Efficient Electrical Systems Design Handbook

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This book is dedicated to my father
who showed me how to install
electrical systems.

Albert Thumann

Contents

Foreword

The understanding of electrical system design has become increasingly important, not only to the electrical designer, but to safety, plant and project engineers as well. With the advent of high energy costs, plant and project engineers have needed to become more aware of electrical systems. Both safety and energy efficiency will be covered in this text along with practical application problems for industrial and commercial electrical design.

Chapter 1

Electrical Basics

The field of electrical engineering is a large and diverse one. Often included under the general title of electrical engineer are the fields of electronics, semiconductors, computer science, power, lighting and electromagnetics. The focus of this book is on the consulting or plant electrical engineer whose responsibilities include facility power distribution and lighting.

The following chapter provides a brief review of basic concepts that serve as background for the electrical engineer. A thorough understanding of these concepts, while helpful, is not essential to understanding the remainder of this book.

ELECTRICAL UNITS

Table 1-1 and the following text provide definitions of the basic electrical quantities.

Table 1-1. Electrical Quantities in MKS Units

Quantity	*Symbol*	*Definition*	*Unit*
Force	f	push or pull	Newton
Energy	w	ability to do work	joule or watt-second
Power	p	energy /unit of time	watt
Charge	q	integral of current	coulomb
Current	i	rate of flow of charge	ampere
Voltage	v	energy /unit charge	volt
Electric field strength	E	force/unit charge	volt/meter
Magnetic flux density	B	force/unit charge momentum	tesla
Magnetic flux	ϕ	integral of magnetic weber flux density	weber

"Force"—A force of 1 newton is required to cause a mass of 1 kilogram to change its velocity at a rate of 1 meter per second.

"Energy"—Energy in a system is measured by the amount of work which the system is capable of doing. The joule or watt-second is the energy associated with an electromotive force of 1 volt and the passage of one coulomb of electricity.

"Power"—Power measures the rate at which energy is transferred or transformed. The transformation of 1 joule of energy in 1 second represents an average power of 1 watt.

"Charge"—Charge is a "quantity" of electricity. The coulomb is defined as the charge on 6.24×10^{18} electrons, or as the charge experiencing a force of 1 newton in an electric field of one volt per meter, or as the charge transferred in 1 second by a current of 1 ampere.

"Current"—The current through an area is defined by the electric charge passing through per unit of time. The current is the net rate of flow of positive charges. In a current of 1 ampere, charge is being transferred at the rate of 1 coulomb per second.

"Voltage"—The energy-transfer capability of a flow of electric charge is determined by the potential difference of voltage through which the charge moves. A charge of 1 coulomb receives or delivers an energy of 1 joule in moving through a voltage of 1 volt.

"Electric Field Strength"—Around a charge, a region of influence exists called an "electric field." The electric field strength is defined by the magnitude and direction of the force on a unit positive charge in the field (i.e., force/unit charge).

"Magnetic Flux Density"—Around a moving charge or current exists a region of influence called a "magnetic field." The intensity of the magnetic effect is determined by the magnetic flux density, which is defined by the magnitude and direction of a force exerted on a charge moving in the field with a certain velocity. A force of 1 newton is experienced by a charge of 1 coulomb moving with a velocity of 1 meter per second normal to a magnetic flux density of 1 tesla.

"Magnetic Flux"—Magnetic flux quantity, in webers, is obtained by integrating magnetic flux density over an area.

RESISTANCE

If a battery is connected with a wire to make a complete circuit, a current will flow. (See the schematic representation in Figure 1-1.) The current that flows is observed to be proportional to the applied voltage. The constant that relates the voltage and current is called "resistance." If the symbol v represents volts, the symbol i represents current, and the symbol R represents resistance (measured in ohms-Ω), the relationship can be expressed by the equation:

FORMULA 1-1 $v = Ri$

This expression is called Ohm's Law.

Since voltage is the energy per unit charge and current is the charge per unit time, the basic expression for electrical energy per unit time, or power, is:

FORMULA 1-2 $P = vi = i^2R$

Consequently, resistance is also defined as a measure of the ability of a device to dissipate power (in the form of heat).

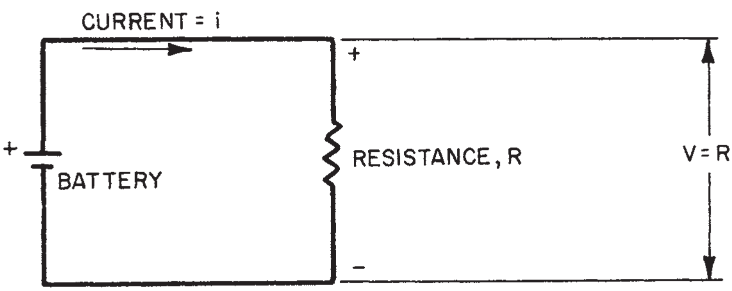

Figure 1-1. Ohm's Law Representation

CAPACITANCE

Now let's connect the battery to two flat plates separated by a small air space between them. (See the schematic representation in Figure 1-2.) When a voltage is applied, it is observed that a positive charge appears on the plate connected to the positive terminal of the battery, and a negative charge appears on the plate connected to the negative terminal. If the battery is disconnected, the charge persists. Such a device that stores charge is called a capacitor.

If a device called a signal generator, which generates an alternating voltage, is installed in place of the battery, the current is observed to be proportional to the rate of change of voltage. The relationship can be expressed by the equation:

FORMULA 1-3 $i = C\, dv/dt$

where C is a constant called "capacitance" (measured in farads) and dv/dt is differential notation representing the rate of change of voltage.

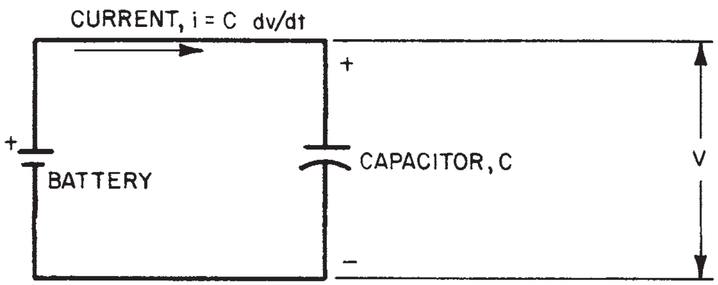

Figure 1-2. Capacitance Law

INDUCTANCE

If the signal generator is placed in a circuit in which a coil of wire is present, it is observed that only a small voltage is required to maintain a steady current. (See the schematic representation in Figure 1-3.) However, to produce a rapidly changing current, a relatively large voltage is required. The voltage is observed to be proportional to the rate of change of the current and can be expressed by the equation:

FORMULA 1-4 $v = L\, di/dt$

where L is a constant called "inductance" (measured in henrys, H) and di/dt is differential notation representing the rate of change of current.

Additionally, when a direct current is removed from an inductor the resulting magnetic field collapses, thereby "inducing" a current in an attempt to maintain the current flow. Consequently, inductance is a measure of the ability of a device to store energy in the form of a magnetic field.

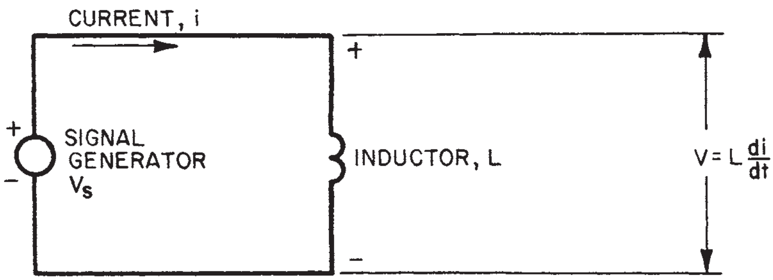

Figure 1-3. Inductance Law

CIRCUIT LAWS

To ease the analysis of complex circuits, circuit laws are utilized. These circuit laws allow voltages and currents to be calculated if only some of the circuit information is known. The two most famous circuit laws are "Kirchoff's Current" and "Voltage Laws." Kirchoff's Current Law states that the sum of the currents flowing into a common point (or node) at any instant is equal to the sum of the currents flowing out.

If current flowing into a node is taken as positive and current flowing out of a node is taken as negative, the summation of all the currents at a node is zero. If the circuit represented by Figure 1-4 is analyzed, Kirchoff's Law would be utilized as follows:

Kirchoff's Voltage Law states that the summation of the voltages measured across all of the components around a loop equals zero. To analyze a circuit using the voltage law, the circuit loop must be traversed in

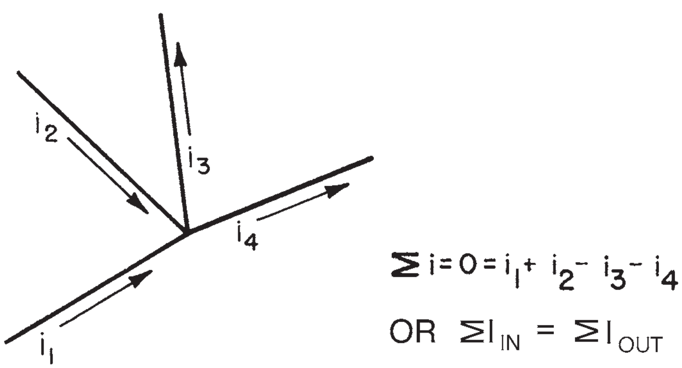

Figure 1-4. Kirchoff's Current Law

one arbitrary direction. If the potential increases when passing through a component in the direction of analysis, the voltage is said to be positive. If the potential decreases, the voltage is said to be negative. Analyzing the circuit of Figure 1-5 gives the following:

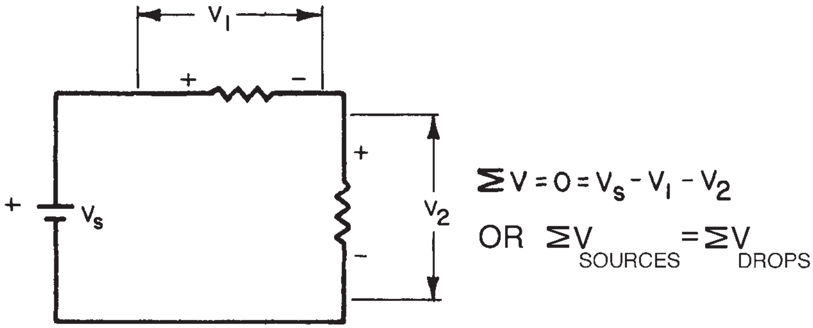

Figure 1-5. Kirchoff's Voltage Law

ALTERNATING CURRENT

Although direct current finds uses in some semiconductor circuitry, the primary focus of electrical design is concerned with alternating currents. Among the many advantages of utilizing alternating currents are: the voltage is easily transformed up or down; an alternating current varying at a prescribed frequency provides a dependable time standard for clocks, motors, etc.; and alternating patterns (i.e., sound and light waves) occur in nature and consequently provide the basis for analysis of signal transmission.

An alternating current, or sinusoid, can be represented by the equation below (see Figure 1-6).

FORMULA 1-5 $a = A\cos(\omega t + \alpha)$

where

a = instantaneous value
A = amplitude or maximum value
ω = frequency in radians per second (omega)
t = time in seconds
α = phase angle in radians (alpha)

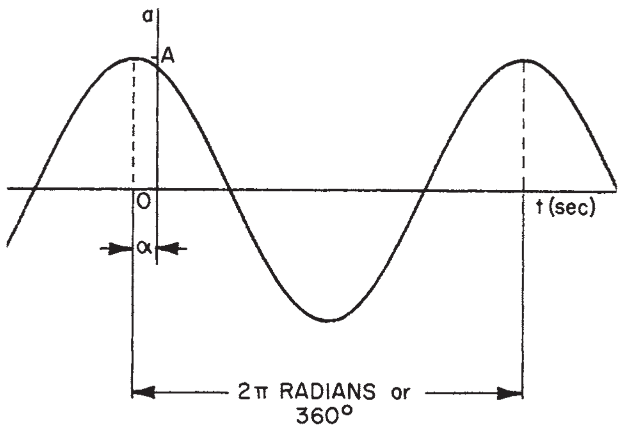

Figure 1-6. Sinusoid Representation

Note that frequency ω is related to frequency (f) in cycles per second, or Hertz (Hz), by:

FORMULA 1-6 $f = \omega / 2\pi$

(In the United States, the common power distribution frequency is 60 Hz.)

The phase angle α represents the difference between the reference time t = 0 and the time that the peak amplitude A occurs.

It is convenient to represent Formula 1-5 and Figure 1-6 by a phasor diagram as shown in Figure 1-7.* In this figure, the sinusoid is represented as a complex vector rotating with a frequency ω from an initial phase angle α. Such a concept allows the sinusoid to be represented by complex constants (composed of real and imaginary parts) instead of functions of time and also allows phasors to be added together using the rules of complex algebra.

Using phasor notation for the sinusoid represented by Figure 1-7, we get:

FORMULA 1-7 $a = b + jc = Ac\ (j\alpha) = A\angle\alpha$

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*For more information on the phasor concept, see *Circuits, Devices and Systems,* R.J. Smith, John Wiley and Sons, Inc.

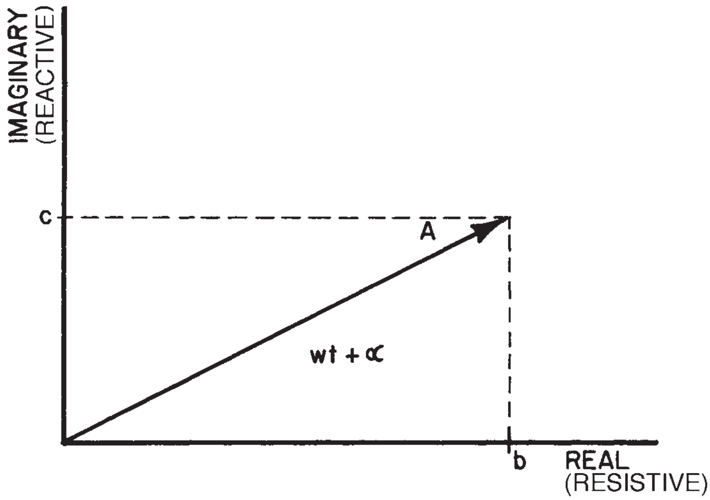


Figure 1-7. Phasor Representation of a Sinusoid

Consequently, the term $A\angle\alpha$ is a simplified representation of Formula 1-5 for a given frequency.

IMPEDANCE

To represent the effect that capacitive and inductive elements have on the current in a circuit, the concept of impedance is introduced.

In a circuit with capacitive and inductive elements present, Ohm's law is modified to be the following, where all symbols are represented by phasors:

FORMULA 1-8 $Z = V/I$

where Z is measured in Ohms.
In a series circuit, Z is defined as:

FORMULA 1-9 $Z = \sqrt{R^2 + X^2}\angle\Theta$

where

R = resistance
X = reactance
Θ = the angle that the voltage phasor leads or lags the current phasor

REACTANCE

An inductive element opposes a change in alternating current. We say that the voltage across an inductive element leads by 90° the current through it. Its reactance is given by:

FORMULA 1-10 $Z_L = V_L / I_L = \omega L\angle 90° = 2\pi fL \angle 90°$,

where $X_L = 2\pi fL$

The voltage across a capacitive element lags by 90° the current through it. Its reactance is given by:

FORMULA 1-11 $Z_C = V_C / I_C = 1/\omega C\angle -90° = 1/2\pi fC\angle -90°$,

where
$$X_C = \frac{1}{2\pi fC}$$

Note that the voltage and current are ill phase across a purely resistive element.

POWER

In a circuit containing resistive elements only, the voltage and current are in phase, and power is calculated by Formula 1-2. When inductive and/or capacitive elements are present, however, the energy is not dissipated in these elements but is stored and returned to the circuit every half cycle. The current and voltage are not in phase in reactive elements; consequently, Formula 1-12 must be used to calculate power consumption.

FORMULA 1-12 $P = VI \text{ COS } \Theta$ watts,
where Θ = angle between V and I

The difference between the power in watts and the "volt-amperes" is the product of a quantity termed the power factor, which is calculated by Formula 1-13.

FORMULA 1-13 $pf = \cos \Theta = P/VI = (\text{watts}/\text{V–A})$

Since in many cases we are interested in the energy transfer capability of an electric current, we often use an effective value for the alternating current. This effective value is found to be the "square root of the mean squared value," or the root mean square (RMS) value. The RMS value produces the same heating effect in a resistance as a direct current of the same ampere value. The RMS value is found to be:

FORMULA 1-14 $I_{RMS} = I_{PEAK} \times 0.707$

FORMULA 1-15 $V_{RMS} = V_{PEAK} \times 0.707$

The RMS values are commonly used when referring to distribution voltages and currents, since this is the value measured by voltmeters and ammeters. Consequently, a rating of 115 volts for an appliance operation is the RMS value. Additionally, RMS values of voltage and current are generally used in Formula 1-12, since average power is generally of primary interest.

SIM 1-1

Using Formula 1-5, write an expression for household voltage (i.e., 115 VAC). Express frequency in terms of Hz and assume the phase angle is zero.

ANSWER

Formula 1-5 is: $a = A \cos(\omega t + \alpha)$. Since 115 VAC is an RMS value, A is 115 volts/0.707 = 163 volts. From Formula 1-6 $\omega = 2\pi f$; therefore, for a 60 Hz distribution frequency the expression is:

$$v = 163 \cos(2\pi 60t) \text{ volts}$$

THREE-PHASE POWER

Most power is generated and transmitted in three phases in which three wires are utilized, with the voltage in each equal in magnitude but differing in phase by 360°/3 = 120° (See Figure 1-8). Three-phase power offers the following advantages over single-phase:

1. Generators are more efficient.
2. Motors start and run smoother.
3. Power is constant rather than fluctuating during the cycle.

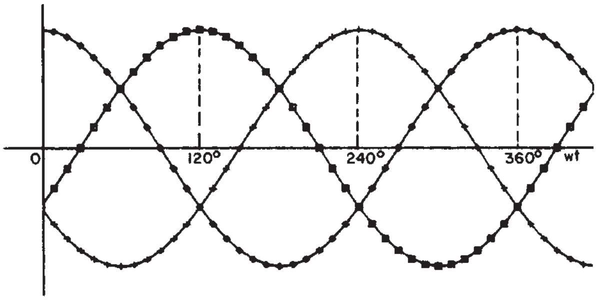


Figure 1-8. Three-phase Voltages

Phasor addition of the currents and voltages of a three-phase power system yield the following expression for power:

FORMULA 1-15 For balanced system
watts = $P_3\phi = \sqrt{3}\ (V_{L-L})(I_L) \cos \Theta$ watts,
where L = line, L–L = line-to-line

FORMULA 1-16 watts = $P_3\phi = 3\ V\phi I\phi \cos \Theta$,
where ϕ = phase

FORMULA 1-17 VARS = $Q_3\phi = 3\ V\phi I\phi \sin \Theta$

FORMULA 1-18 V–A = $S_3\phi = 3\ V\phi I\phi$

TRANSFORMERS

$$\frac{V_{out}}{V_{in}} = \frac{N_{out}}{N_{in}} = \frac{I_{in}}{I_{out}} \quad \text{where N = \# turns}$$

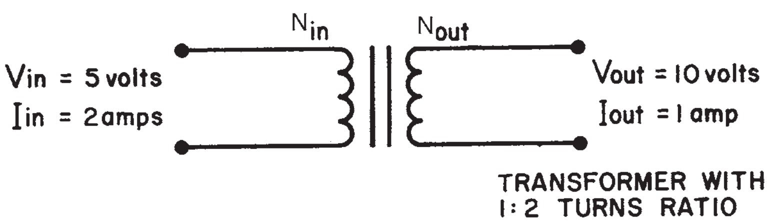


Figure 1-9. Transformer Operation

A transformer is an electrical device which converts alternating voltages and currents from one value to another (either up or down). This is accomplished with approximately equal power transfer (i.e., if the voltage is increased, the current is decreased a proportionate amount). See Figure 1-9.

Transformers contain two separate coils of insulated wire wound on an iron frame. Alternating current flowing through a coil develops a magnetic field that expands and contracts in step with the changes in current. The magnetic field in one coil induces current to flow in the other coil by cutting through the turns of wire.

Transformers are used in many stages in distributing power from the generating station to the user. Power is generally transferred at very high distribution voltages (several thousand volts), since the associated current is relatively low and the distribution losses are much decreased. (Remember that power loss = i^2R and that, for a fixed value of line resistance, the lower the current the much lower the power loss.) Additionally, lower current values allow smaller wires and associated current-carrying equipment to be used. Electrical substations near the point of use, consisting of banks of transformers, are then used to reduce voltages to usable levels.

DISTRIBUTION VOLTAGES

Modern electrical distribution within facilities has tended toward higher voltages, for many of the same reasons as utilities have (i.e., lower costs associated with lower current carrying needs). Consequently, wiring for appliances, outlets, lights, etc. (called branch circuit wiring) has tended to be routed relatively short distances to strategically located transformer load centers, which are then linked to a central distribution panelboard. This approach allows power to be delivered at the required voltage while minimizing long branch circuit runs at low voltage. There are three basic voltage distribution systems that are used today as described below. (Note that more than one of these systems may be present in a facility.)

SINGLE-PHASE

This is a commonly used system in residential and small commercial buildings. See Figure 1-10. 240 volt branch circuits can be used for power

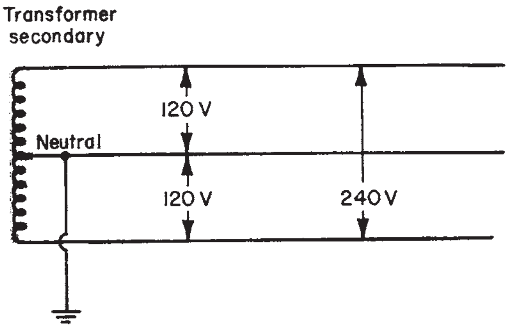


Figure 1-10. Single Phase Distribution

loads such as clothes dryers, electric ranges, etc. 120 volt branch circuits are used for lighting and receptacles.

WYE SYSTEM

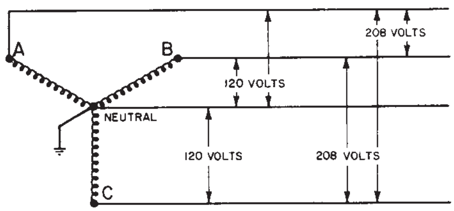
This system is designated "wye" because the connection of the transformer secondary coils resembles a "Y." This system provides three-phase and single-phase power at a variety of voltages. See Figure 1-11.

The 120/208 volt configuration is generally available in all except heavy industrial facilities, to some extent. The 120 volt circuits are used for receptacles and lighting, while the 208 volt circuits can be used for motor loads.

The 277/480 volt system is rapidly becoming the system of choice in commercial and industrial facilities because of the advantages mentioned earlier of utilizing higher distribution voltages. 480 volt, three-phase circuits are used for motor loads; 277 volt single-phase circuits are used for fluorescent and HID (high intensity discharge) lighting; 120, 240 or 120/208 volt circuits are available from transformers for receptacles and miscellaneous loads.

In a balanced wye system, the magnitude of line currents equal the phase currents, and the line-to-line voltage is th $\sqrt{3}$ times the phase voltage.

In a wye system with a fourth neutral wire, and *un*balanced load, the line current magnitude of each particular phase equals the phase current of that phase. Note, however, that the currents from one phase to the other and not necessarily equal, but due to the neutral wire the line-to-neutral voltage remains the same even if the load becomes *un*balanced.



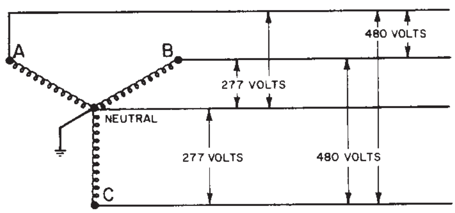


Figure 1-11. Wye Distribution

SIM 1-2

Refer to the second drawing in Figure 1-11. If a given balanced wye load is attached to the source of the system where the wye load has for each of its phases an impedance of (3, 12) with resisstive ohms = 3 and inductive reactive ohms = 12, find the magnitude of the current of each line and the three-phase load watts, vars, v-a and power factor.

Answer

Note (3, 12) rectangular form of the impedance converts to impedance Z = 12.4 ∠ 76

V ϕ load = V line-to-line/(√3) = 480 volts/1.732 = 277 volts

I ϕ load = 277/12.4 = 22.3 amps

I line = I phase = 22.3 amps

Power factor = p.f. = cos (76 degrees) = 0.24 → 24% lagging.

Note that the power factor lags due to positive reactive ohms load.

$P_{3\phi}$ loads = 3 (277) (22.3) 0.24 = 4.4 kW

$Q_{3\phi}$ loads = 3 (277) (22.3) sin 76 degrees = 18 kVARs

$S_{3\phi}$ loads = 3 (277) (22.3) = 18.53 kVA

DELTA SYSTEMS

The delta-connected secondary system (Figure 1-12) is available with phase-to-phase voltages of 240,480 or 600 volts. This system is used where

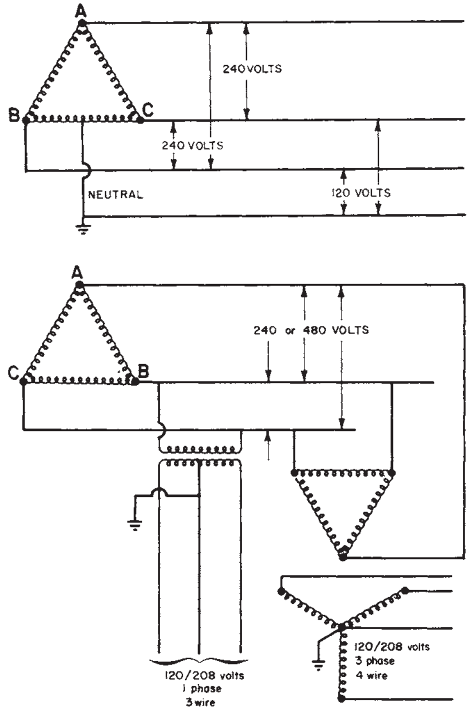


Figure 1-12. Delta Distribution

motor loads represent a large part of the total load (i.e., some industrial facilities). In a typical installation, 480 volt three-phase circuits supply motor loads while lighting and receptacle circuits are supplied by a single or three-phase step-down transformer (as shown in the figure).

A variation on the delta connection is also shown in Figure 1-12. In this system one of the transformer secondary windings is center-tapped to obtain a grounded neutral conductor to the two-phase legs to which it is connected. Motors are supplied at 240 volts three-phase, while 120-volt single-phase circuits are supplied by the neutral conductor and phases B or C.

In a balanced delta system, the line-to-line voltage equals the phase voltage, and the line-current is the √3 times the phase voltage.

SIM 1-3

Refer to the second drawing in Figure 1-12. If a given balanced delta load is attached to the source of the system where the delta load has for each of its phases an impedance of (3, 12) with resisstive ohms =

3 and inductive reactive ohms = 12, find the magnitude of the current of each line and the three-phase load watts, vars, v-a and power factor.

Answer

Note (3, 12) rectangular form of the impedance converts to impedance $Z = 12.4 \angle 76$

$V\,\phi$ load = V line-to-line = 480 volts

$I\,\phi$ load = 480/12.4 = 38.7 amps

I line = (√3) 38.7 = 67 amps

Power factor = p.f. = cos (76 degrees) = 0.24 → 24% lagging.

Note that the power factor lags due to positive reactive ohms load.

$P_{3\phi}$ loads = 3 (480) (38.7) 0.24 = 13.37 kW

$Q_{3\phi}$ loads = 3 (480) (38.7) sin 76 degrees = 54 kVARs

$S_{3\phi}$ loads = 3 (480) (38.7) = 55.7 kVA

MEASURING ELECTRICAL SYSTEM PERFORMANCE

The ammeter, voltmeter, wattmeter, power factor meter, and foot-candle meter are usually required to do an electrical survey or audit. These instruments are described below.

Ammeter and Voltmeter

To measure electrical currents, ammeters are used. For most audits, alternating currents are measured. Ammeters used in audits are portable and are designed to be easily attached and removed. Ammeters must have relatively low resistance, and are put in series or clamped around.

There are many brands and styles of snap-on ammeters commonly available that can read up to 1000 amperes continuously. This range can be extended to 4000 amperes continuously for some models with an accessory step-down current transformer.

The snap-on ammeters can be either indicating or recording with a printout. After attachment, the recording ammeter can keep recording current variations for as long as a full month on one roll of recording paper. This allows studying current variations in a conductor for extended periods without constant operator attention.

The ammeter supplies a direct measurement of electrical current, which is one of the parameters needed to calculate electrical energy. The second parameter required to calculate energy is voltage, and it is measured by a voltmeter.

A voltmeter measures the difference in electrical potential between two points in an electrical circuit. Voltmeters must have relatively high resistance and are put in parallel.

In series with the probes are the galvanometer and a fixed resistance (which determine the voltage scale). The current through this fixed resistance circuit is then proportional to the voltage, and the galvanometer deflects in proportion to the voltage.

The voltage drops measured in many instances are fairly constant and need only be performed once. If there are appreciable fluctuations, additional readings or the use of a recording voltmeter may be indicated.

Most voltages measured in practice are under 600 volts; there are many portable voltmeter/ammeter clamp-ons available for this and lower ranges.

Several types of electrical meters can read the voltage or current.

Wattmeter and Power Factor Meter

The portable wattmeter can be used to indicate by direct reading the electrical energy in watts. It can also be calculated by measuring voltage, current, and the angle between them (power factor angle).

The basic wattmeter consists of three voltage probes and a snap-on current coil that feeds the wattmeter movement.

The typical operating limits are 300 kilowatts, 650 volts, and 600 amperes. It can be used on both one- and three-phase circuits.

The portable power factor meter is primarily a three-phase instrument. One of its three voltage probes is attached to each conductor phase and a snap-on jaw is placed about one of the phases. By disconnecting the wattmeter circuitry, it will directly read the power factor of the circuit to which it is attached.

It can measure power factor over a range of 1.0 leading to 1.0 lagging, with ampacities up to 1500 amperes at 600 volts. This range covers the large bulk of the applications found in light industry and commerce.

The power factor is a basic parameter whose value must be known to calculate electric energy usage. Diagnostically it is a useful instrument to determine the sources of poor power factor in a facility.

Portable digital kWh and kW demand units are also now available.

Digital units can have read-outs of energy usage in both kWh and kW demand, or in dollars and cents. Instantaneous usage, accumulated usage, projected usage for a particular billing period, alarms when over-target levels are desired for usage, and control-outputs for load-shedding and cycling are possible.

Continuous displays or intermittent alternating displays are available at the touch of a button for any information needed such as the cost of operating a production machine for one shift, one hour, or one week.

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