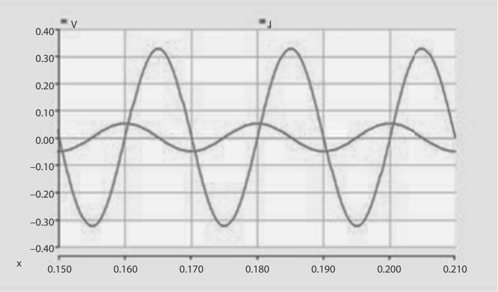
A single phase 230 V, 50 Hz AC supply powers a resistive load of 2Ω. Circuit diagram of ideal resistive load connected to AC supply is shown in Figure 1.43.

Figure 1.44 shows the relationship between voltage and current wave shape for unity power factor load. The connected load resistance of 2Ω draws the peak current from the source is sqrt (2) x V/R = 162 A is shown in Figure 1.44.

Example 1.26: Unity power factor using practical measurement

A resistive load bank of 190 kW is connected in the output side of UPS system whose name plate details are 500 kVA at 0.8 PF, output voltage is

Table 1.1 Voltage and current relation for resistive, inductive and capacitive loads.

Type of load	Relation of voltage and current	Power factor	Waveform
Resistor	Current in phase with voltage	Unity	
Inductor	Current lags the voltage by 90°	Lagging	
Capacitor	Current leads the voltage by 90°	Leading	

400V, 50 Hz, three phase, four wire. The schematic diagram of the power distribution is shown in Figure 1.45. Power quality analyzer is used to monitor the power parameters at the output side of the UPS system for the duration of one minute and 50 seconds between 12:36:00 to 12:37:50 hours.

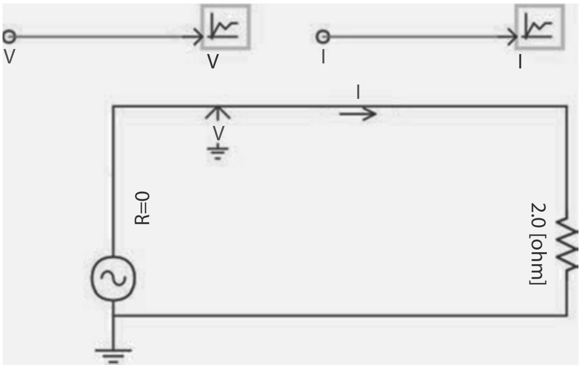


Figure 1.43 Circuit diagram of pure resistive load.

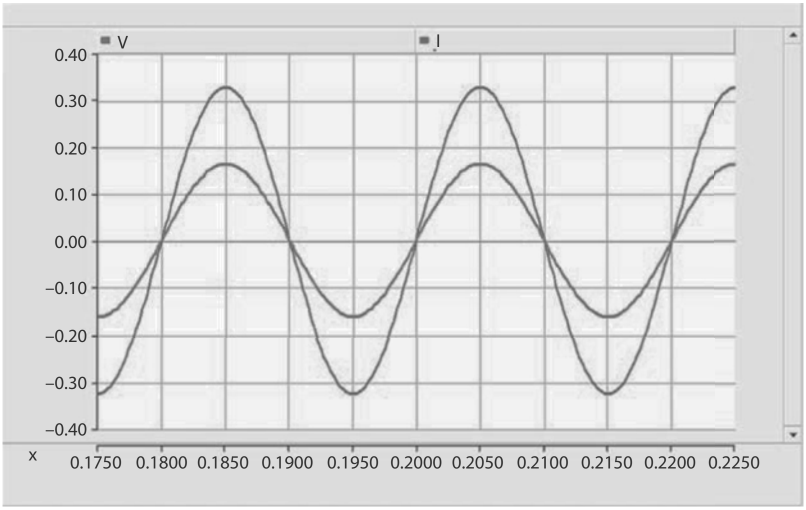


Figure 1.44 Voltage and current relation for unity power factor load.

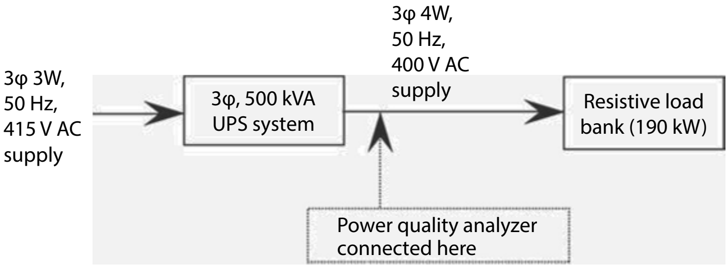


Figure 1.45 Schematic diagram.

Figure 1.46 shows the relationship between voltage and current characteristics drawn by resistive load.

Figure 1.47 shows the relationship between real power, apparent power and PF trend. The ratio of real power (69.97 kW) to apparent power (69.97 kVA) is equal to 1. That means, the resistive loads draws the real power from the UPS system at unity power factor.

Lagging power factor (Power factor value is between 0 and 0.99): The lagging power factor is the angular displacement of voltage and current greater than 0° but less than or equal to 90°. Current wave shape drawn by an ideal inductor lags the voltage wave shape by 90°. The lagging power factor is generally denoted by a '+' sign. The following loads are inductive in nature and draw the real power at lagging power factor.

- ➢ Transformers
- ➢ Motors
- ➢ Induction furnace

Example 1.27: Lagging power factor representation using PSCAD simulation

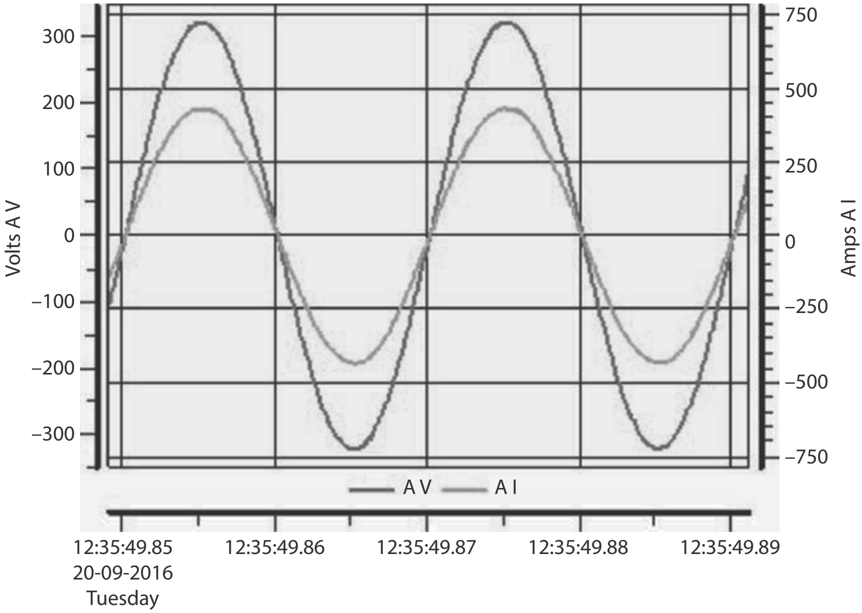
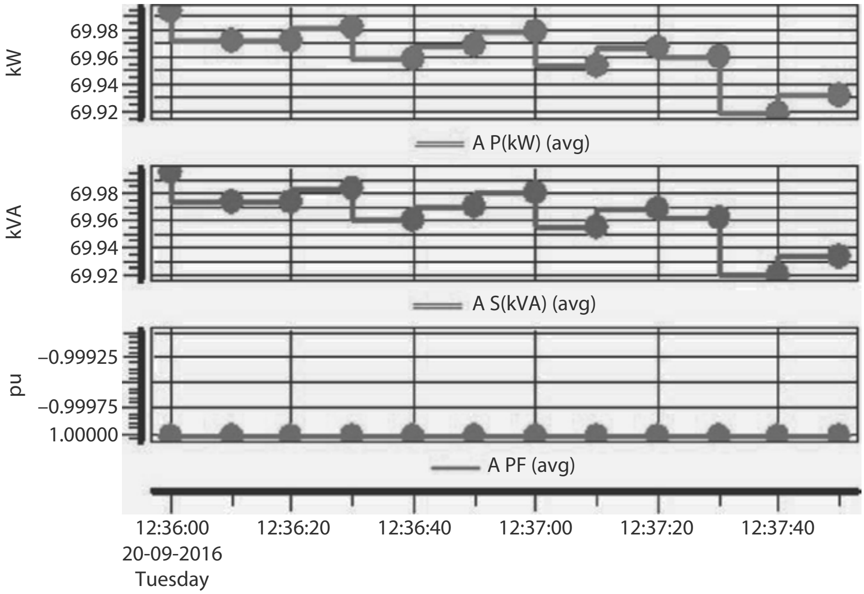


Figure 1.46 Voltage and current wave shape for unity power factor load. Note: This figure is captured using Dranetz Power Quality analyser.



	Min	*Max*	*Avg*
AP(kW)	*69.92*	*69.99*	*69.97*
AS(kVA)	*69.92*	*69.99*	*69.97*
APF	*1.0000*	*1.0000*	*1.0000*

Figure 1.47 kW, kVA and PF trend.

A single phase 230 V, 50 Hz AC supply is powering an ideal inductive load of 10 mH. Circuit diagram of ideal inductive load connected to AC supply is shown in Figure 1.48.

Figure 1.49 shows the relationship between voltage and current wave shape for an ideal inductive load. From Figure 1.49, it is evident that current drawn by an ideal inductor lags the voltage by 90°.

Example 1.28: Lagging PF using practical measurement
A three-phase, induction motor of 5 HP is connected in three-phase, 415V, 50 Hz AC power supply. The schematic diagram of power distribution is shown in Figure 1.50. Power quality analyzer is used to monitor the power parameters at Motor Control Center (MCC) outgoing to motor feeder for the duration is 11 minute and 40 seconds between 11:12:30 to 11:24:10 hours.

Figure 1.51 shows the relationship between voltage and current characteristics of 5 HP induction motor. From Figure 1.51, the current drawn by 5 HP induction is lags the voltage wave shape by 35.156°. This load is

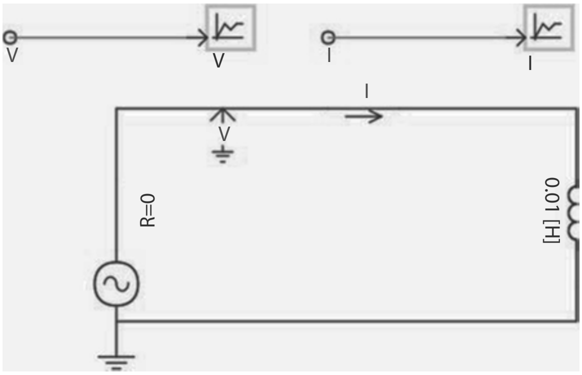


Figure 1.48 Circuit diagram of ideal inductor.

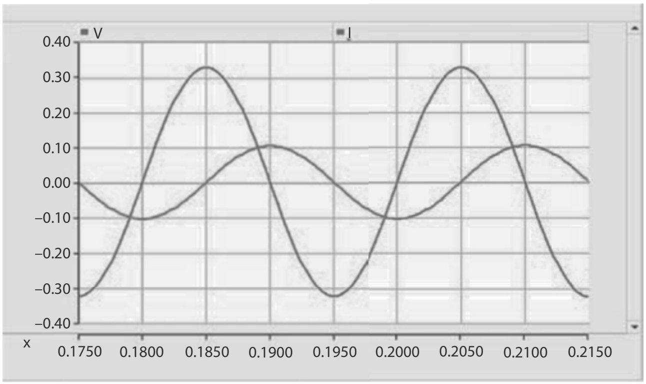


Figure 1.49 Voltage and current relation for lagging power factor load.

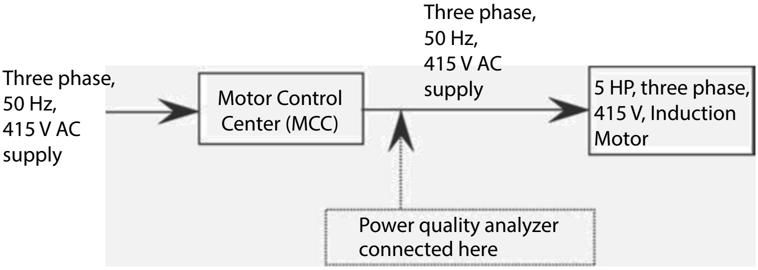


Figure 1.50 Schematic diagram.

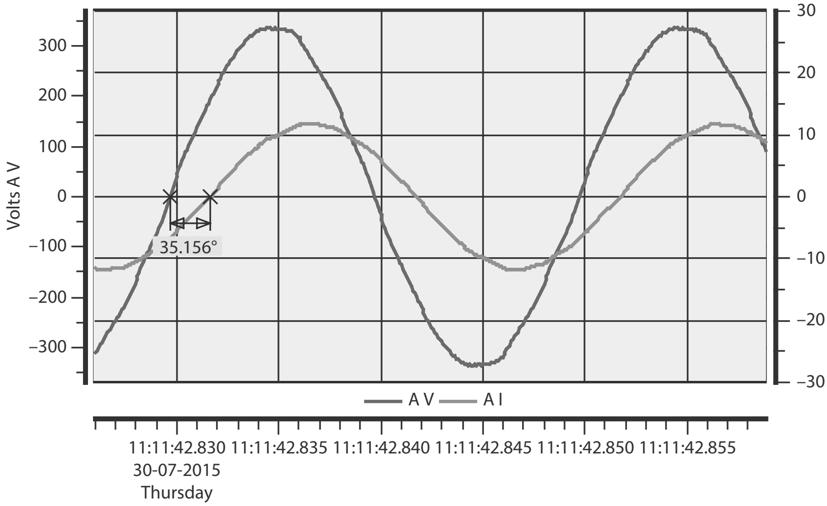


Figure 1.51 Instantaneous voltage and current wave shape (R phase) of 5 HP induction motor.

called lagging power factor load and the power factor for this load is cos (35.156°) equals 0.82.

Figure 1.52 shows the relationship between real power, apparent power and power factor trend of 5 HP induction motor. The ratio of real power (1.597 kW) to apparent power (1.961 kVA) is equal to 0.814 lagging power factor by practical measurement and which is theoretically calculated as 0.82 lagging power factor. The power factor of 0.814 lagging is denoted as '+'0.81.

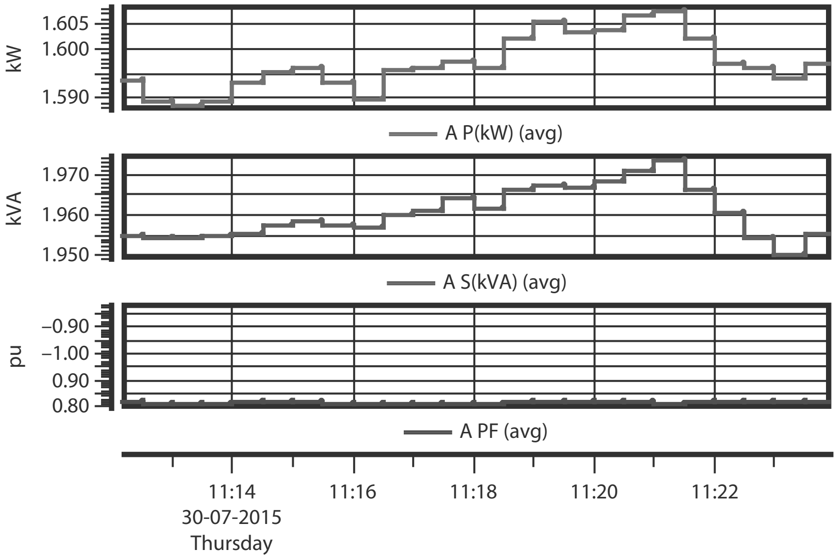
Leading PF (PF value between -0.99 and 0):

The leading PF is the angular displacement of voltage and current greater than 0° but less than or equal to 90°. The current drawn by an ideal capacitor leads the voltage by 90°. The leading PF is denoted by a '-' sign.

Example 1.29: Leading PF using PSCAD simulation

A single-phase 230 V, 50 Hz AC supply is powering the ideal capacitor of 500μF. The circuit diagram of ideal capacitor connected to AC supply is shown in Figure 1.53.

Figure 1.54 shows the relationship between voltage and current characteristics of an ideal capacitor. From Figure 1.54, it is evident that current drawn by the ideal capacitor leads the voltage by 90°.



	Min	*Max*	*Avg*
AP(kW)	*1.589*	*1.607*	*1.597*
AS(kVA)	*1.950*	*1.974*	*1.961*
APF	*0.8124*	*0.8174*	*0.8145*

Figure 1.52 Real, apparent power and power factor trend of 5 HP induction motor.

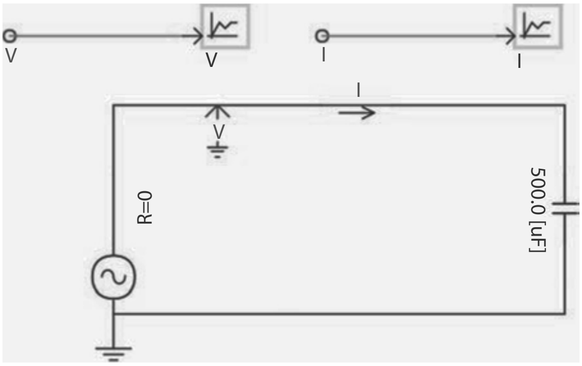


Figure 1.53 Circuit diagram for an ideal capacitor.

Example 1.30: Leading power factor using practical measurement

A three-phase, 415 V, 50 Hz AC supply is powered to a combination of resistive and inductive loads (RL load). Automatic Power Factor Corrector

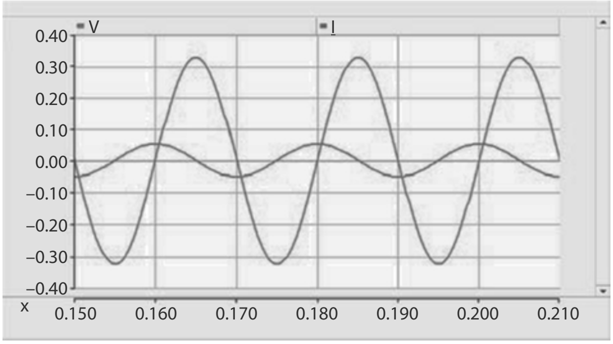


Figure 1.54 Voltage and current relation for leading power factor load.

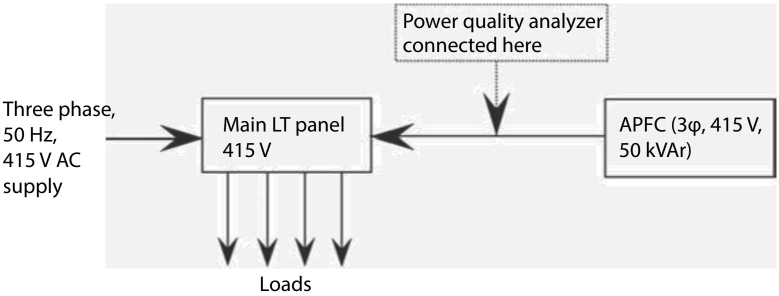


Figure 1.55 Schematic diagram of power distribution.

(APFC) circuit is used to improve the power factor as shown in Figure 1.55. The power quality analyzer is used to monitor the power parameters of APFC feeder connected to the Main LT panel for the duration of 30 minutes data logging 12:56 to 13:26 hours.

Figure 1.56 shows the relationship between voltage and current characteristics of APFC feeder during the operation. From Figure 1.56, the capacitor current wave shape leads the voltage wave shape by 90°. This load is called leading power factor load and the power factor for this load is cos (90°) equals 0.

Figure 1.57 shows the relationship between active power and apparent power. The ratio of real power (0.17 kW) and apparent power (14.97 kVA) is equal to 0.01 leading power factor and which is theoretically calculated as 0. The power factor of 0.01 leading is denoted as '-'0.01.

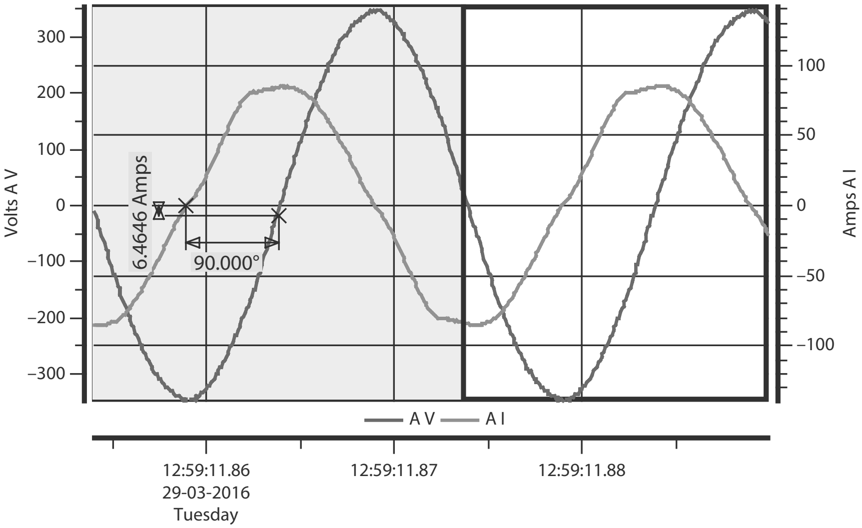
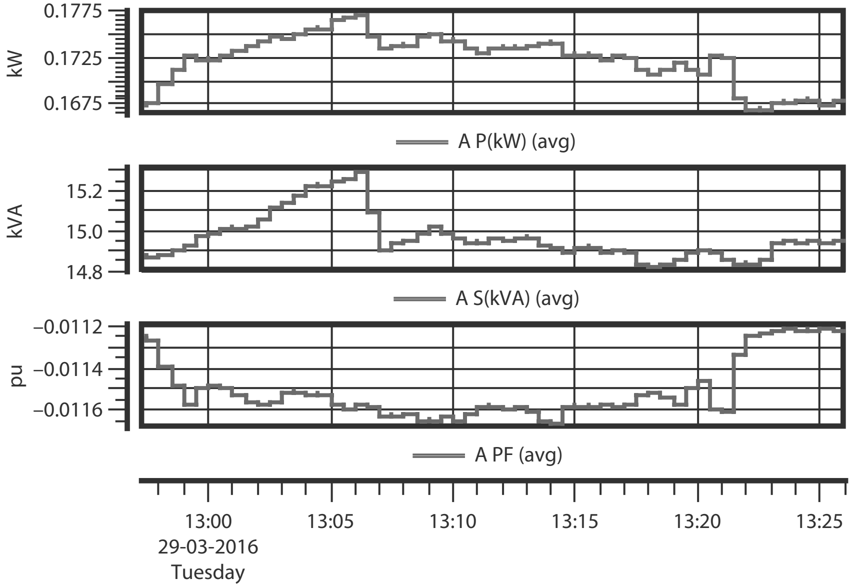


Figure 1.56 Instantaneous voltage and current wave form of capacitor.



	Min	*Max*	*Avg*
AP(kW)	*0.1668*	*0.1770*	*0.1723*
AS(kVA)	*14.82*	*15.29*	*14.97*
APF	*−0.01166*	*−0.01121*	*−0.01151*

Figure 1.57 kW, kVA and PF trend for leading PF load.

1.4.2 Classification Based on Harmonics Producing Loads

The advancement in electronic control systems, power electronics based loads are widely used in various applications in distribution system [28, 29]. These power electronics based loads are having nonlinear voltage and current characteristics, which changed the concept of power factor into three different forms:

- Displacement power factor
- Distortion power factor
- True power factor

Displacement power factor:

Displacement power factor or conventional power factor is defined as the cosine of angle of voltage and current at fundamental frequency without presence of harmonics. The displacement power factor is applicable for linear loads at fundamental frequency (50 Hz or 60 Hz only). If harmonics are present in the system, linear power factor is not the correct terminology to measure the power factor and distortion power factor that are to be used in such an environment.

Distortion power factor:

The distortion power factor is used where load (equipment's) current wave shape does not follow the voltage wave shape and these loads are called non-linear loads. These loads demand, non sinusoidal current wave shape, which are resolved into multiple sinusoidal wave of different amplitude and frequencies called fundamental component and harmonic component. As the RMS current is vector sum of fundamental current and harmonic current, fundamental current are less than the RMS current as given in eqn 1.23.

$$I_F < I_{RMS} \tag{1.23}$$

If there is no distortion, harmonic current component become zero leading to the expression (1.24)

$$I_F = I_{RMS} \tag{1.24}$$

Distortion power factor is the ratio upon fundamental current to RMS current. The more harmonic distortion, the less will be the distortion power factor. If the connected load is linear load, distortion power factor is unity. The expression for distortion power factor is given in eqn 1.25.

$$\text{PF (distortion)} = \frac{I_F}{I_{RMS}} \tag{1.25}$$

Where

I_F is fundamental current
I_{RMS} is total current

True power factor:
True power factor is the overall power factor of the presence of both linear and non-linear (harmonics) loads. It is the product of the displacement power factor and distortion power factor. The expression for true power factor is given in eqn. 1.26.

$$\text{PF (true)} = \text{PF (displacement)} \text{ X } \text{PF (distortion)} \tag{1.26}$$

When the connected loads are linear, both displacement and distortion power factor is unity and true power factor is unity.

1.4.3 The Need for Power Factor Improvement

The drawl of entire reactive power demanded by the plant loads from the power source (DISCOMs) affects the power factor limits specified by the particular DISCOMs. Drawl of real power at low power factor will increase the apparent power requirement of the plant and additional demand capacity to be purchased from the DISCOMs. This could be reduced by supplying the localised reactive power to the loads as a localised compensation and increase the real power consumption at the same apparent power from the DISCOMs power supply. Supplying the localised reactive power to increase real power has the following advantages in the system:

- Reduces the apparent power demand of the system
- Avoids the penalty imposed by the power supply company or DISCOMs
- Reduces electricity cost
- Reduction of circuit components rating like cable, switchgear, etc
- Reduction of I^2R losses in the system equipment's like cables
- Reduces the voltage drop in the cable

1.4.4 Methods of Power Factor Improvement

The power factor improvement are obtained majorly by two ways:

1. Capacitor banks
2. Synchronous condenser

Power factor improvement by installing the capacitor banks:
The capacitor banks are an economical way to produce the reactive power requirements. These capacitor banks are used to improve the power factor by supplying the required reactive power locally in the power system. It Improves power factor by reducing the phase angle between voltage and current by supplying the reactive power demanded by inductive loads [19]. Generally, these capacitor banks are connected parallel to the loads which require the reactive power for their operation.

The capacitor banks are used to improve the power factor as shown in Figure 1.58.

In Figure 1.58, there are multiple Motor Control Centers (MCC) that are connected in MV switchgear at 11 kV voltage level. This MCC has multiple motors which operate in different load cycles in 24 hours. These motors require reactive power for their operation. The Automatic Power Factor Capacitor (APFC), is connected at 11 kV MV switchgear which is used to supply the varying reactive power required by MCC-1 to MCC-5.

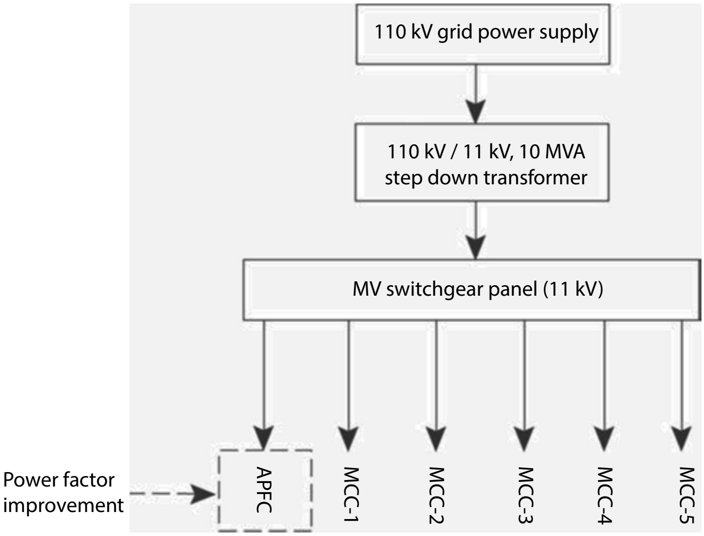


Figure 1.58 Power factor improvement by capacitor bank.

Synchronous condenser:
The synchronous condenser is one of the methods for power factor compensation in the transmission and distribution system. The synchronous motor has the capability of operating in all the power factor (lagging, leading or unity) based on the excitation. Whenever the synchronous motor is operating at no load and over excited condition, this draws the real power from the power supply and it injects the reactive power to the power supply to improve the power factor. Nowadays, power factor compensation by synchronous condenser methods are not widely used because of higher costs involved.

The synchronous condenser is used to improve the power factor; this is represented in Figure 1.59.

1.5 Types of Loads

The electrical loads are classified into two types based on the voltage and current relationship:

- Linear loads
- Non-linear loads

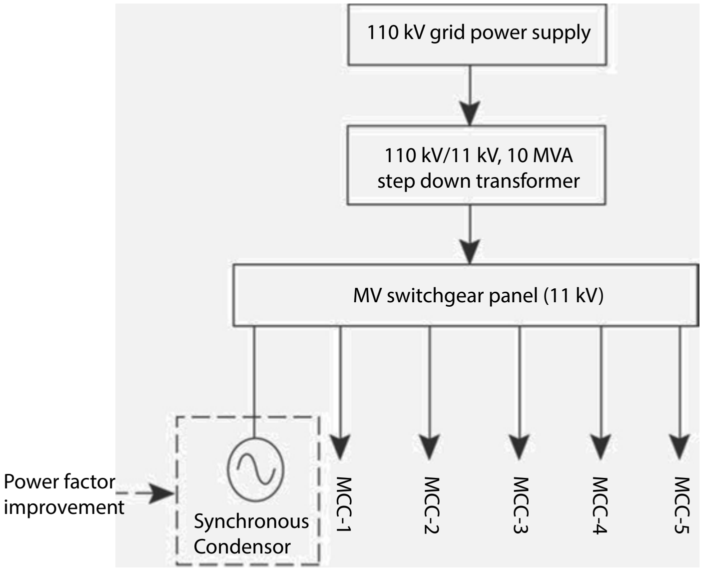


Figure 1.59 Power factor improvement by synchronous condensor.

1.5.1 Linear Loads

Linear loads are loads which draw a sinusoidal current pattern when sinusoidal voltage is applied. Linear loads operate at fundamental frequency of 50 Hz or 60 Hz only. In other words V/I is a straight line which means the loads that obey Ohm's law is a linear load. The Figure 1.60 shows the voltage and current relationship of linear loads.

Examples for linear loads are electric heater, incandescent lamp and electric motor.

1.5.2 Non-Linear Loads

Non-linear loads are loads which draw a non-sinusoidal current pattern when sinusoidal voltage is applied across its terminals. The characteristics of non-linear loads are explained in section 1.1.4.2 under distortion power factor. Figure 1.61 shows the voltage and current relationship of non-linear loads.

Example for non-linear loads are power electronic based equipment's like VFD, UPS, SMPS and Cyclo converter, etc.

The voltage - current relationship for VFD, UPS and SMPS are shown in Table 1.2.

1.6 Three-Phase Power Measurement

In a three-phase circuit, the loads are whether Star connected or Delta connected, the total power (P) is expressed in eqn 1.27.

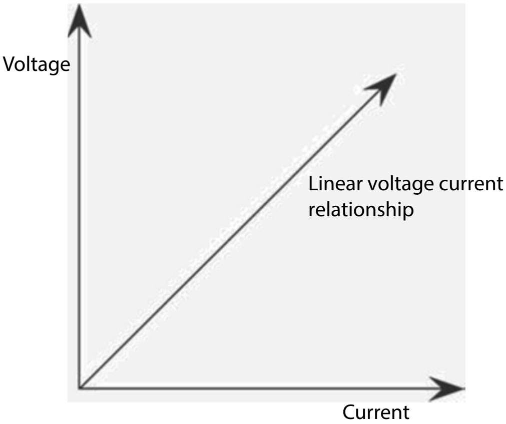


Figure 1.60 Linear voltage – current relationship.

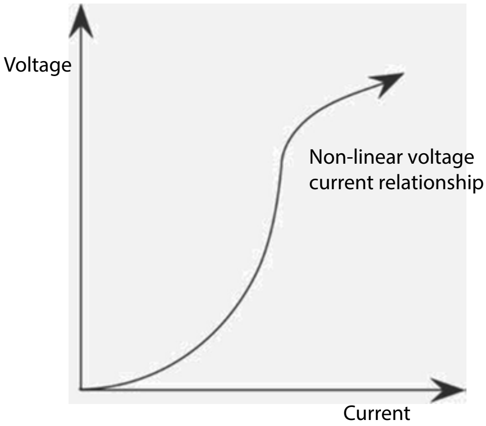


Figure 1.61 Non-linear voltage – current relationship.

$$P = \sqrt{3} V_L I_L \cos(\phi) \tag{1.27}$$

Where

P is power in Watts

V_L is line voltage

I_L is line current

cos (ϕ) is power factor

The Wattmeter is a measurement device, which is used to measure the power in a single-phase and/or three-phase system. It consists of two coils, namely current coil and voltage coil.

(i) Current Coil

The current coil is connected in series with the load and used to sense the current flowing in the circuit. It is similar to ammeter and the resistance of the coil is kept as low as possible. Hence, it requires higher cross sectional area and less number of turns. The current coil is shown in Figure 1.62.

(ii) Voltage Coil

The voltage coil or pressure coil is connected in parallel with the load and used to sense the voltage across the power supply terminals. It is similar to voltmeter and the resistance of the coil is as high as possible. Hence, it requires less cross sectional area and a greater number of turns. The pressure coil is shown in Figure 1.63.

Table 1.2 Voltage – current relationship of VFD, UPS and SMPS.

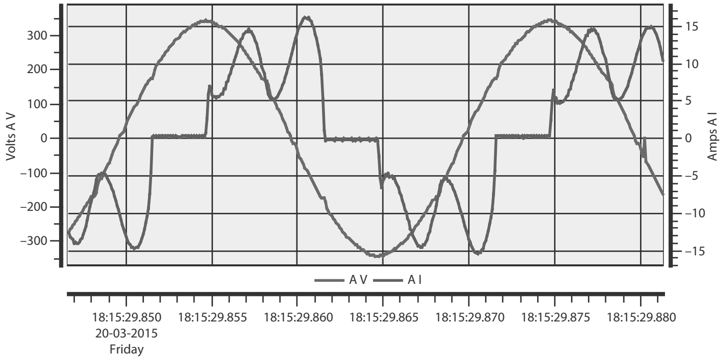
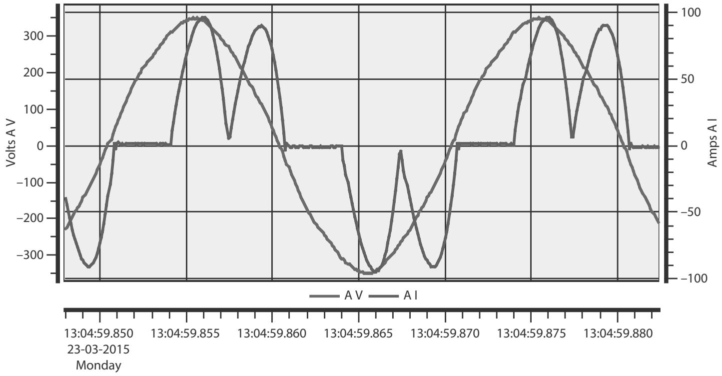
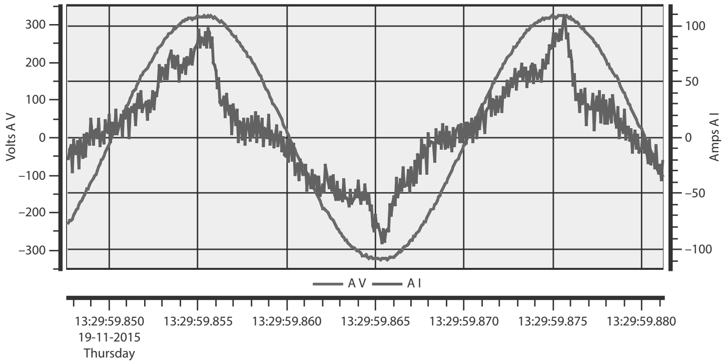
Type of load	Waveform
VFD	
UPS	
SMPS	

Figure 1.62 Current coil.

Figure 1.63 Pressure coil.

Where
M is from mains
L is to load (for current coil)
C is common
V is voltage (pressure coil)

In general, power in three phase circuit is measured by the following methods:

1) Two-Wattmeter method
2) Three-Wattmeter method

A. Two-Wattmeter Method:

The two-Wattmeter method is generally used to measure the power in a three-phase, three-wire circuit; it is shown in Figure 1.64. The two Wattmeter are namely W_1 and W_2 connected to either two phase or three phase.

The Wattmeter W_1 is connected in R and B phase and Wattmeter W_2 is connected in Y and B phases. In Wattmeter W_1, current coil terminal M is connected to R phase and L is connected to load terminal of R phase. Voltage coil terminal C is connected to M and V is connected to B phase.

In Wattmeter W_2, current coil terminal M is connected to Y phase and L is connected to load terminal of Y phase. Voltage coil terminal C is connected to M and V is connected to B phase.

Similar type of connection is used for delta connected load.

In this method, total power in Watts is the algebraic sum of Wattmeter W_1 and Wattmeter W_2 expressed in equation 1.28.

$$W = W_1 + W_2 \tag{1.28}$$

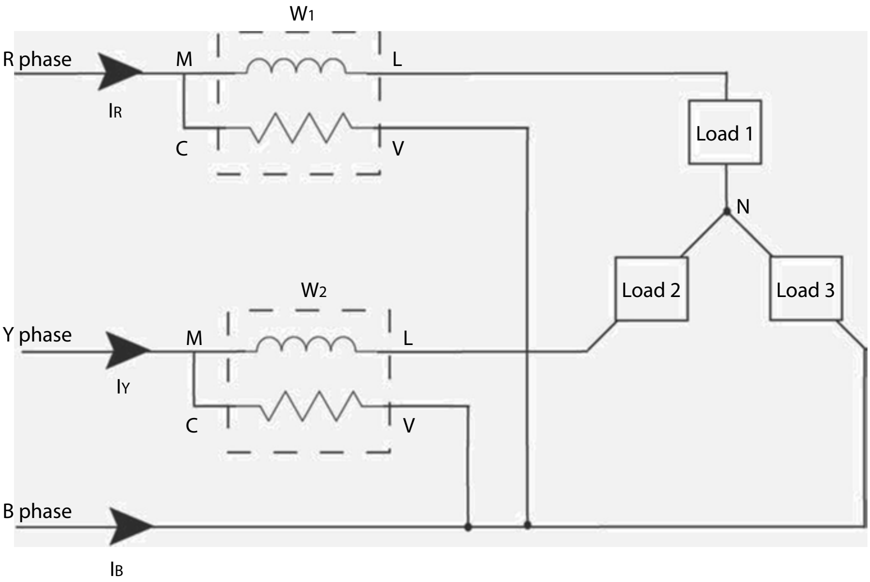


Figure 1.64 Two-Wattmeter method for three-phase power measurement.

Where

W is total power in (W)
W_1 is power (W) in Wattmeter 1
W_2 is power (W) in Wattmeter 2

The advantages of the two-wattmeter method are as follows

- The method is suitable for both balanced and unbalanced loads
- Neutral point for star connected load is not necessary to connect the Watt meters
- Two-Wattmeter's are sufficient to measure the total power

The disadvantages of two-Wattmeter methods are as follows

- This method is not suitable for three-phase, four-wire loads
- Higher possibilities of measurement error due to sign of both Wattmeter W_1 and W_2

B. Three-Wattmeter method:

The three-Wattmeter methods are generally used to measure the power in three-phase, three-wire circuits and three-phase, four-wire circuits.

The connections for star connected loads for measuring power by the three-wattmeter method is shown in the following Figure 1.65. The three-wattmeters are namely W_1, W_2 and W_3.

The Wattmeter W_1 is connected in R phase and neutral, Wattmeter W_2 is connected in Y phase and neutral, Wattmeter W_3 is connected in B phase and neutral. In Wattmeter W_1, current coil terminal M is connected to R phase and L is connected to load terminal of R phase. Voltage coil terminal C is connected to M and V is connected to neutral.

In Wattmeter W_2, current coil terminal M is connected to Y phase and L is connected to load terminal of Y phase. Voltage coil terminal C is connected to M and V is connected to neutral.

In Wattmeter W_3, current coil terminal M is connected to B phase and L is connected to load terminal of B phase. Voltage coil terminal C is connected to M and V is connected to neutral.

In this method, total power in Watts is the algebraic sum of wattmeter W_1, wattmeter W_2, wattmeter W_3 and expressed in equation 1.29.

$$W = W_1 + W_2 + W_3 \tag{1.29}$$

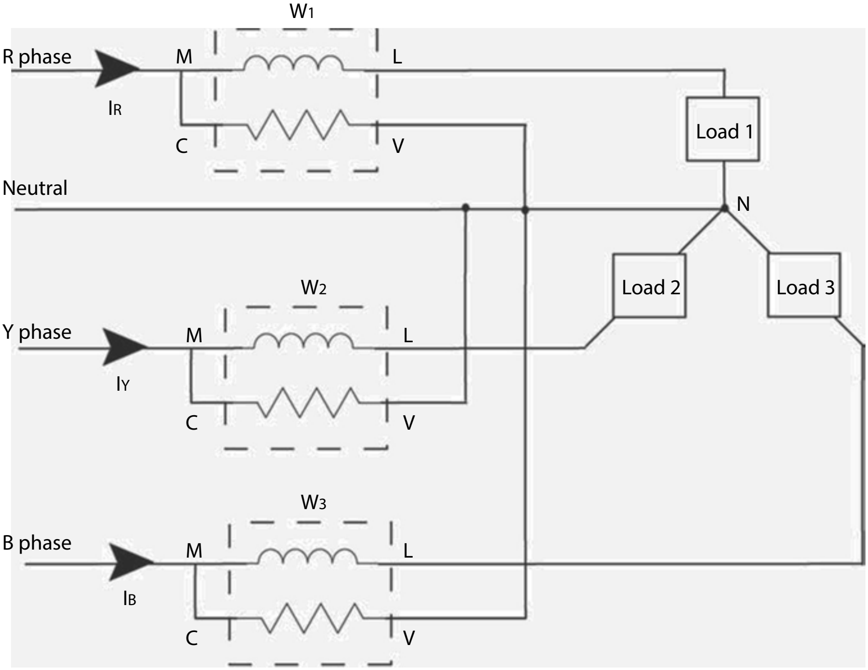


Figure 1.65 Three-Wattmeter method power measurement.

Where

W is total power in (W)
W_1 is power (W) in wattmeter 1
W_2 is power (W) in wattmeter 2
W_3 is power (W) in wattmeter 3

1.7 Overview of Power Systems

The power plant or power station, power transmission and power distribution systems are the main parts of an electrical power system [2]. The generated power at a power plant, in a nuclear, coal or solar power plant, is transmitted to the loads through transmission and distribution systems [16, 21]. The general structure of the power system is shown in Figure 1.66.

Power plant or power station:

The power plant generates the power from conventional sources like coal, nuclear, diesel, etc., and non-conventional sources like solar, wind, biomass, etc [15, 32–34]. The voltage level of the power generation at the power plant is between 6.6 kV to 22 kV based on the requirement.

Transmission system:

The transmission system is used to transfer power from the power plant or power station to the load center, i.e., it transfers the bulk power from power plant to end-users loads. It interconnects the two or more power stations and forms as a power pool.

The transmission systems are generally classified into:

1) Primary transmission system
2) Secondary transmission system.

The generated power at medium voltage level is converted into higher voltage level and transmitted through primary transmission system because transferring the power at lesser voltage level will cause the higher power loss [20]. So, the generated voltage is stepped up to a higher voltage level by means of a step up transformer in the sending end substation. The primary transmission system is used to transfer the power at higher voltage level like 132kV, 220 kV or 230 kV, 400 kV and 765 kV.

At the receiving end substation, the voltage at higher magnitude (132kV, 220 kV or 230 kV, 400 kV and 765 kV) is stepped down to 66 kV or 33 kV by means of a step down transformer. The secondary transmission system

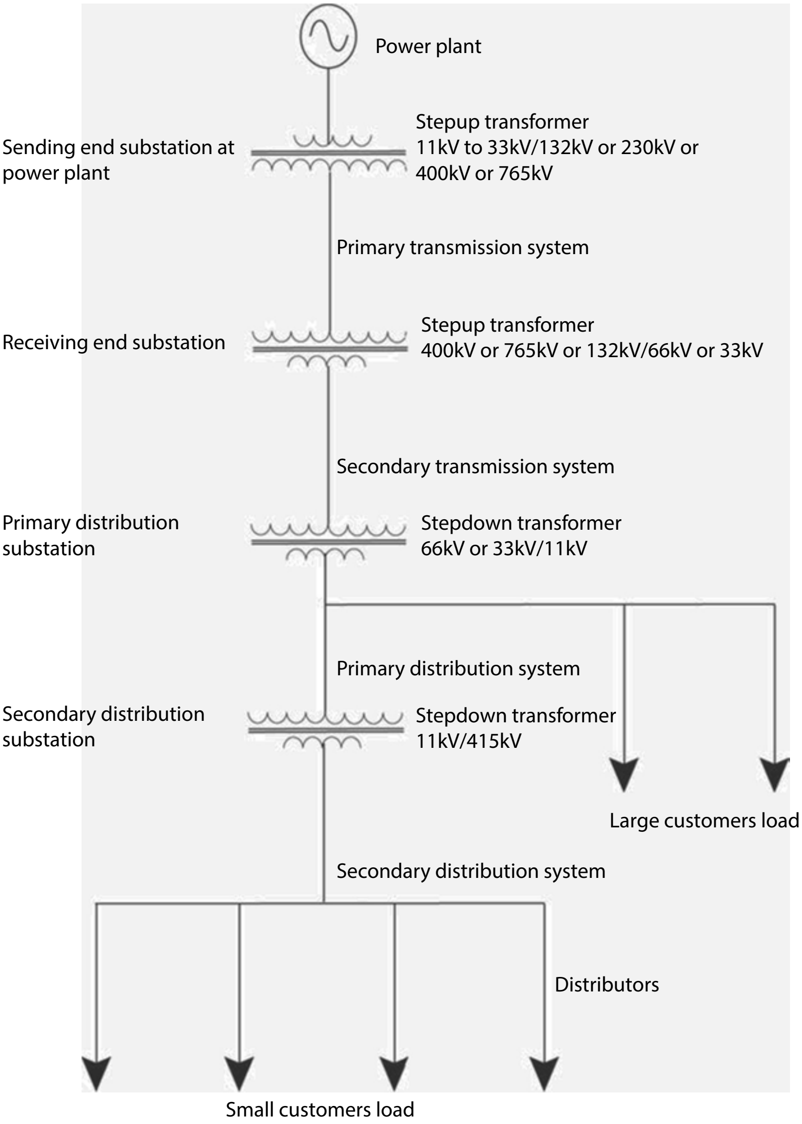


Figure 1.66 General structure of power system.

is used to transfer the power to the primary distribution system and large-scale end user loads at 33 kV or 66 kV.

Distribution system:

The distribution system is used to provide the power supply to end-users' loads [9, 13, 18]. It generally classified into two types:

1) Primary distribution system
2) Secondary distribution system

The primary distribution system is used to provide the power supply to large-scale end-users' loads and powering the secondary distribution system [14]. The typical voltage levels of primary distribution systems are 2.2kV, 3.3kV, 6.6kV, 11kV, 22kV and 33kV.

The secondary distribution system is used to power small- and medium-scale end-user loads. The typical voltage level of secondary distribution systems are 415V, 690V, etc, in three phase and 240V in single phase.

1.7.1 Components of an Electric Power System

The main components of any electric power systems are as follows [4, 5]:

1) Generators
2) Transformers
3) Transmission lines
4) Distribution Lines
5) Cables
6) Loads
7) Compensation devices such as shunt capacitors, series and shunt reactors

Generators:
A generator is a device used to produce electric power by converting rotating mechanical energy into electrical energy. The physical installation of generator at an actual site is shown in Figure 1.67.

Transformer:
A transformer is a static device which is used to transfer the power at one voltage level to another voltage level (step up or step down the voltage) without changing the frequency. The transformer used to change the voltage from lower voltage to higher voltage is called a step-up transformer, and the transformer that is used to reduce the voltage level from higher voltage level to lower voltage level is called a step-down transformer.

The physical installation of a transformer at an actual site is shown in Figure 1.68.

Transmission Lines:
Overhead transmission lines are used to transfer electric power from one location to another at higher voltage level in a primary transmission

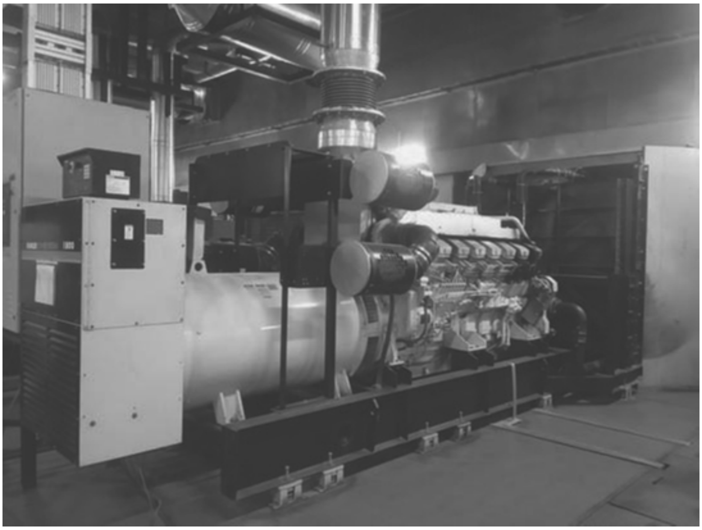


Figure 1.67 Installation of generator at actual site.

Figure 1.68 Installation of transformer at actual site.

system and a secondary transmission system. Based on number of circuits, the transmission lines are classified as follows:

i) Single-circuit transmission line
ii) Double-circuit transmission line
iii) Four-circuit transmission line

The single-circuit transmission line consists of one circuit of R, Y and B phases. The actual site installation of single-circuit transmission lines is shown in Figure 1.69.

The double-circuit transmission line consists of two numbers of single circuit of R, Y and B phases. Actual site installation of double-circuit transmission lines is shown in Figure 1.70.

Figure 1.69 Installation of transmission lines 110 kV single circuit.

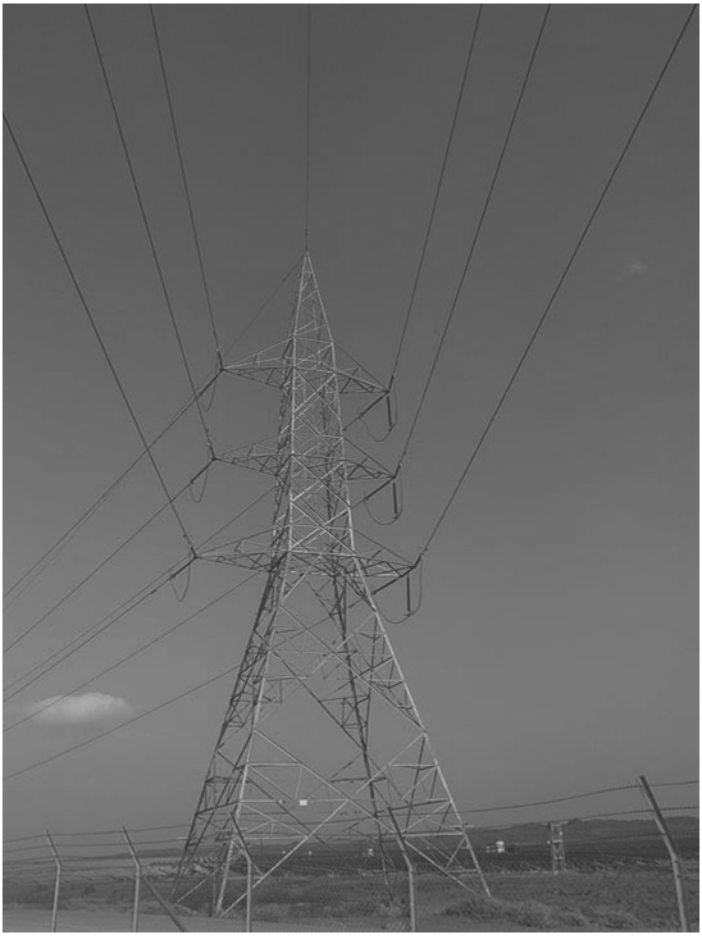


Figure 1.70 Installation of transmission lines 220 kV double circuit.

The four-circuit transmission line consists of four numbers of single circuit of R, Y and B phases. Actual site installation of four-circuit transmission lines is shown in Figure 1.71.

The distribution lines are used to transfer electric power from one location to another location at medium voltage level in a primary distribution system and low voltage level in a secondary distribution system [12]. The actual site installation of a medium voltage primary distribution line is shown in Figure 1.72.

The actual site installation of low voltage secondary distribution line is shown in Figure 1.73.

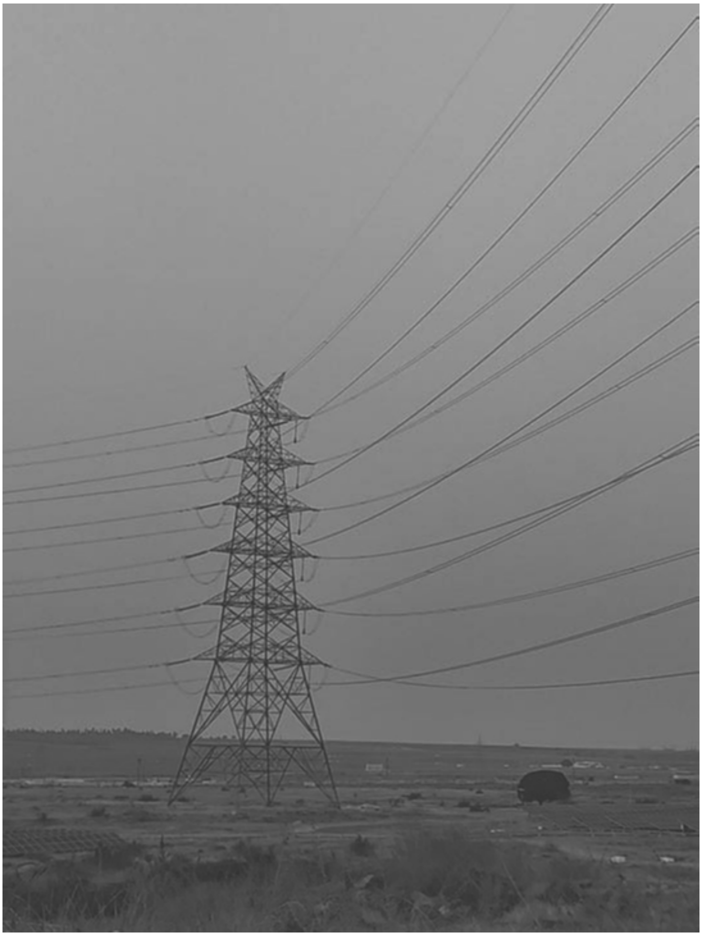


Figure 1.71 Installation of transmission lines.

Cables:

Power cables are a replacement for transmission lines in various places to transfer the power from one location to another location. These power cables are used to transfer electric power from one location to another location in both transmission and distribution system. Generally, power cables are installed in cable trays or conduits or in trenches. The cables are buried; these cables are called underground cables.

The actual site installation of underground cable for medium voltage primary distribution system is shown in Figure 1.74.

Figure 1.72 Installation of primary distribution line 11 kV single circuit.

The selection installation whether overhead lines or underground cables are depends on the following factors:

1) Location of installation
2) Technical and commercial considerations

The comparison of both overhead transmission system and underground transmission system are listed and given in Table 1.3.

1.8 Protection of Power System

The power system protection deals with the safety of the electrical equipment's in the power system from faults by isolating the faulty portion from other healthy equipment's in the system [17]. When abnormalities (faults) are present in the system, current flow in the (line or cable) circuit increases drastically. Compared to normal operation current, current flow during

Figure 1.73 Installation of secondary distribution line 415 V.

the faulted condition is very high (more than several times of full load current). The equipment's get damaged due to this high current flow during the faulted condition. Hence, it is essential to protect the equipment's from the high current during the fault condition. The aim of the power system protection is to maintain the equipment's safety and stability of the power system by isolating the faulty equipment's during the system faults, ensuring the continuous operation of healthy equipment's in the network. The devices which are used to protect the system from faults are called switchgears or protection devices.

The combination of Current Transformers (CTs), Potential Transformers (PTs), relays and circuit breakers are used to achieve the protection. The power system protection is selected for low voltage, medium voltage and high voltage based on the system operating voltage [23]. The general flow chart of power system protection is shown in Figure 1.75.

The basic components of power system protection are listed as follows:

Figure 1.74 Installation of underground cables in buried cable trench.

1) Current Transformers (CTs) and Voltage Transformers (VTs)
2) Protective Relays
3) Circuit Breakers
4) Other accessories like batteries, charger and communication interface, etc.

Current Transformers:

Current transformers are used to reduce the high current magnitude flowing in the circuit to lesser current magnitude to a convenient level suitable

Table 1.3 Comparison of overhead and underground transmission system.

S. No.	Overhead system	Underground system
1	De-rating factor is less	De-rating factor is high
2	The required amount of insulation for same voltage level is less	The required amount of insulation for same voltage level is high
3	Heat dissipation of the conductor is easy	Heat dissipation of the conductor is difficult
4	Lesser economics involved in same power rating	Higher economics involved in same power rating
5	Fault identification is easy	Fault identification is difficult
6	Maintenance is simple	Maintenance is complicated
7	Long distance transmission	Short distance transmission
8	Safety is less	Safety is high
9	Affected by lightning discharge	Not affected by lightning discharge
10	Highly affected by natural disaster	Less affected by natural disaster

for the operation of metering instruments and/or relays. It has two windings, namely primary winding and secondary winding. Primary winding is connected at high current side and secondary winding is connected to metering equipment's and relays. The installation of CTs at 11 kV medium voltage is shown in Figure 1.76.

The primary current of the CTs is based on the current flow in the particular circuit, and secondary current rating of the CTs are either 1 A or 5 A. For example, the current flow in the circuit is 100 A and required secondary current is 1 A, then the required CT ratio is 100/1 A. Figure 1.77 shows the typical 100/1 A two core CT, core 1 is accuracy class 1 for metering and core 2 is accuracy class 5P20 for protection.

The construction requirements for both metering and protection requirements are different. Thus, metering CTs are not suitable for protection purpose and protection CTs are not suitable for metering purpose.

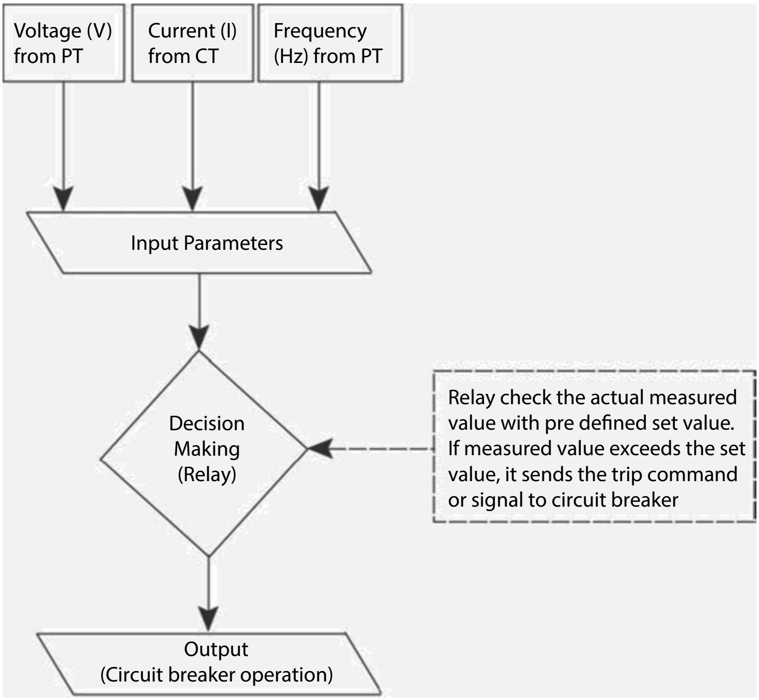


Figure 1.75 Flow chart of power system protection.

Figure 1.76 CTs at 11 kV (Courtesy: Schneider Electric).

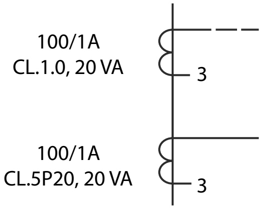


Figure 1.77 100/1 A CT.

Some of the important parameters of the CTs are accuracy class, burden, etc.

Accuracy class is error of the current transformer under the defined operating conditions. The standard accuracy class of the metering CTs are 0.1, 0.2, 0.5, 1, 3 and 5, special application accuracy class is denoted "S" along with the standard accuracy class [24]. The accuracy class for special applications are 0.2S and 0.5S.

The standard accuracy class of the protection CTs are 5P, 10P and 15P, special application accuracy class is denoted by "PX" or "PS" [25]. The accuracy class for special applications are PX and PS, where P stands for protection.

Burden is secondary circuit impedance in Ohms and power factor of the connected equipment's like relays, meters, transducers, etc.

Here the multiple cores are used for both metering and protection purposes; name plate details of the multi-core CT are listed in Table 1.4.

Voltage Transformers:

Voltage transformers are used to reduce the high voltage magnitude in the circuit to lesser voltage magnitude to a convenient level suitable for operation of metering instruments and/or relays. Voltage transformers are also called Potential Transformers (PTs). It has two windings, namely primary winding and secondary winding. Primary winding is connected at high voltage side

Table 1.4 Name plate details of the multi-core CT.

S. No.	Specification	Metering core	Protection core
1	Ratio (A)	400/1	400/1
2	Accuracy class	0.5	5P10
3	Burden (VA)	5	5

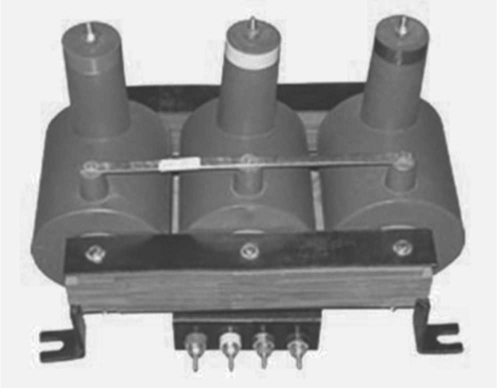


Figure 1.78 VTs at 11 kV.

and secondary winding is connected to metering equipment's and/or relays. The typical PT for 11 kV medium voltage is shown in Figure 1.78.

The primary voltage of the PTs is selected based on the voltage at the point of connection and secondary voltage rating is 110V.

Like CTs, the construction requirements for both metering and protection requirements are different. Thus, metering PTs are not suitable for protection purpose and protection PTs are not suitable for metering purpose. Some of the important parameters of the PTs are accuracy class, burden, etc.

Accuracy class is the error of the potential transformer under the defined operating conditions. The standard accuracy class of the metering PTs are 0.1, 0.2, 0.5, 1 and 3 [27]. The standard accuracy class of the protection PTs are 3P, 6P [26].

Burden is secondary circuit impedance in Ohms of the connected equipment's like relays, meters, transducers, etc.

The name plate details of the multi-core PT in which the multiple cores for both metering and protection purpose are listed in Table 1.5.

Table 1.5 Name plate details of the multi-core PT.

S. No.	**Specification**	**Metering core**	**Protection core**
1	Ratio (V)	33000/110	33000/110
2	Accuracy class	0.5	3P
3	Burden (VA)	15	15

Protective Relays:

Protection relays are used to sense the abnormalities (fault) from the inputs (voltage, current and frequency). If the relay senses the abnormalities, then it will initiate the trip command to circuit breaker to isolate the faulty portion from the system. There are different type of relays that are used in a power system to identify the abnormalities, such as

1) Current
2) Voltage
3) Frequency
4) Impedance
5) Direction of current flow

   Etc.

Based on the application, different types of relays are required to protect the equipment's during the system faults. They are listed below:

- ➢ Over current and earth fault relay
- ➢ Over voltage and under voltage relay
- ➢ Over frequency and under frequency relay
- ➢ Differential relay
- ➢ Distance relay
- ➢ Directional relay

  Etc.

Figure 1.79 Instantaneous earth fault relay (Courtesy: Alstom).

Figure 1.80 Instantaneous over voltage relay (Courtesy: Areva).

The instantaneous earth fault relay is shown in Figure 1.79.

The instantaneous over voltage relay is shown in Figure 1.80.

Circuit Breaker:

A circuit breaker is a device which is used to open and close the circuit contacts by means of manual as well as automatic (electrical) operation. There are different types of circuit breakers that are used for protection purposes: Vacuum Circuit Breaker (VCB), Sulfur Hexa Fluoride (SF_6), etc., in a high voltage system.

The actual installation of an SF6 breaker at site is shown in Figure 1.81.

Other accessories:

Batteries are used to provide the continuous and uninterrupted auxiliary power supply to relays, metering instruments and circuit breakers. Communication channels are used to analyse the voltage and current at the remote end of a line and tripping the circuit using the circuit breaker in case of abnormalities.

In a modern power system, disturbance recorders are used to monitor the system disturbance during the faulted conditions.

Figure 1.81 Installation of SF_6 breaker.

The power system protection has the following performance measures to check the effectiveness of the protection:

- Selectivity
- Speed
- Reliability
- Economy
- Simplicity

Basic Concepts:

Current: The movement of charges or flow of electrons in a circuit is called current. Unit of the current is "Ampere".

Voltage: The potential difference between the two terminals in the circuit is called voltage. Unit of the voltage is "Volts".

Power: The rate at which the work is being done in an electrical circuit is called an electric power. The power is measured in terms of "Watts".

Energy: The power and time required to complete the work is called energy. It is measured in terms of "Watt hour". Energy = Power*time (Whr)

Single-Phase Power Supply: A single-phase power supply has one line conductor and one neutral conductor. For example, the potential difference between the line conductor and neutral is 230 Volts.

Three-Phase Power Supply: A three-phase power supply has three line conductors and/or one neutral conductor. For example, the potential difference between the two line conductors is 415 V and potential difference between line conductor to neutral conductor is $1/\sqrt{3}$ times of line to line voltage which is 240 V. The phase difference between the three phases are 120 degrees electrical each other or by 1/3rd of the time period. That is in a 50 Hz supply has 6.6 milliseconds lag between each of the three phases crossing a certain voltage value.

Star Connection: The Star connection is formed by connecting starting or terminating ends of all the three windings together. The ends R_1-Y_1-B_1 are connected or ends R_2-Y_2-B_2 are connected together. This common point is called Neutral point. The remaining three ends are brought out for connection purpose. These ends are generally referred to as R-Y-B, to which loads are to be connected.

Delta Connection: The Delta is formed by connecting one end of the winding to starting of the other winding end connection which are made to form a closed loop. The supply terminals are taken out from the three junction points. Delta connection always forms a closed loop.

Line Voltage: The potential difference between the two phases.

Phase Voltage: The potential difference between the phase and neutral.

Line Current: The current passing through line (only line to line).

Phase Current: The current passing through the load (i.e., Phase to load).

Balanced Load: The impedance of all the three phases are equal. It is also called symmetrical load.

Unbalanced Load: The impedance of all the three phases are not equal. It is also called unsymmetrical load.

Methods of Three-Phase Power Measurements:

i. Single-watt meter method
ii. Two-watt meter method
iii. Three-watt meter method

Main Components of the Electrical Power System:

i. Generator
ii. Transformers
iii. Transmission line (primary transmission and secondary transmission)
iv. Distribution line (Primary distribution and secondary distribution)
v. Control equipment's

Types of Electrical Transmission Systems:

i. Overhead transmission systems
ii. Underground transmission systems

Protection of Power System: The power system protection is a branch of electrical power engineering that deals with the protection of electrical power systems from faults by isolating the faulty parts from the rest of the electrical network.

Power Factor: The power factor is defined as the ratio of real power to the apparent power.

$$\text{Power factor} = \text{Real power}/\text{Apparent power}$$

Why the power factor has to be maintained at around unity level: In general, most of the loads we use are inductive loads, so the power factor is always less than unity power factor. If the power factor is reduced, then the availability of real power in the same apparent power is reduced. Hence, we need to maintain the power factor at around the unity.

Benefits of Power Factor Improvement:

- Reduces the apparent power demand of the system
- Avoids the penalty imposed by the power supply company or DISCOMs
- Reduces electricity cost
- Reduction of circuit components rating like cable, switch-gear, etc.
- Reduction of I^2R losses in the system equipment's like cables
- Reduces the voltage drop in the cables

Methods of Power Factor Improvement:

- Capacitors banks
- Synchronous condenser

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