Power
Electrical & Computer PE

Exam Textbook

Spring 2021 CBT Edition
Updated for Latest CBT Exam


Learn the key concepts and skills necessary to pass the PE Exam

Engineering Pro Guides

by **Justin Kauwale, P.E.**

Electrical PE: Power Textbook

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1 – Introduction

Introduction

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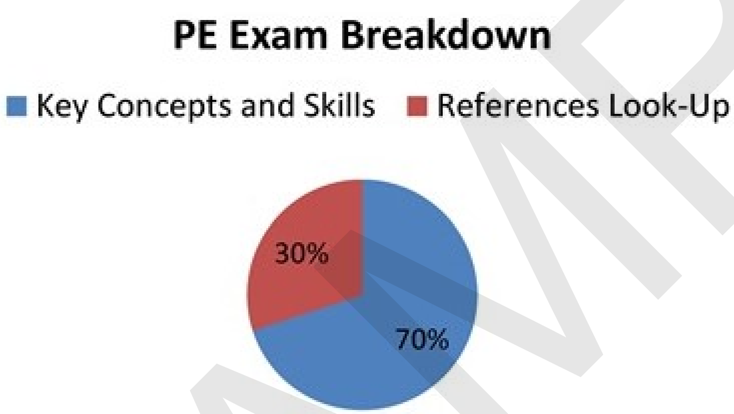
1.0 INTRODUCTION

One of the most important steps in an engineer's career is obtaining the professional engineering (P.E.) license. It allows an individual to legally practice engineering in the state of licensure. This credential can also help to obtain higher compensation and develop a credible reputation. In order to obtain a P.E. license, the engineer must first meet the qualifications as required by the state of licensure, including minimum experience, references, and the passing of the National Council of Examiners for Engineering and Surveying (NCEES) exam. Engineering Pro Guides focuses on helping engineers pass the NCEES exam through the use of free content on the website, http://www.engproguides.com and through the creation of books like sample exams and guides that outline how to pass the PE exam.

The key to passing the PE exam is to learn the key concepts and skills that are tested on the exam. There are several issues that make this very difficult. First, the key concepts and skills are unknown to most engineers studying for the exam. Second, the key concepts and skills are not taught in a single document. This technical guide teaches you all of the key concepts and skills required to pass the Electrical Power PE Exam.



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1.1 Key Concepts and Skills

How are the key concepts and skills determined?

The key concepts and skills tested in this sample exam were first developed through an analysis of the topics and information presented by NCEES. NCEES indicates on their website that the PE Exam will cover an AM exam (4 hours) followed by a PM exam (4 hours) and that the exam will be 80 questions long, 40 questions in the morning and 40 questions in the afternoon. The Power Electrical PE exam will focus on the following topics, as indicated by NCEES. (http://ncees.org/engineering/pe/):

I. General Power Engineering (21-32 questions)

A) Measurement and Instrumentation *(4-6 questions)*

1 Instrument transformers
2 Insulation testing
3 Ground resistance testing

B) Applications *(7-11 questions)*

1 Lightning protection
2 Surge protection
3 Reliability
4 Illumination/lighting and energy efficiency engineering
5 Demand calculations
6 Energy management
7 Engineering economics
8 Grounding

C) Codes and Standards *(10-15 questions)*

1 National Electrical Code (NFPA 70, NEC 2017)
2 National Electrical Safety Code (ANSI C2, NESC-2017)
3 Standard for Electrical Safety in the Workplace: Shock and Burns (NFPA 70E-2018)
4 Hazardous Area Classification (NFPA 497-2017, 499-2017, 30B-2015)

II. Circuits (14-21 questions)

A) Analysis *(8-12 questions)*

1 Three-phase circuits
2 Symmetrical components
3 Per unit system
4 Phasor diagrams
5 Single phase circuits
6 DC circuits
7 Single-line diagrams

B) Devices and Power Electronic Circuits *(6-9 questions)*

1 Battery characteristics and ratings

2 Power supplies
3 Relays, switches and PLCs
4 Variable speed drives

III. Rotating Machines and Electromagnetic Devices (14-21 questions)

A) Rotating Machines *(7-11 questions)*

1 Induction and Synchronous Machines
- i) Generator/motor applications
- ii) Equivalent circuits and characteristics
- iii) Motor starting
- iv) Electrical machine theory

B) Electric Power Devices *(7-11 questions)*

1 Transformers
2 Reactors
3 Testing
4 Capacitors

IV. Transmission and Distribution (High, Medium and Low Voltage) (21-32 questions)

A) Power System Analysis *(10-15 questions)*

1 Voltage drop
2 Voltage regulation
3 Power factor correction and voltage support
4 Power quality
5 Fault current analysis
6 Transformer connection
7 Transmission line models
8 Power flow
9 Load sharing parallel generators or transformers
10 Power system stability

B) Protection *(11-17 questions)*

1 Overcurrent protection
2 Protective relaying (differential, distance, undervoltage, pilot)
3 Protective devices (e.g., fuses, breakers, reclosers)
4 Coordination

Next, each of these broad topics were investigated and filtered for concepts and skills that met the following criteria:

(1) First, the concept and skill must be *commonly encountered* in the Power Engineering field of study. For example: Voltage drop, phasor diagrams, three-phase power, NEC and transmission analysis are regular occurrences in the Power Engineering field.

(2) Second, the skill and concept must be testable in roughly *6 minutes per problem*. There are (40) questions on the morning exam and you will be provided with 4 hours to complete the exam. The same is true for the afternoon portion of the exam. This results in an average of 6 minutes per problem. This criterion limits the complexity of the exam problems and the resulting solutions. For example, power flow calculations are common in the Power Engineering field, but the calculation is often very lengthy because of the number of steps involved, especially if the circuit is complex. Thus, the exam uses simple circuits and the math required to solve the problems is also very simple.

(3) Third, the key concepts and skills must be used or be known by practicing electrical engineers in the Power field. This criterion is similar to the first criterion. However, this criterion filters the concepts and skills further by limiting the field to material encountered and used by *practicing engineers*. The Power Engineering field is vast and there are many different avenues an engineer can take. Two diverging paths are those engineers involved in research and those who practice. Research engineers are pushing the boundaries of the field and are highly focused in their specific area of the field. The Professional Engineering Exam does not cover emerging technologies or highly focused material.

(4) The PE Exam must test the *principle or application* of the skill and concept and not the background knowledge of the topic or concept. The exam also does not cover background information on the NCEES topics. The PE Exam is meant to prove that the test taker is minimally competent to **practice** in the Electrical Engineering field. The exam is less concerned with theory and more with the principle or application of the theory, skill or concept. For example, the PE Exam is less concerned with the theory of thyristors or magnetic flux and more with the performance of a rectifying circuit and the voltage output of a transformer.

In summary, this book is intended to teach the necessary skills and concepts to develop a minimally competent, practicing professional engineer in the Electrical Engineering Power field, capable of passing the PE Exam. This book and the sample exams do this through the following means:

(1) Teaching commonly used skills and concepts in the Power field.

(2) Providing sample problems that can be completed in roughly 6 minutes per problem.

(3) Teaching skills and concepts used by practicing Power engineers.

(4) Teaching the application of the skill and concept.

1.2 UNITS

The primary units that are used in the PE Exam are United States Customary System Units (USCS). As such, this guide focuses exclusively on the USCS. However, it is recommended that the test taker have a conversion book, because certain areas of the PE Exam may use the International System of Units (SI).

1.3 COMPUTER BASED TEST (CBT)

As of December 2020, the exam will be converted from the paper-pencil/scantron testing method to a computer based platform. This allows the test to be offered year round instead of twice per year. This also means you will not have the same set of the questions as the next person. The style of the testing interface will be very similar to the fundamentals of engineering (FE) exam that is also administered by NCEES. If you have gone through the computer based version of the FE exam, you should be familiar with the format. The main difference is the number and difficulty of questions and the length of the exam. It is important to review the NCEES Examinee Guide to understand the testing rules and format. Below is a summary of the major content.

(1) Year Round: The exam may be taken any time throughout the year, as long as the testing facility is open. However, you are only allowed to take the exam once per quarter (Jan – March, April – June, July – Sept, Oct – Dec) and at most 3 times per 12 months. The turnaround time from your exam application to test date will be much faster and the results should be received within 7-10 days. The only thing holding you up may be your state approval.

(2) Day of Timeline: The overall time at the testing facility will be 9 hours, with 1 hour allotted for prep time and breaks and 8 hours of actual exam time. You can take as long as you want to complete the first half of the exam, but that time is subtracted from the total 8 hour time. Once you submit the first section you cannot return to those questions. You will then have a maximum of 50 minutes of break time, where you are allowed to leave the facility. If you arrive after the 50 minutes, then that time is subtracted from your 8 hours. Finally, you will have a the remaining of the 8 hours to complete the second half of the exam.

(3) Question Types: One of the main changes in the actual content of the computer-based test is the ability to incorporate different question types. Majority of the questions will be multiple choice with one answer out of four options, but additional question types include (1) multiple answers, (2) selecting a point, (3) drag and drop for matching, sorting, labeling, etc, and (4) fill in the blank. These question types are called AIT (Alternative Item Type) questions. There are only FOUR of the AIT questions.

The exam questions are written in a way that can be confusing or meant to trick the examinee, so you can imagine how this can really add to the difficulty of the problem.

(4) NCEES Reference Handbook: Perhaps the greatest consequence of shifting to the computer based conversion is that examinees are no longer able to bring in outside resources. Your only aid during the test is the *NCEES PE Power Reference Handbook*, see the following

2 – Circuits Analysis

Three phase circuits | Symmetrical components | Per-unit system | Phasor diagrams | Single phase circuits | DC circuits | Single-line diagrams

Section 2.0 – Circuits Analysis

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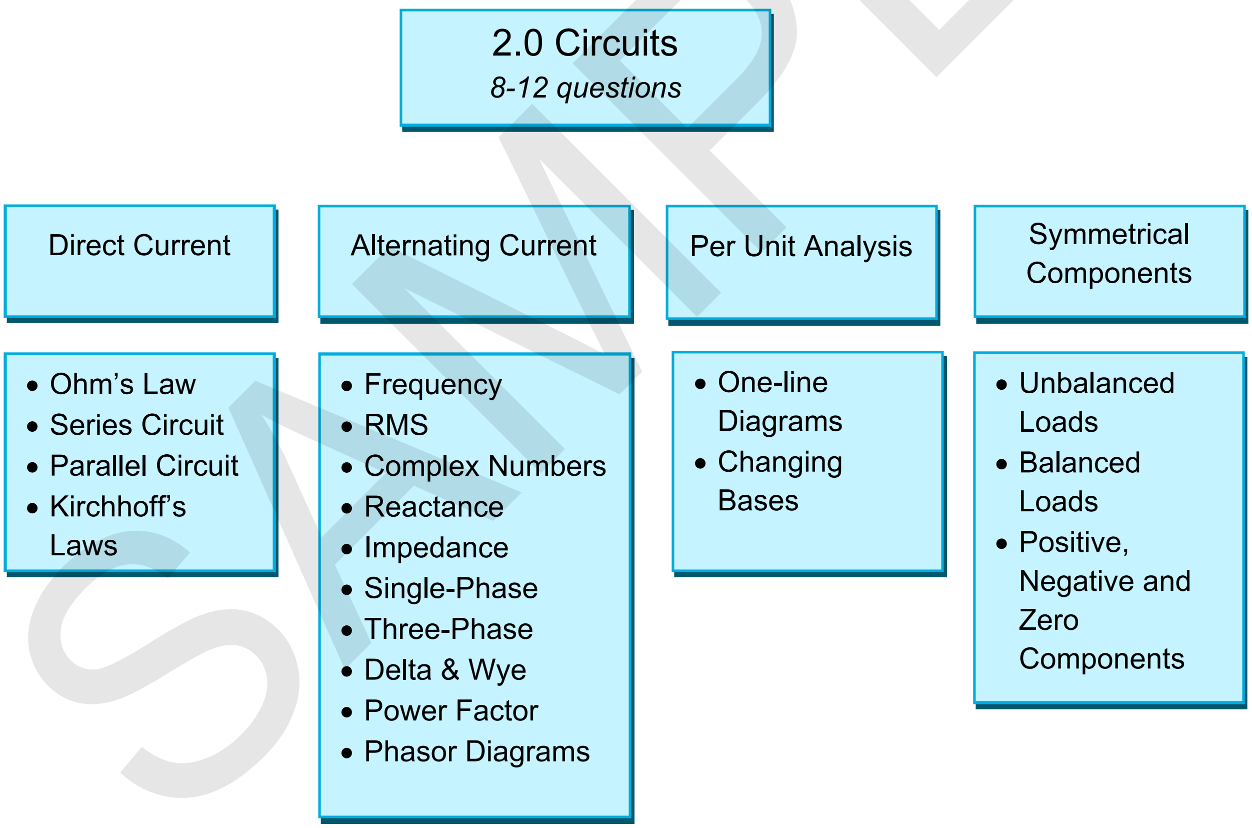
1.0 INTRODUCTION

Circuits Analysis accounts for approximately 8-12 questions on the Electrical & Computer, Power PE exam.

This section provides a refresher on the basic electrical engineering concepts, beginning with direct current. Following the direct current section, exam type material will be covered with alternating current, per-unit analysis and symmetrical components.

The circuit analysis section of this book will serve as the basis for many of the other application sections. Therefore, the terms explained here will be used in sections such as *4.0 Rotating Machines*, *5.0 Electromagnetic Devices*, and *6.0 Transmission*. In the latter sections, it will be expected that that you have a strong understanding of the material presented in this section, *2.0 Circuits*. Specifically, this section will introduce three methods of understanding circuits, (1) one line diagrams, (2) phasor diagrams and (3) waveforms. These three methods are the basic tools that will be used in the other sections previously mentioned. The symmetrical components and the three methods will also be used in *8.0 Protection*.



2.0 DIRECT CURRENT

The PE exam will most likely not have any easy direct current problems, so you may skip this section if you are already familiar with the basics of electricity. This section is only provided as a basis for the terms that are used in the other sections throughout this book.

Direct current (DC) is the supply of current in one direction. In a circuit, current flows from the positive voltage terminal to the negative terminal. Current is deemed positive when it flows in this direction. Current is considered negative when it flows from a negative terminal to a positive terminal. DC current is a constant source and does not switch between negative and positive. Alternating current (AC) is able to supply current in both directions, positive to negative and negative to positive. This is shown in the graph below, where the current can be positive (above the 0-axis) or negative (below the 0-axis).

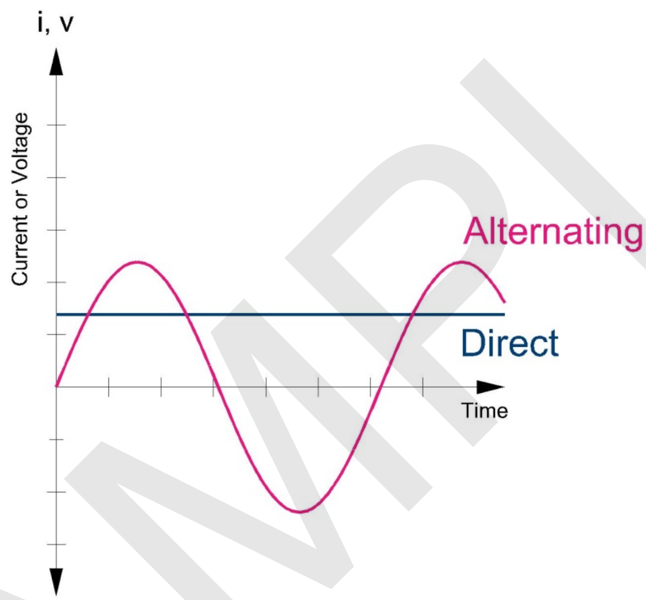


Figure 1: In an AC circuit, current can alternate its flow from positive to negative. In a DC circuit, current is constant.

There are three main elements to a basic circuit, (1) current, (2) voltage and (3) resistance. The flow of electrons in a circuit is called current (I) and current is given in units of amperes. The energy that drives the flow of electrons is called the voltage (V) and is given in units of volts. The voltage is measured between two points because it is the difference in energy (also known as the potential) that drives the current from one point to the next. The third term is resistance, which is measured in units of ohms (Ω). Resistance (R) is the opposition to the flow of current. One ohm is described as the level of resistance that will allow 1 ampere to flow when 1 volt is applied to a circuit.

In the following sections you will read about voltage in terms of “voltage between phases” or “voltage across two phases” or “voltage between phase and neutral”.

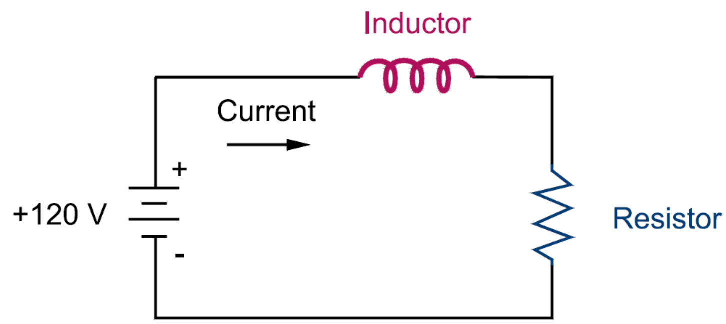


Figure 12: When an inductor is added in series with a resistor, the inductor will impede the rate of change in current. Once the circuit reaches steady state, then there will be no change in current, so the inductor will act like a "short". This means that there will be no voltage drop through the inductor, at steady state. Once the circuit is de-energized, there will again be a rate of change in current, so the inductor will impede this new rate of change in current.

The following figures show the current and voltages across an inductor in series with a resistor (solid line) as a constant voltage is applied, i.e. it is charging, and as the voltage source is removed, i.e. it is discharging. This is compared to only a resistor connected to the same voltage source (dashed line).

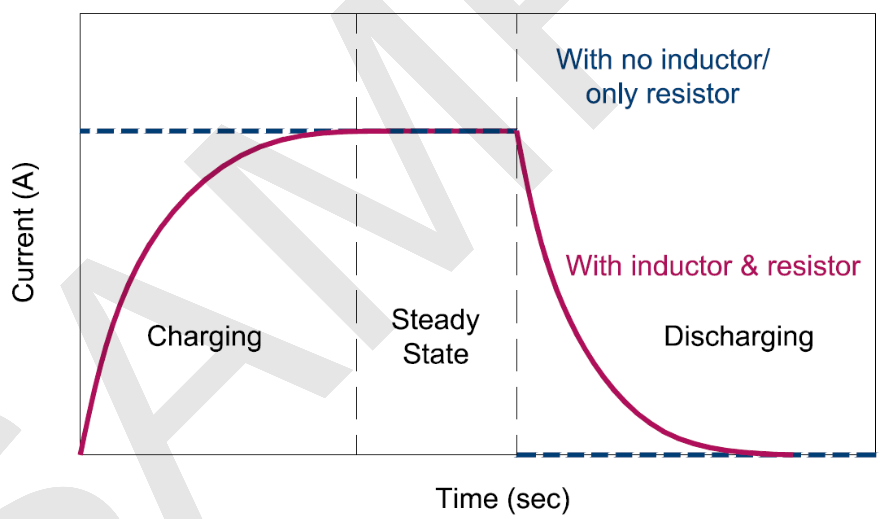


Figure 13: When the circuit is first connected, the inductor will impede the rate of change in current. This is shown in the charging section. Once it reaches steady state, then the current in the circuit will be a function of only the voltage and the resistance of the resistor. When the circuit is disconnected, the inductor will impede the rate of change in current. The current is trying to go down to zero, but the inductor is impeding the change, until finally the current reaches zero. This is shown in the discharge section.

$$\Rightarrow \quad C_{total} = \frac{1}{1/C_1 + 1/C_2 + \cdots 1/C_N}$$

3.0 ALTERNATING CURRENT

Alternating current is most commonly used on the PE exam and in most power applications. Alternating current describes the alternating directions of flow in a circuit. Current quickly alternates flow direction from positive to negative many times a second. In the figure below, positive current is shown flowing in a clockwise direction in the figure on the right and this flow direction corresponds to the positive portions of the graph on the left.

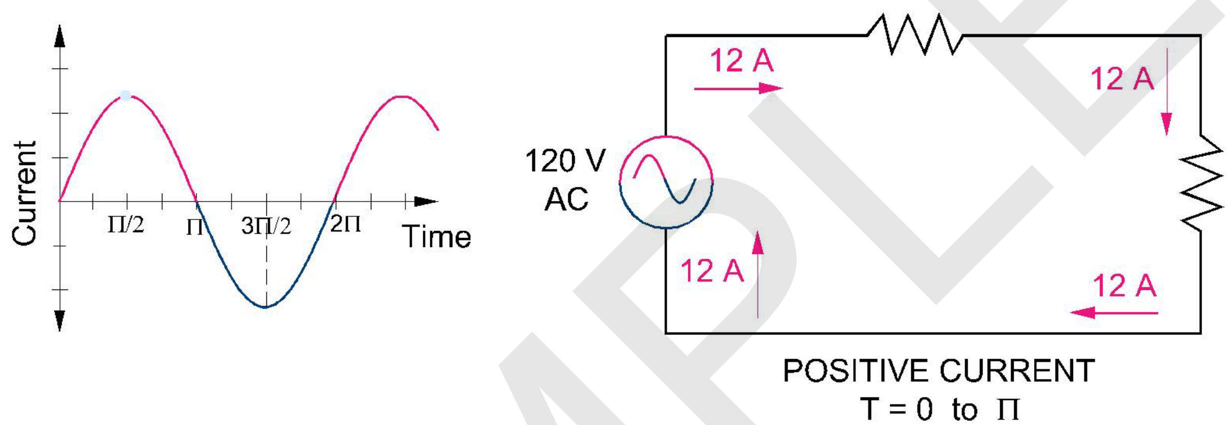


Figure 18: Alternating current consists of positive and negative flowing current. This figure shows positive current flow.

In this next figure, negative current is shown flowing in a counter-clockwise direction. The current flow in the figure on the right corresponds to the negative portions of the graph on the left.

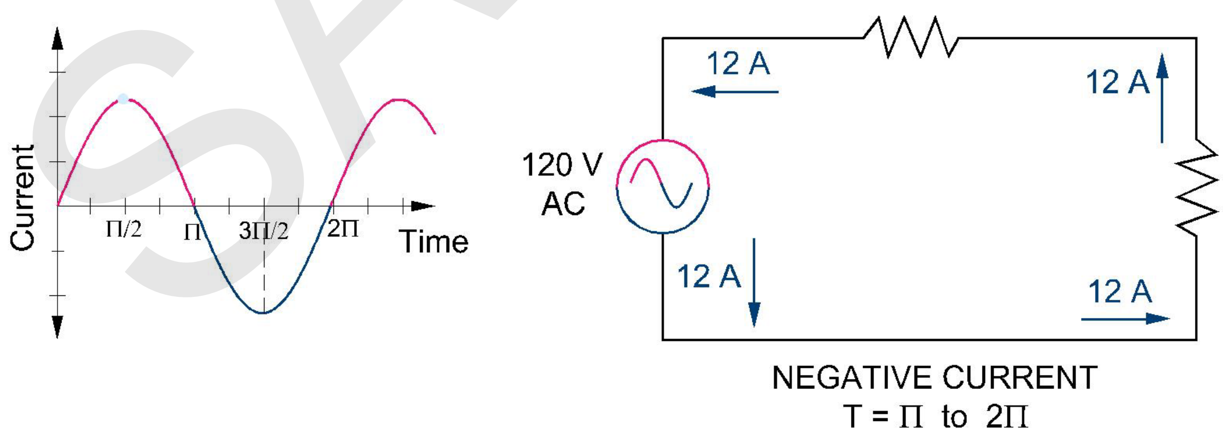


Figure 19: Alternating current consists of positive and negative flowing current. This figure shows negative current flow.

3.4.1 Resistance (Resistors)

Resistance describes the resistors ratio of voltage to current in units of ohms. In the Power Engineering field, resistors are used to describe any electrical load that does useful work. A resistive load can be any light (incandescent, fluorescent, LED, etc.), any motor, any electronic device (computers, cellphone, printers, copy machines) and much more. These resistive loads are true power users because current is dissipated at the load and results in actual work (i.e. motor spins a rotor and a light illuminates). The motor load also has inductive loads, which will be described in the next set of paragraphs.

$$R = Resistance\ (ohms) = \frac{V}{I}$$

In the previous figure, the phasor diagram shows resistance as $R\angle 0°$, which is characterized as a positive vector on the real axis.

3.4.2 Inductance or Inductive Reactance (Inductors)

An inductor is made up of a wire wound about a coil. As the current flows through the wound coil, the current builds a magnetic field. This concept of the magnetic field is used heavily in the *5.0 Electromagnetic Devices*, *4.0 Rotating Machines* and *6.0 Transmission* sections. Inductive loads or inductive reactance are any loads that create a magnetic field. This load is not deemed useful since the current is not dissipated. The current builds the magnetic field and when the current is shut off, then the magnetic field dissipates.

$$X_L = wL = 2\pi f L$$

$$Z_L = jX_L$$

In the previous figure, the phasor diagram shows inductance as $X_L\angle 90°$, which is characterized as a positive vector on the imaginary axis.

3.4.3 Capacitance or Capacitive Reactance (Capacitors)

A capacitor is made up of two conductors separated by a dielectric. As current is supplied to the capacitor on the positive side, charge is built up, which restricts current. Then the current alternates and charge is built up on the negative side, which also restricts current. Capacitors are used in the next section, *3.0 Devices,* to smooth waveforms because of its timing component. It takes time to fill the capacitor with charge, which delays any sudden inrush of voltage.

$$X_C = -\frac{1}{wC} = -\frac{1}{2\pi f C}$$

$$Z_c = -jX_C$$

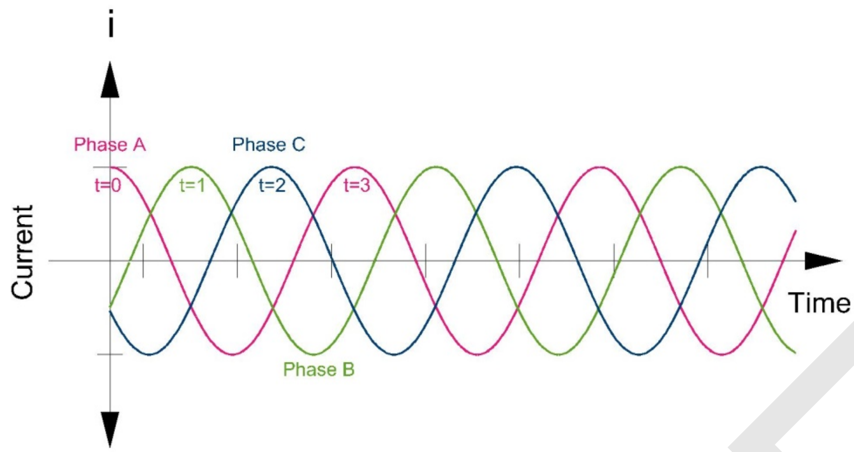


Figure 30: Three-phase power waveform

The next question is how the wires are physically arranged in three-phase power. In single-phase power, there is a hot wire which enters the input of the load and a neutral that leaves the exit of the load. However, in three-phase wire, you need three hot wires entering the load and possibly a neutral that leaves the exit of the load. There are two major arrangements for three-phase circuits, called Delta and Wye. These arrangements will be described in detail in the next sections.

3.6 Delta versus Wye Arrangements

On the exam, loads and power sources will be given in delta or wye arrangements. You will need to be able to distinguish between the phase currents/voltages and line currents/voltages for the two arrangements. You will also need to be able to calculate power in both arrangements.

In a three-phase arrangement, the terms phase and line are introduced. The term phase describes the insides of the load or power source and the term line describes the wires that enter the load or power source. The easiest way to describe line current and voltage is to envision a three-phase motor. There are three wire leads at the entrance to the motor and these are the line currents/voltages. The phase voltage and current is measured inside the equipment.

phase voltage. This is common of your simple single-phase power equation. However, in practice you are not often given the phase current and the phase voltage, since these measurements are within the equipment (motor or generator). In practice, you are able to measure the line current and line voltage entering the equipment. So you start with the first equation and then use the relationships between the phase current and line current and the phase voltage and line voltage to get the three-phase power equation below.

$$S_{3ph} = I_{ph,AB} * V_{ph,AB} + I_{ph,BC} * V_{ph,BC} + I_{ph,AC} * V_{ph,AC}$$

$$but\ I_{ph} = \frac{I_L}{\sqrt{3}}\ and\ V_L = V_{ph}\ and\ in\ a\ balanced\ load\ all\ phase\ current\ and\ voltages\ are\ equal$$

$$S_{3ph} = \frac{I_L}{\sqrt{3}} * V_L + \frac{I_L}{\sqrt{3}} * V_L + \frac{I_L}{\sqrt{3}} * V_L$$

$$S_{3ph} = 3\frac{I_L}{\sqrt{3}} * V_L \rightarrow S_{3ph} = \sqrt{3}\, I_L V_L$$

3.6.2 Wye Arrangement

In a wye arrangement, the line currents and the phase currents are equal to each other. The line voltage, however, is $\sqrt{3}$ times greater than the phase voltage. *(The line voltage leads the phase voltage by 30 degrees when transitioning from delta to wye.)*

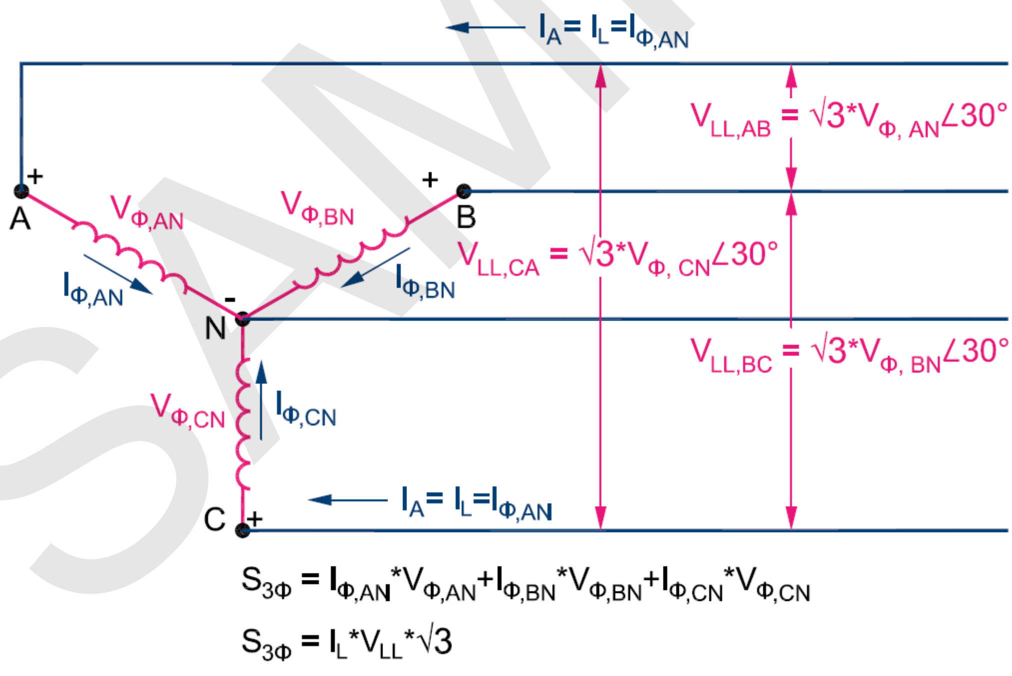


Figure 33: Wye circuit (The line voltage leads the phase voltage by 30 degrees when transitioning from delta to wye.)

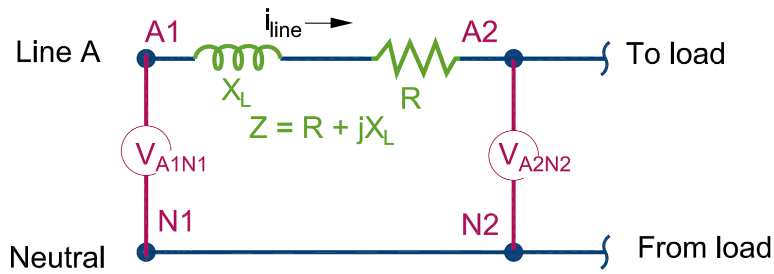


Figure 70: In a single phase system, the voltage is compared to a neutral. The maximum amount of power that can be sent across a transmission/distribution line is a function of the voltage and the impedance of the line.

The voltage drop through a three phase system will follow Ohm's law with the addition of the "root 3" term. The power lost along the impedance of a three phase system will be found through the following equations.

$$V_{line} = I_{phase} Z * \sqrt{3};\ S_{3ph} = 3V_{ph-n} I_{ph};$$

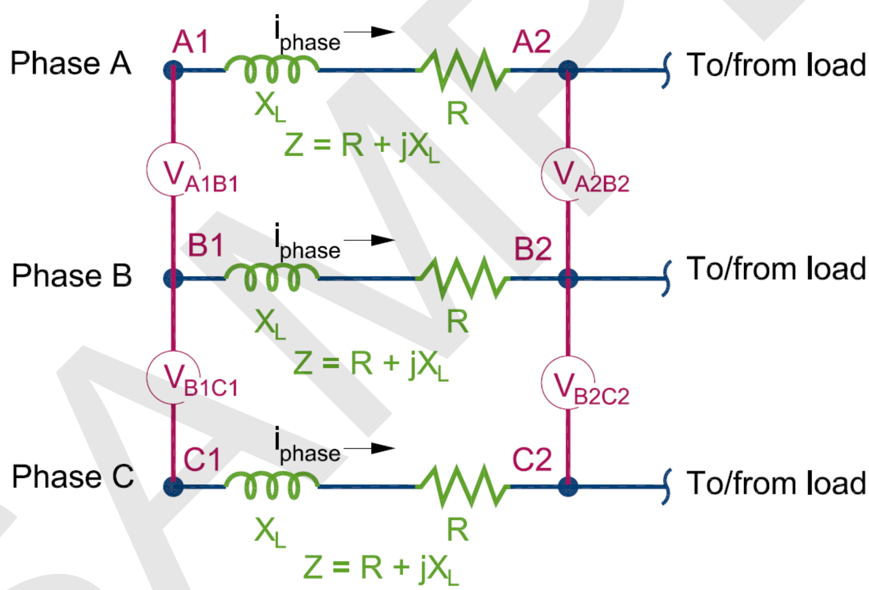


Figure 71: In a three phase system, the line voltage drop is compared to the other lines. The maximum amount of three phase power that can be sent across a transmission/distribution line is a function of the line voltage and the impedance of the line.

The voltage drop across A1 to A2 will be the same as the phase to neutral voltage drop from the single phase equations. However, when you want to find the line voltage at A2 and compare it to points B2 or C2, you will need to take into account the "root 3" term. This is because the voltage at B1 & B2 and C1 & C2 are different, as opposed to N1 & N2.

7.0 Practice Problems

7.1 Problem 1 – Per Unit

A 3-phase, 1,000 KVA, 480V/120V transformer has a percent impedance of 6%. What is the actual impedance for the transformer on the high voltage side?

(A) 0.014 Ω

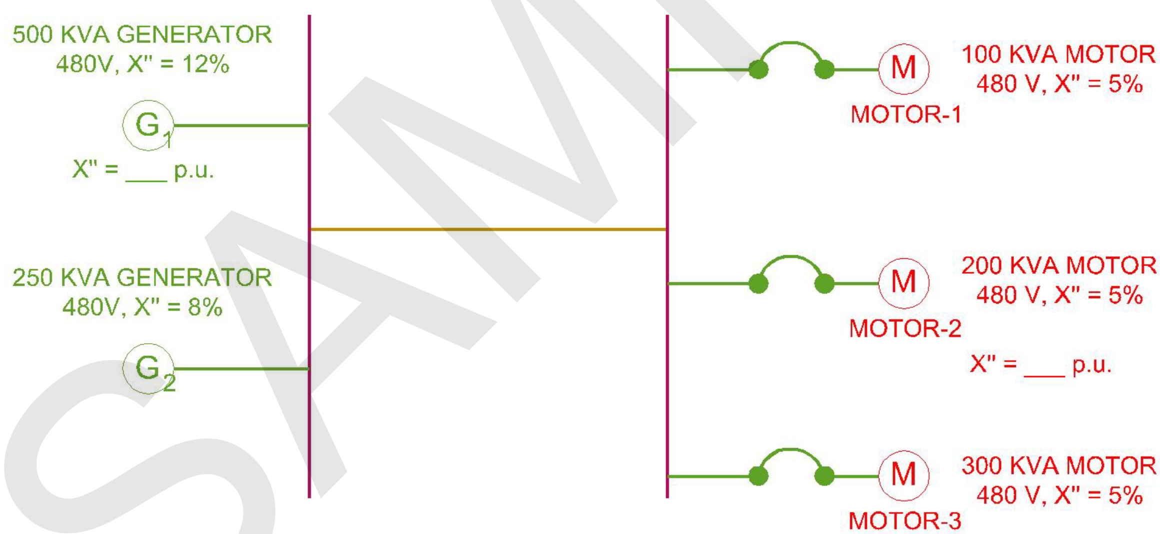
(B) 0.06 Ω

(C) 0.14 Ω

(D) 2.3 Ω

7.2 Problem 2 – Per Unit

Based on the diagram below and given a Generator G2 as the per-unit base, what is the per-unit reactance values for Generator G1?



(A) 0.06 pu

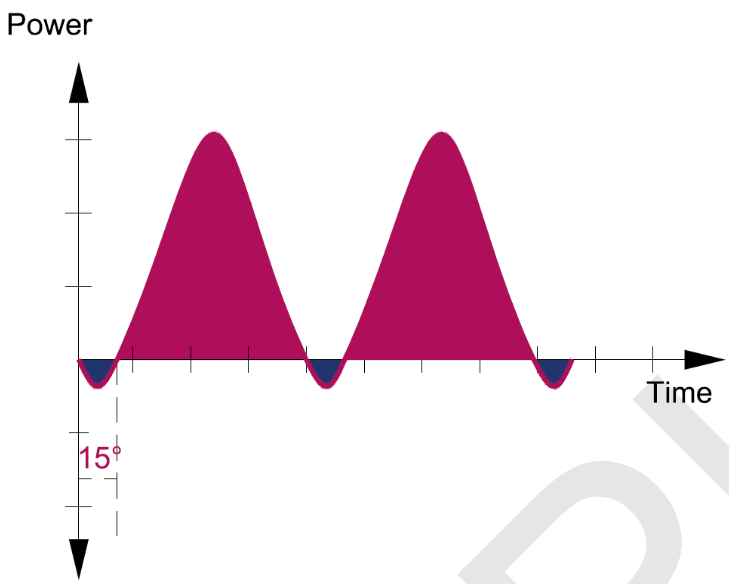
(B) 0.16 pu

(C) 0.24 pu

(D) 0.48 pu

7.12 Problem 12 – Power

Given the figure below, what does the shaded blue region most likely represent?



(A) Complete real power

(B) Complete reactive power

(C) Partial real power

(D) Partial reactive power

8.0 SOLUTIONS

8.1 SOLUTION 1 – PER UNIT

A 1,000 KVA, 480V/120V transformer has a percent impedance of 6%. What is the actual impedance for the transformer on the high voltage side?

First solve for the base current and actual impedance.

$$Z_{base} = \frac{V_{ll.base}^2}{S_{3ph,base}} = \frac{(480\ V)^2}{1{,}000 * 1{,}000} = .23\ \Omega$$

Next, use the per-unit value to find the actual impedance.

$$Z_{pu} = \frac{Z_{actual}}{Z_{base}};$$

$$0.06 = \frac{Z_{actual}}{.23\ \Omega};$$

$$Z_{actual} = 0.014\ \Omega$$

The correct answer is most nearly, (a) 0.014 Ω.

Another equation that can be used is shown below.

$$Z_{base} = \frac{V_{ph.base}^2}{S_{1ph,base}}$$

8.2 SOLUTION 2 – PER UNIT

Based on the diagram below and given a Generator G2 as the per-unit base, what is the per-unit reactance values for Generator G1?

Reactive Power: This power flows in both directions. A generator provides reactive power and inductors receive reactive power. A capacitor can also act as a source of reactive power. You cannot convert reactive to real power and vice versa. Reactive power has units VAR.

The blue portion is in the negative region, so it cannot be real power and must be reactive power. However, only some of the reactive power is shown, because only the negative direction is shown. Reactive power consists of both the positive and negative directions on the waveform. The actual reactive graph will look like positive and negative pulses, like the figure below.

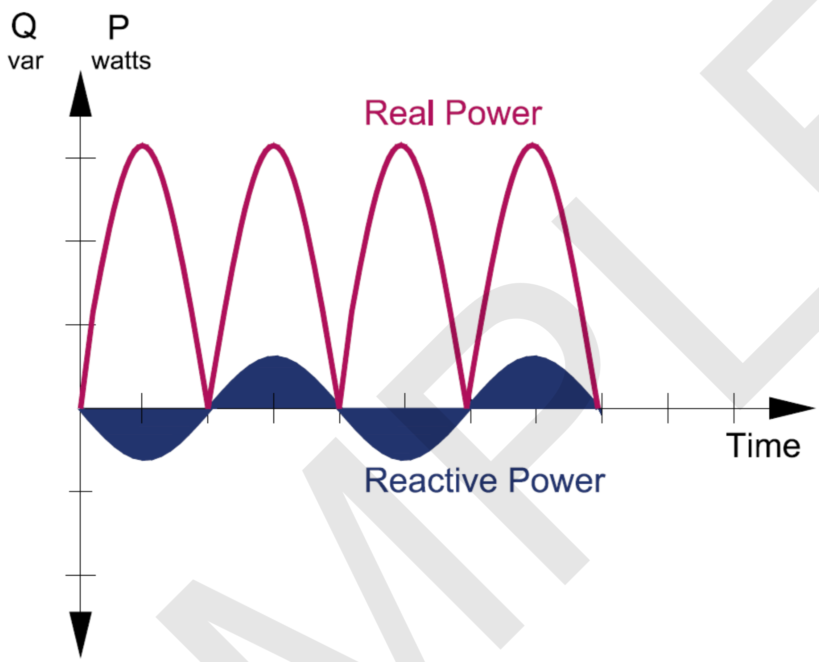


Figure 80: It is very important to note that these two powers cannot be added or subtracted. Real and reactive power are two different powers, with different units. This problem is only intended to show that reactive power flows back and forth between the source and the load. Reactive power flows to a load where it builds up a magnetic field, then discharges the magnetic field and flows back to the source.

The correct answer is most nearly, (D) Partial reactive power.

T

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W

Z

3 – Devices & Power Electronic Circuits

Battery characteristics & ratings | Power supplies and converters | Relays, switches and ladder logic | Variable speed drives

Section 3.0 – Devices & Power Electronic Circuits

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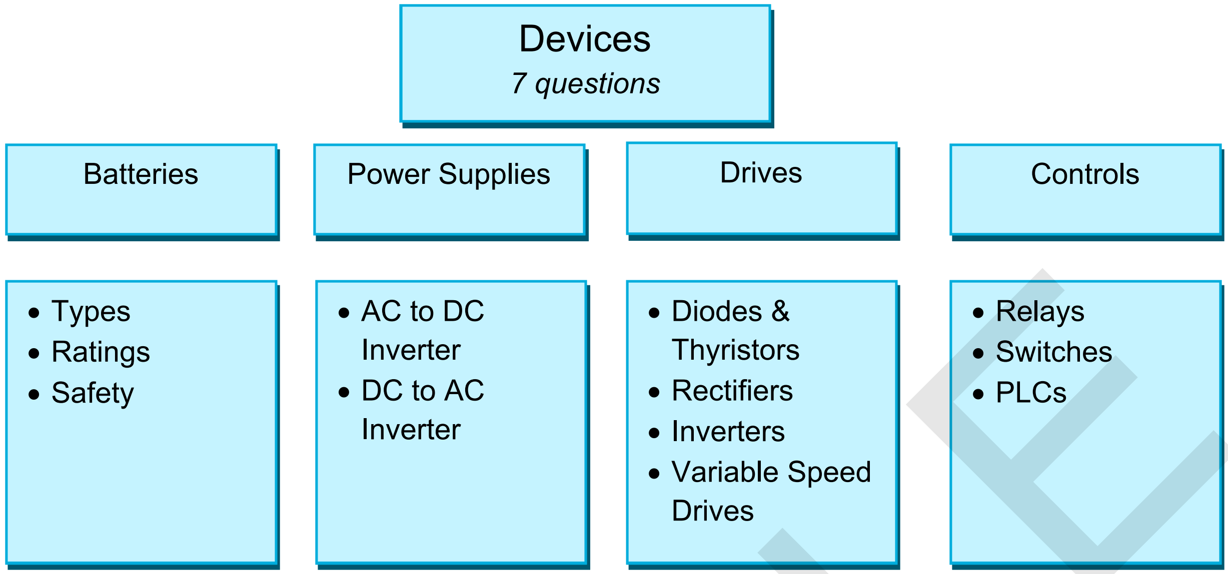
1.0 INTRODUCTION

The section, Devices & Power Electronic Circuits, accounts for approximately 7 questions on the Power Engineering, Electrical PE exam.

This section discusses the Devices and Power Electronic Circuits section. At first this section may seem very different from Power Engineering. However, upon closer inspection you will see how this section is important to practicing Power Engineering. Batteries are beginning to play an increasingly important role in the power field as intermittent renewable energy requires a form of energy storage. Power supplies, drives and controls are used heavily in the motor control section to reduce electricity costs and this effect is large, since motors account for more than 50% of all industrial electricity usage. Some estimates indicate that motors account for more than 2/3 of industrial electricity usage. But with these electricity savings comes unwanted effects to power quality, which Power Engineers must be equipped to resolve. As you can see this section is closely related to the *4.0 Machines* section *and the 7.0 Power System Performance* section, so please be sure to read through this section before reading those sections.



2.0 BATTERIES

Batteries are used to store electrical energy as chemical energy. A battery consists of an electrolyte medium and two electrodes, one positive and the other negative. Current flows from the positively charged end of the battery, through the circuit, then to the negatively charged portion of the battery. Chemically, electrons are negatively charged and are attracted to the positively charged end of the battery.

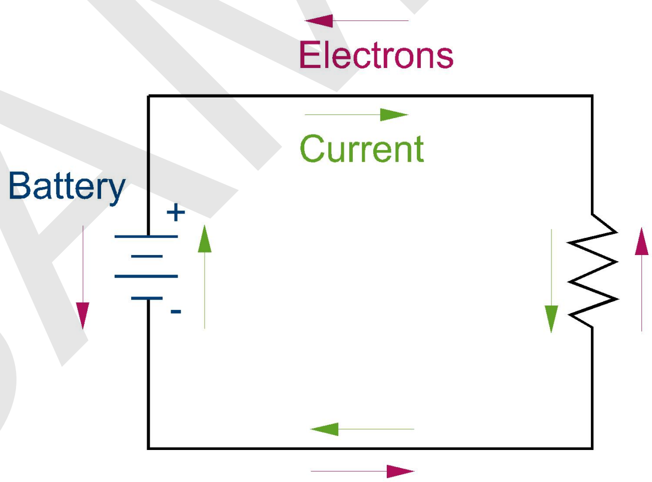


Figure 1: A battery provides direct current to a circuit. Current flows from the positive terminal to the negative terminal.

This transfer of electrons creates this voltage potential, which drives the current during discharge as shown in the figure above. The same principal is used when the battery is being charged but in reverse.

If an inductor is present, then the output current will have the waveform as shown in the Handbook. If an inductor is not present, then the current will be a square waveform.

The equations presented show current values as a function of time. One thing that is not defined in the equations is the tau value.

$$\tau = \frac{L}{R}$$

A common question would be to find the maximum current value at the output.

3.2 DC to AC Inverters

A DC to AC inverter converts direct current from alternating current. These types of inverters are used in the power engineering field in PV installations, where the direct current output from a PV module must be converted to AC in order for it to be used in the normal power distribution system. Inverters are also commonly used in an uninterruptible power supply or UPS. A UPS stores energy as a battery, which normally supplies power in DC. However, in order to power electronics, this DC power must be converted to AC.

3.3 DC to DC Converters

3.3.1 Buck Converter

In a buck converter, the output voltage will be LOWER than the input voltage.

Switch Closed (On): When the switch is closed, the inductor will create an opposing voltage to decrease the voltage sent to the load. If the switch allows the system to reach steady state, then the voltage will go down to zero. But before this happens, the switch transitions to the off state.

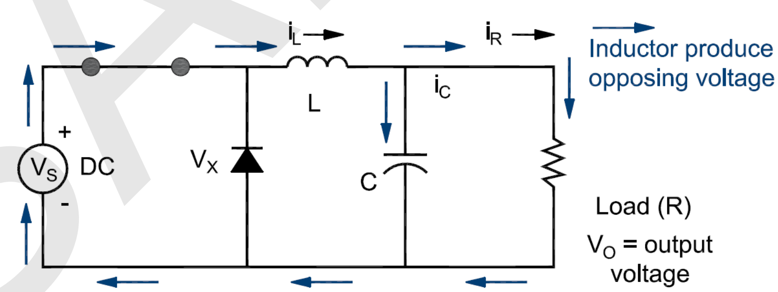


Figure 12: When the switch is closed, current flows from the voltage source through the inductor (charges the inductor) and to the load. The voltage seen by the load is reduced due to the inductor.

Switch Opened (Off): When the switch is opened, the inductor wants to fight against the change in current, so the inductor now becomes a current source. The energy that was stored in the

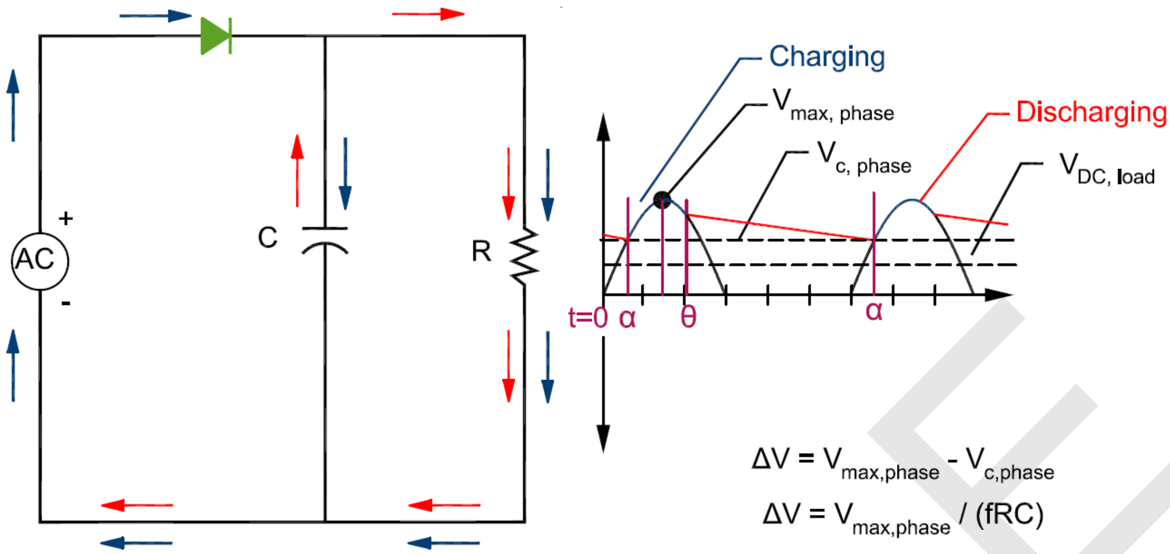


Figure 26: From time, t = a, there is no power from the AC voltage source. The voltage is from the capacitor. Once the voltage drops to V_c, which is shown at time t = a, then the voltage is from the AC voltage source. During t = a through Θ, the voltage is provided by the AC voltage source to the load, but the capacitor is in parallel with the load too, so charging is also occurring during this time. After t = Θ, the voltage from the AC voltage source reaches its peak and starts to decrease. This decrease in voltage, causes the capacitor to now provide current to the load. The capacitor will continue to be the voltage source to the load, until the voltage has dropped to V_c.

The difference between the peak voltage and the voltage at which the capacitor shuts off is found through the equation below.

$$\Delta V_0 = V_{max}\left(\frac{2\pi}{\omega RC}\right) = \frac{V_{max}}{fRC}$$

The following example will go through the types of problems that the exam can and cannot ask you. Given a half-wave rectifier connected to a 480 V RMS, 60 HZ voltage source and a resistive load of 70 ohms and a capacitor sized at 750 uF, determine the following.

<u>Maximum Voltage at Load (can appear on the exam):</u>

$$V_{max} = 480\ x\ \sqrt{2} = 679\ V$$

<u>Angle when capacitor serves as voltage source to load (cannot appear on exam):</u>

$$\theta = -\tan^{-1}(2\pi f * R * C) + \pi$$

$$\theta = -\tan^{-1}(2\pi(60) * 70 * 750x10^{-6}) + \pi = 92.9°$$

The angle should be pretty close to the peak at 90 degrees. It is often just assumed that the capacitor turns on after the peak.

$$V_{DC\ RMS} = \sqrt{3\frac{V_{AC,MAX}^2}{2\pi}\int_{\pi/6}^{5\pi/6}\frac{1}{2}[1-\cos(2\theta)]}$$

$$V_{DC\ RMS} = \sqrt{3\frac{V_{AC,MAX}^2}{4\pi}\int_{\pi/6}^{5\pi/6}[1-\cos(2\theta)]}$$

$$V_{DC\ RMS} = \sqrt{3\frac{V_{AC,MAX}^2}{4\pi}\left[\left[5\pi/6-\frac{1}{2}\sin(10\pi/6)\right]-\left[\pi/6-\frac{1}{2}\sin(2\pi/6)\right]\right]}$$

$$V_{DC\ RMS} = \sqrt{3\frac{V_{AC,MAX}^2}{4\pi}\left[\frac{5\pi}{6}+\frac{\sqrt{3}}{4}-\frac{\pi}{6}+\frac{\sqrt{3}}{4}\right]}$$

$$V_{DC\ RMS} = \sqrt{3\frac{V_{AC,MAX}^2}{4\pi}\left[\frac{4\pi}{6}+\frac{\sqrt{3}}{2}\right]}$$

$$V_{DC\ RMS} = 0.841 * V_{AC\ MAX}$$

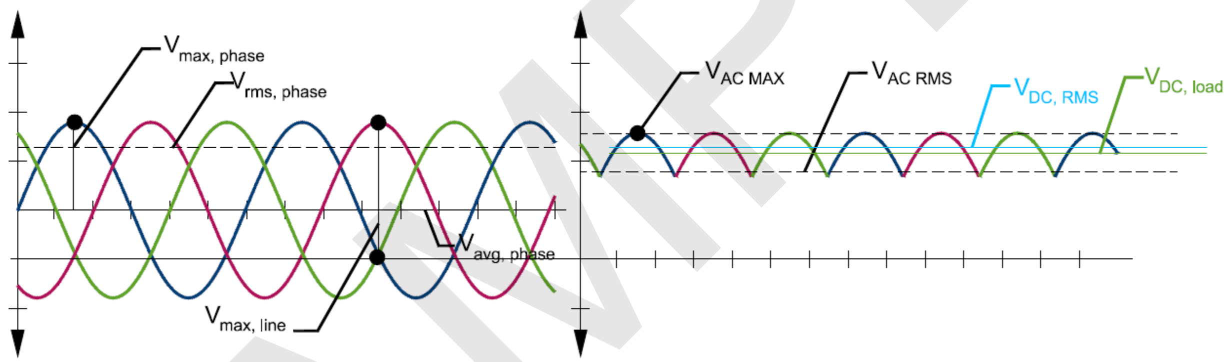


Figure 36: This figure shows the AC input on the left and the DC output after the rectifier. These two figures can be a little confusing, because there are phase and line RMS & Max values. The line AC maximum and RMS values are translated from the left figure to the right figure. This was done by shifting the y = 0, horizontal line down to where the line AC max value is shown on the left. The DC RMS value is shown in light blue and the DC load (average value) is shown in green.

4.5.4 Three Phase Full Wave Rectifier

The fourth rectifier is the three-phase, full-wave rectifier. The input to the rectifier are three voltages or currents each at the same RMS value and MAX value. For the purposes of these derivations, voltage will be used, but just understand that voltage can be replaced with current.

6.5 Problem 5 – Variable Frequency Drives

The AC input voltage to a variable speed drive is 440 V RMS. What will be the voltage measured at the DC link (DC RMS) after the rectifier? Assume 3-phase.

(a) 480 V DC

(b) 597 V DC

(c) 622 V DC

(d) 678 V DC

6.6 Problem 6 – Variable Frequency Drives

Which of the following is methods will provide the greatest reduction in total harmonics caused by a standard 6-pulse variable frequency drive?

(a) Installing a 3% line reactor:

(b) Upgrading from a 6-pulse to an 18-pulse VFD

(c) Upgrading from a 6-pulse to a 12-pulse VFD

(d) Installing a DC inductor

7.7 SOLUTION 7 – BATTERIES

This question is provided to ensure that you have read through the recommended resources.

Which of the following is NOT a characteristic of a VRLA battery?

(a) Regular maintenance includes filling of electrolyte – A VRLA battery does not normally allow for its battery to be opened and filled with electrolyte, when its electrolyte is depleted. VLA batteries regularly require the filling of electrolyte, since it is regularly open to the atmosphere. This can cause electrolyte (water) to evaporate quickly.

(b) Can possibly release gases – In the event of excess pressure in the battery, the valve will open and release any build-up of gases.

(c) Subject to negative strap corrosion – Negative strap corrosion is the most common cause of failure in a VRLA battery. The strap is the connection between the plate and the terminal. In a VLA battery, the positive plate will corrode, but in a VRLA battery, the negative strap will corrode often.

(d) Its electrolyte can dry out – Although a VRLA battery is technically "sealed", its electrolyte can still dry out or evaporate. This is the second most common cause of failure of a VRLA battery.

The correct answer is most nearly, **(a) Regular maintenance includes filling of electrolyte**.

7.8 SOLUTION 8 – BATTERIES

Which of the following batteries has the SHORTEST service life? Assume that all batteries are properly maintained, the same size and are installed in the same environment.

(a) Lithium Ion – These batteries have a service life of around 10 years.

(b) VLA – The vented lead acid batteries have a service life of around 15 years.

(c) VRLA – The valve regulated, lead-acid batteries have a service life of around 5 years.

(d) Flooded battery – This is the same as the vented battery. It has a service life of around 15 years.

The correct answer is most nearly, **(c) VRLA**.

4 – Rotating Machines

Induction & Synchronous Machines | Generator applications | Motor applications | Equivalent circuits and characteristics | Motor starting | Electrical machine theory

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Section 4.0 – Rotating Machines

Table of Contents

1.0 INTRODUCTION

The section, Rotating Machines, accounts for approximately 7-11 questions on the Power Engineering, Electrical PE exam.

The rotating machines section on the PE exam focuses on two main types of machines, (1) Synchronous machines and (2) Induction machines. These two types of machines are important in electrical power engineering, because these two machines define the primary sources and loads for AC power. Induction motors are one of the largest loads for electricity and synchronous generators are the leading power sources for AC power.

In order to do well on rotating machines exam problems, you should understand how electricity is generated through a synchronous generator and how electricity is used by a motor. You should be able to follow the flow of electricity through the equivalent circuit of a generator and motor.

The exam also does have miscellaneous questions on starting methods, speed and torque. These three terms are also discussed in this section.

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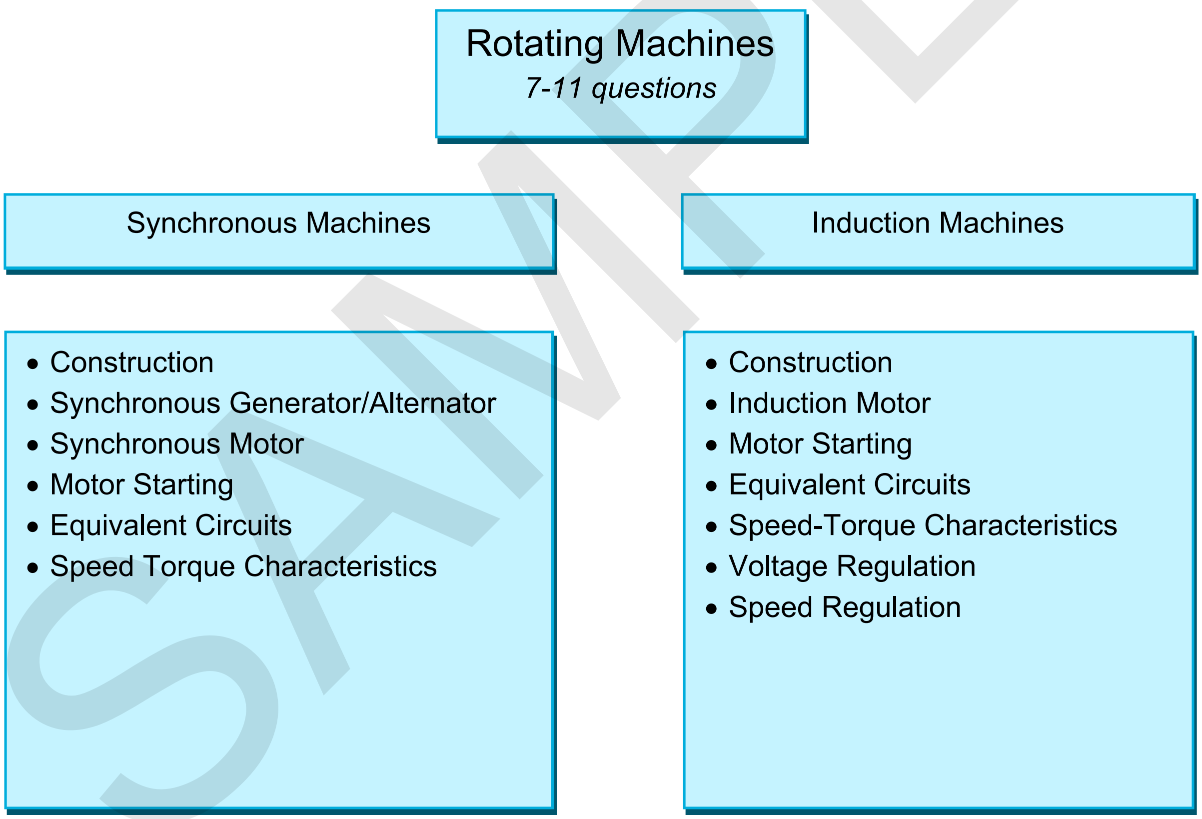


2.0 Synchronous Machines

A synchronous machine is a machine that rotates at the same frequency as the alternating current. This frequency is called the synchronizing frequency and in the USA this frequency is 60 Hz. An induction machine rotates at a frequency slightly less than this synchronous frequency.

- 2.0 Synchronous Machines: The synchronous machine has a steady state rotation that is synchronized with the frequency of the alternating current.

- 3.0 Induction Machines: Instead of two separate magnets used to create rotation like the synchronous machine does, the induction machine induces a magnetic field from one coil to the other (between the stator and rotor). The transfer of current via electromagnetic induction causes a lag and therefore, the induction machine will always have a speed less than the synchronous speed.

This section will primarily focus on synchronous machines and the following section will focus on induction machines.

Both synchronous machines and induction machines can then be separated into two main types of machines, (1) Generator or (2) Motor.

- 2.3 Generator: A generator uses the mechanical energy from rotation to produce alternating current electrical energy.

- 2.4 Motor: Motors use alternating current electrical energy to produce mechanical energy in the form of rotation.

These two types of machines are discussed in further detail in this section, but first you should understand the general construction of a synchronous machine.

2.1 Construction

There are three main parts of a rotating synchronous machine.

- Mechanical Stator: The stator is the stationary part of the synchronous machine. The stator contains slots of stator windings.

- Electrical Field Windings: A winding is another term for electrical coil. The field refers to the rotating magnetic field component. In a motor, the stator receives three-phase alternating current which creates the rotating magnetic field, and in a generator the rotor is rotated to create a rotating magnetic field.

- Mechanical Rotor: The rotor is the rotating part of the synchronous machine. The rotor contains rotor windings that are served by a DC source. The DC source is used to create north and south poles. Sometimes permanent magnets are used instead of windings and a DC source.

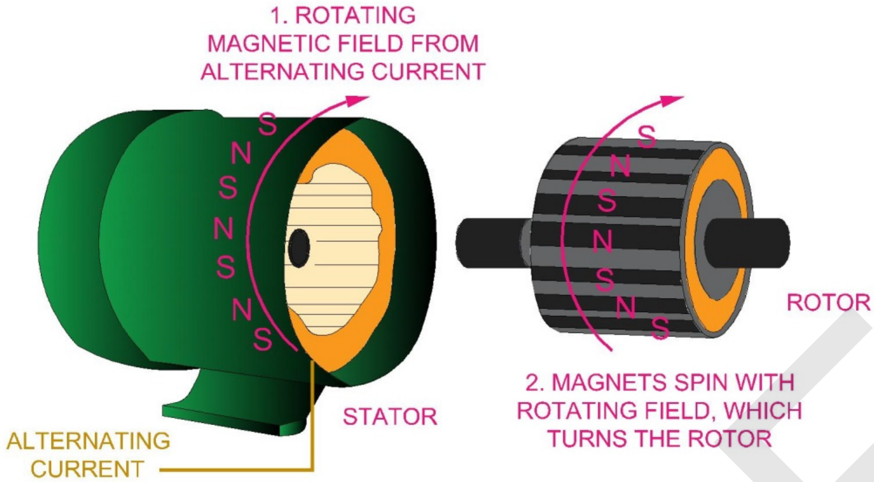


Figure 1: A synchronous machine consists of a stator and a rotor. Motor shown in figure.

2.1.1 Rotating Magnetic Field

A key part of the synchronous and induction machines section is the rotating magnetic field. In a motor, the stator creates a rotating magnetic field. In a generator the rotor creates the rotating magnetic field.

Synchronous Motor: In a motor, alternating current creates a rotating magnetic field in the stator. As one phase becomes reaches its peak it becomes the "North Pole". There is a corresponding "South Pole" that is circuited opposite of that phase's North Pole.

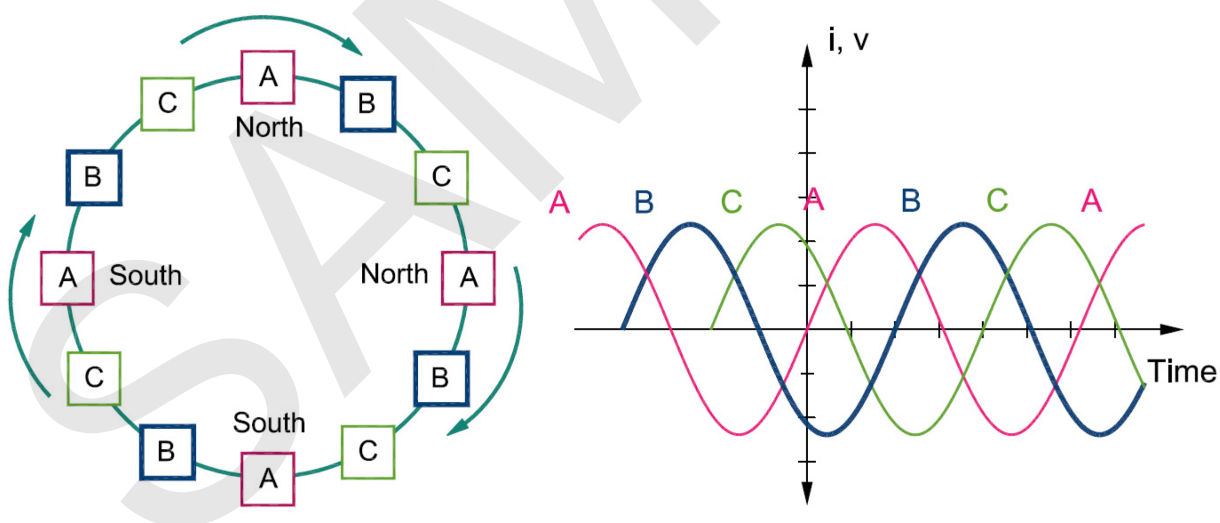


Figure 2: A rotating magnetic field in the clockwise direction, A-C-B sequence.

First, all the "A" slots are either North or South. Then "B" is North or South and then C. This creates a magnetic field rotating clockwise. If the alternating current had a phase sequence of A-

2.3.4.2 Speed Regulation

Real power is controlled by maintaining the speed at which the prime mover is rotating the rotor. Increasing the speed of the generator will linearly increase the frequency of the power system (see Section 3.2 for the speed and frequency relationship), and since the power system must remain at constant frequency, the generator controls are set to maintain the speed of the shaft by adding or decreasing the amount of fuel to the generator. This is accomplished via a speed governor control system that converts the relationship between frequency and power in a linear fashion, as seen in the figure below. Note that the real frequency vs. power curve is not linear, but it is adjusted as such via the speed governor for simplified controlling. In the figure below, if the load power requirements are increased, then the frequency at the generator will decrease. To maintain constant frequency, the curve must rise vertically by adding more fuel to the prime mover.

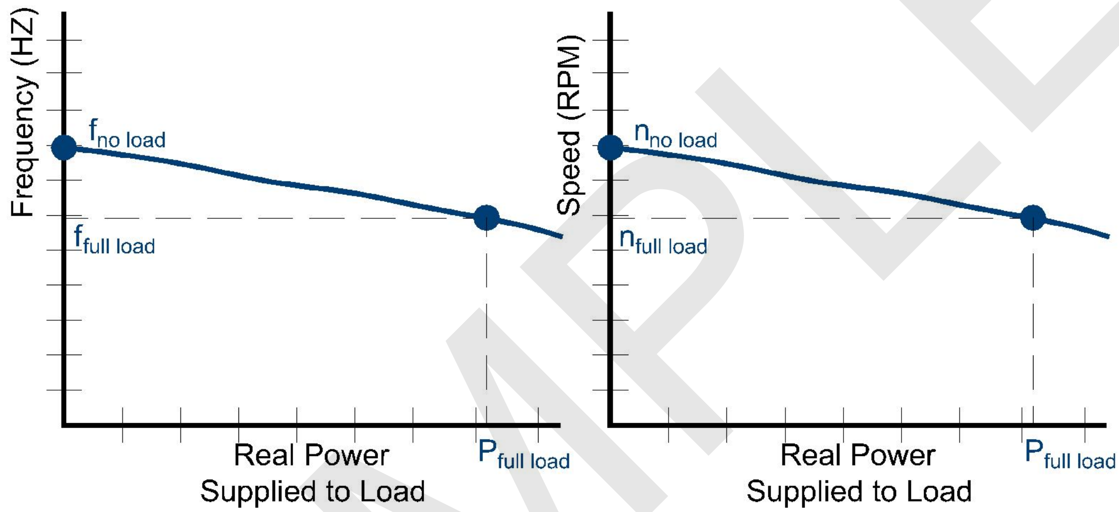


Figure 18: The frequency or speed of the rotor affects the real power supplied to the load.

Conceptually this can be described as an increase in input power, and therefore increase in torque, to sustain the increased resistance from a load, similar to how driving uphill will require more gas to maintain the car at the same speed than if it were on flat ground. The power input is related to the shaft torque by the following equation.

$$P_{in}[kW] = Shaft\ Torque[N*m] * Angular\ Rotation\ \left[\frac{rad}{s}\right]$$

To understand how the speed mathematically affects the real power of a generator, the *torque angle* is introduced. Just as a car shaft will require more torque going uphill, so will the generator shaft require more torque for large real power loads. The torque angle is the angle between the stator and rotor magnetic fields and, alternatively, the angle between the internal generator voltage and the terminal voltage.

The terminal voltage is the voltage provided by the electrical distribution system or the power source. There is a voltage drop through the stator due to the armature reactance and resistance. The resulting voltage at the air gap is the voltage that the motor will use to rotate the rotor.

On the exam, you should be able to quickly understand the flow of current and voltage drop sequence in the previous equivalent circuit and you should be able to visualize the voltage drop equation in phasor form. The following figures will construct the voltage drop equation in phasor form for a leading power factor load.

2.4.1 Synchronous Motor - Leading Power Factor

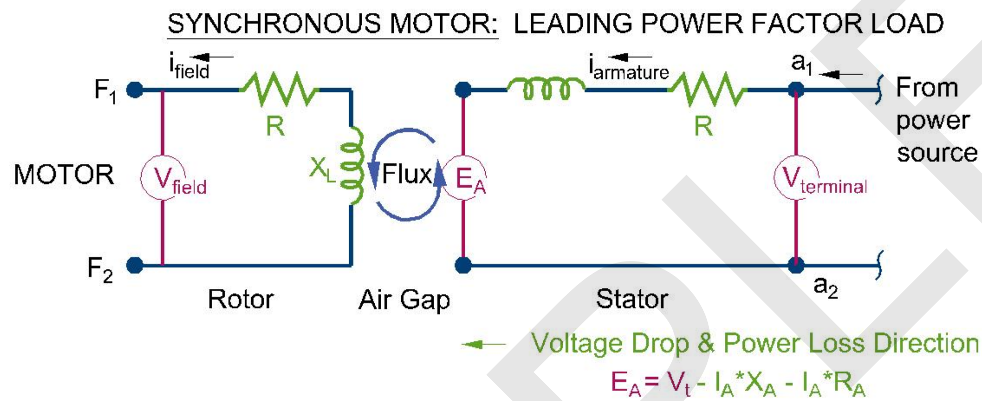


Figure 20: This figure shows the equivalent circuit of a synchronous motor. The circuit is the same for both a leading and lagging power factor, but the following phasor steps are for a leading power factor.

Figure 21: Step 1 - Assign your voltage as having a 0 degree reference point and the armature current leads the voltage phasor by the power factor angle.

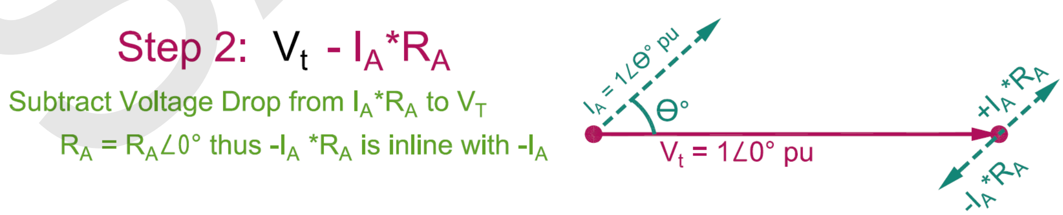


Figure 22: Step 2 - There will be a voltage ***subtraction*** *from the terminal voltage equal to the voltage drop through the resistive losses. Remember that the current in the equivalent circuit moves from right to left; it starts at the terminal and works its way to the motor. Voltage is being*

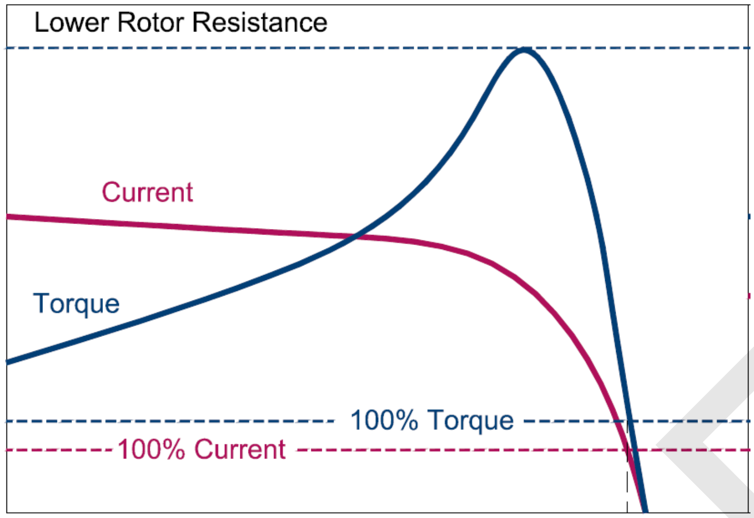


Figure 38: A lower rotor resistance will have a higher inrush current, but a lower initial torque.

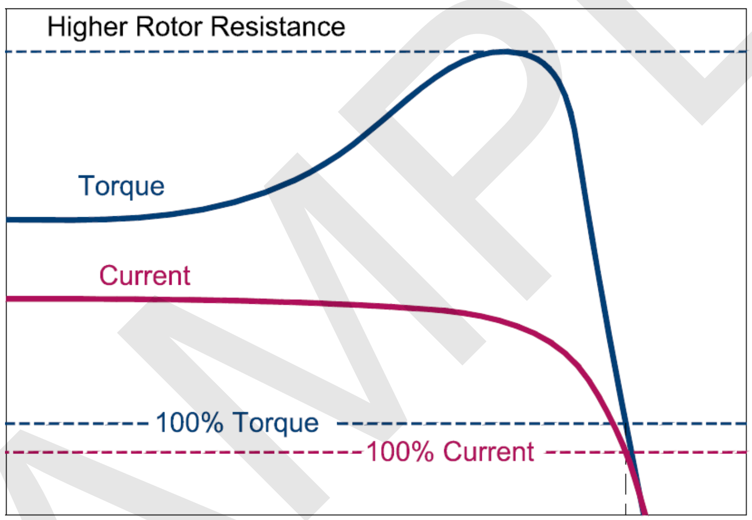


Figure 39: A higher resistance will lower the inrush current, but the initial torque will be increased. The breakdown torque remains the same for both scenarios.

4.1.4 Induction Motor Characteristics as a Function of Percent Load

Once the motor is started and the rated speed is reached, then the motor can be varied based on the percent load required. In order to change the percent load, the slip must be changed. Practically this is done by changing the loading that is acting upon the equipment (pump, fan, compressor, etc.). As the mechanical load on the equipment is varies, this changes the electrical load on the motor, which changes the slip. As the load decreases, the slip decreases, until the slip reaches zero. When this occurs, there is no load and the induction motor rotates at synchronous speed. As the load increases, the slip increases, which causes the induction motor to rotate at a slower rate.

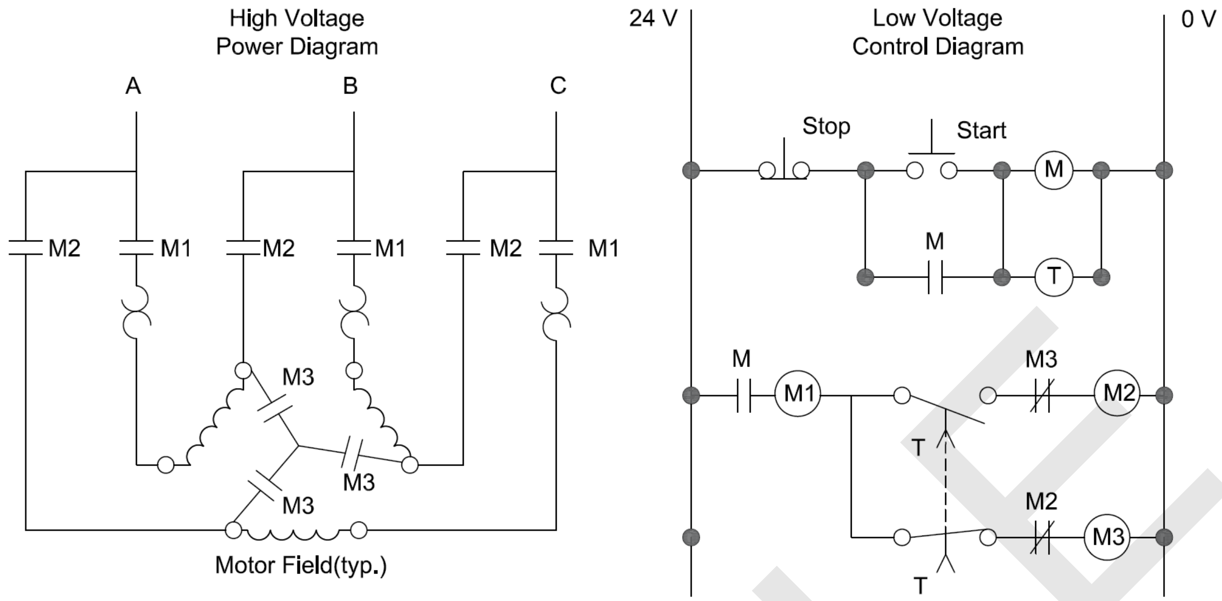


Figure 45: This figure shows the high voltage diagram that can be either a delta or wye arrangement depending on whether or not M3 or M2 is closed. The left side shows the control diagram that controls how M1, M2 and M3 open and close.

5.3 Variable Speed Drive as a Starter

A variable speed drive (VSD) or variable frequency drive (VFD) was discussed in the previous section. This type of drive is able to control the voltage and frequency to a motor, which is especially useful during the starting process of a motor. During the start, the drive increases the frequency from 0 Hz up to the normal frequency (50 or 60 Hz). The low frequency tricks the circuit into thinking that the motor is running at its "rated full load speed". By gradually increasing the frequency like this, the motor can be considered running at its rated speed for that frequency. Also, since the motor can be considered running at its rated speed, the rated motor torque is available already from start and the current will be around the nominal current. Usually, the drive trips if the current reaches 1.5 times the rated current.

This method uses the reduced voltage method, so the reduced voltage relationships will apply like the reduction in current. But at the same time the voltage is reduced, the frequency is also reduced. This allows the torque-speed curve shape to remain the same, but to be shifted to the left. The torque provided is sufficient to get the rotor running, but since the voltage is also reduced, the current will be reduced.

This method is called the V/f method. The ratio of voltage to frequency is kept constant. So you start off with a smaller voltage but proportionally smaller frequency, then you slowly increase both the voltage and frequency.

For example, the rated voltage and frequency could be 480 V & 60 HZ.

7.0 PRACTICE PROBLEMS

7.1 PROBLEM 1 – POLES

A 3-phase motor, 60 Hz, induction motor has the following values on its nameplate:

Efficiency (50% , 75%, 100% load)	94%, 95%, 96%
Efficiency (50% , 75%, 100% load)	0.78 pu, 0.85 pu, 0.88 pu
Full Load Speed	1,784 RPM
Full Load Torque	1,473 lb-ft
Locked Rotor Torque	90% full load
Breakdown Torque	220% full load
Voltage	4,160 V

How many poles does the motor have? The answer is most nearly,

(a) 1

(b) 2

(c) 3

(d) 4

7.2 PROBLEM 2 – BREAKDOWN TORQUE

A 3-phase motor, 60 Hz, induction motor has the following values on its nameplate. What is the breakdown torque?

Horsepower	50 HP
Full Load Speed	1,784 RPM
Locked Rotor Torque	90% full load
Breakdown Torque	220% full load
Voltage	4,160 V

The answer is most nearly,

(a) $147\ lb - ft$

(b) $200\ lb - ft$

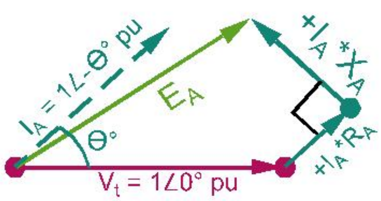
(c) $310\ lb - ft$

(d) $324\ lb - ft$

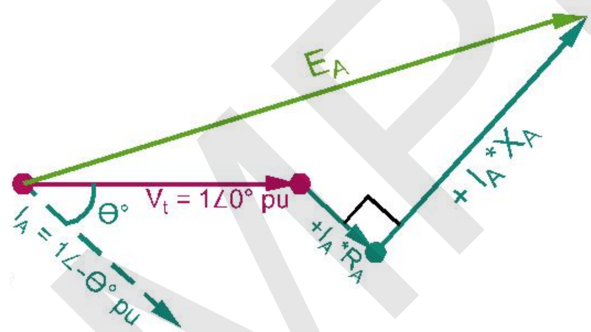
8.9 Solution 9 – Synchronous Machines

A 3-phase synchronous generator currently provides power to a total load with a leading power factor of 0.9. Which of the following is NOT true, if the total load changes to a lagging power factor of 0.9?

During a leading power factor the magnitude of the internal generator voltage (E_A) is less than the magnitude of the voltage at the terminal (load).



When the load switches to a lagging power factor. The internal generator voltage must be greater than the magnitude of the voltage at the terminal (load).



The voltage magnitude of the internal generator must be increased, which is caused by increasing the excitation. The synchronous speed will remain the same.

The correct answer is most nearly, (c) The torque angle must be increased.

8.10 Solution 10 – Synchronous Machines

A synchronous generator, 3-Ph, 480 V, 60 Hz, 100 KW, 1,800 RPM is operating at a speed of 1,700 RPM. Which of the following will most likely be true?

The answer is most nearly,

(a) The rated synchronous speed will be increased.

8.17 Solution 17 – Induction Motor

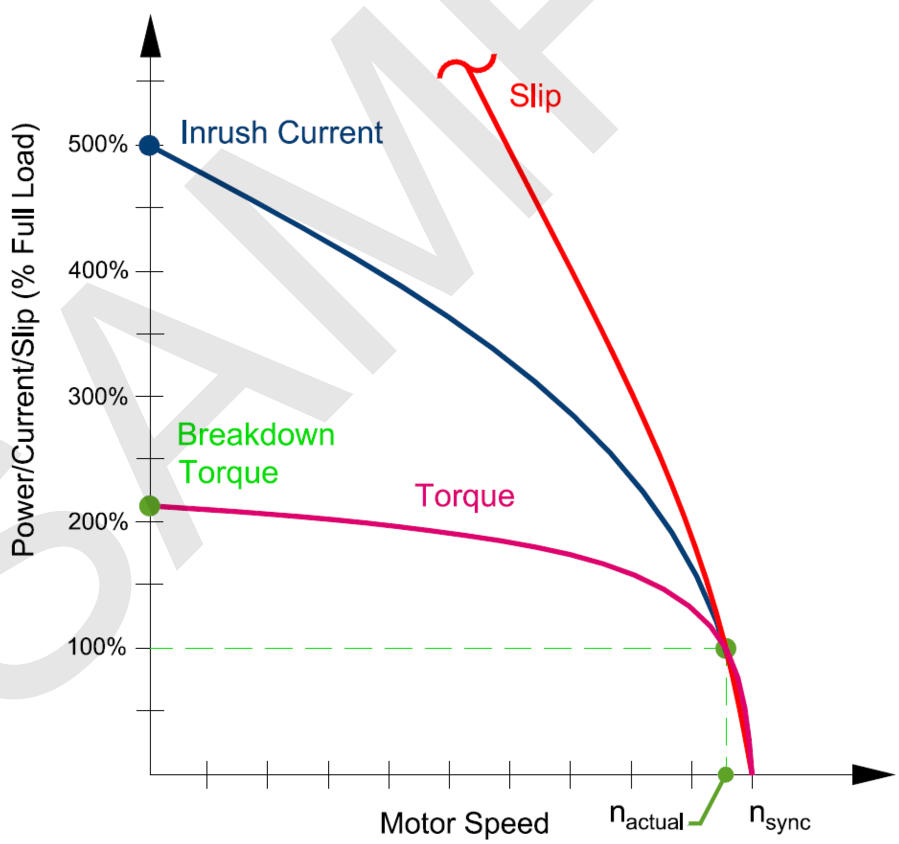
As the speed is increased during start-up, the slip and inrush current values decrease, but they decrease at varying rates. Thus the active power delivered to the rotor makes a curve similar to the ones shown below.

If the motor is artificially sped up above the design speed towards the synchronous speed, through another means (instead of mechanical load, there is a mechanical rotational supply), then the current, slip and real power will drop to zero. This could also be done by removing the load.

This power will cause a motor torque to be applied and this torque will cause the motor shaft to accelerate. Since the power is very high, there will be a high torque value.

$$T_{supplied} = \frac{9.55 * P_{motor}}{n_{sync}}$$

The torque will decrease once its breakdown torque value is reached. The breakdown torque is the maximum torque during acceleration. Since the breakdown torque is achieved at 0 RPM, then the torque-speed graph will look like the graph below.



5 – Electric Power Devices

Transformers | Reactors | Testing | Capacitors

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SECTION 5.0 – ELECTRIC POWER DEVICES

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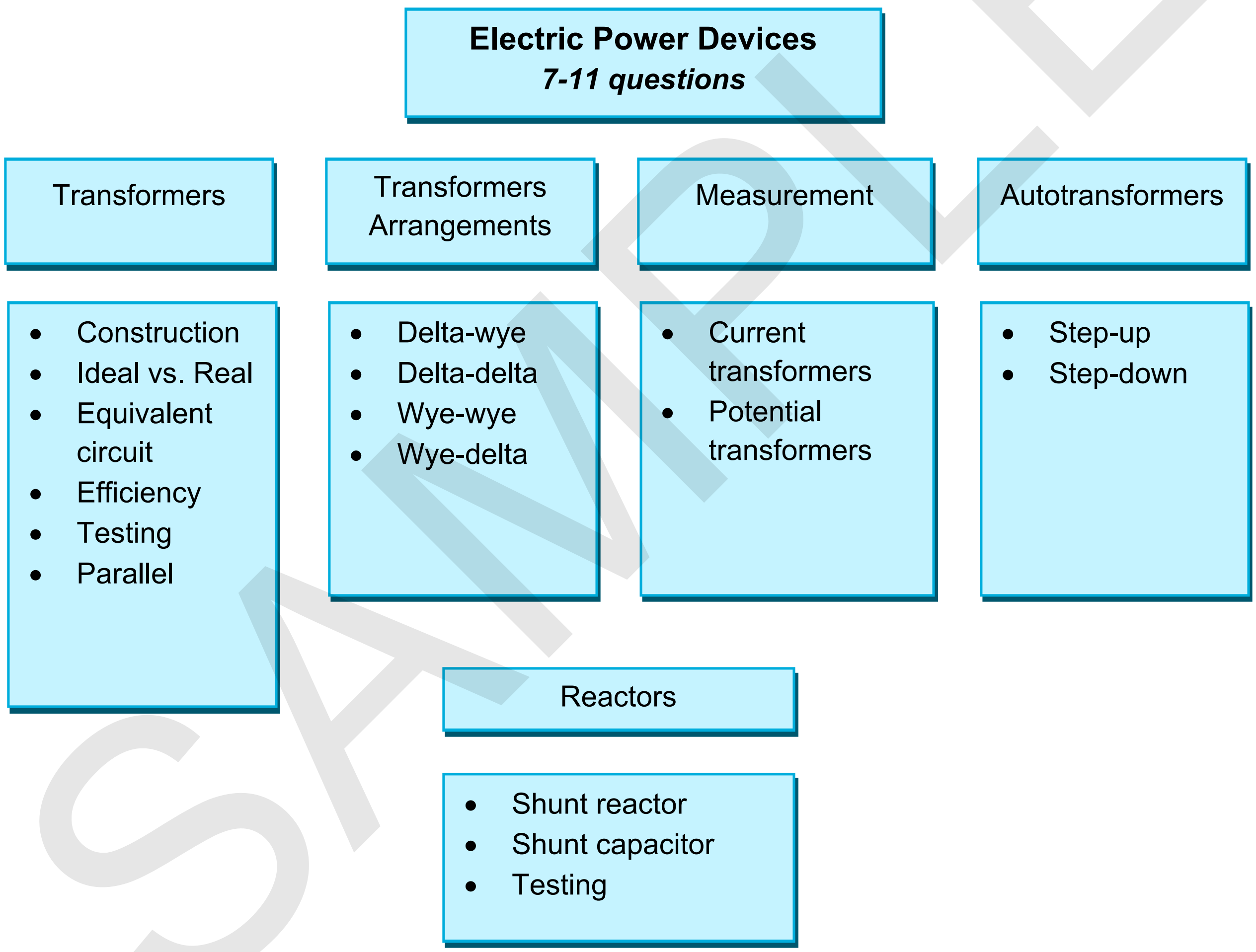
1.0 INTRODUCTION

The section, Electric Power Devices, accounts for approximately 7-11 questions on the Power Electrical PE exam.

The *Electric Power Devices* section covers all different types of transformers and reactors. Transformers and reactors generate current through electromagnetic fields, hence the term electromagnetic devices. Transformers are the biggest topic from this section on the exam, because of the many types of transformers and the ease in which questions can be constructed for the exam. The *Transformers* topic also overlaps with the *Measurement & Instrumentation* section.



2.2 Construction

A power transformer is made up of a metal core and two windings, or wires that wrap around the core. The core itself is made up of thin laminates with insulation between each layer to electrically isolate the laminates. Using thin laminates instead of one solid core reduces the amount of eddy current losses through the core. Eddy current losses are explained in the *Real Transformer* section.

The basic operation of a transformer begins with an AC current that is sent through the primary winding. As the current flows through the wire and around the core, a magnetic flux is created through the core. The magnetic flux in the core then induces current through the secondary windings to produce AC current at a different voltage, which is specified by the number of turns in the windings. This will be discussed in the next section.

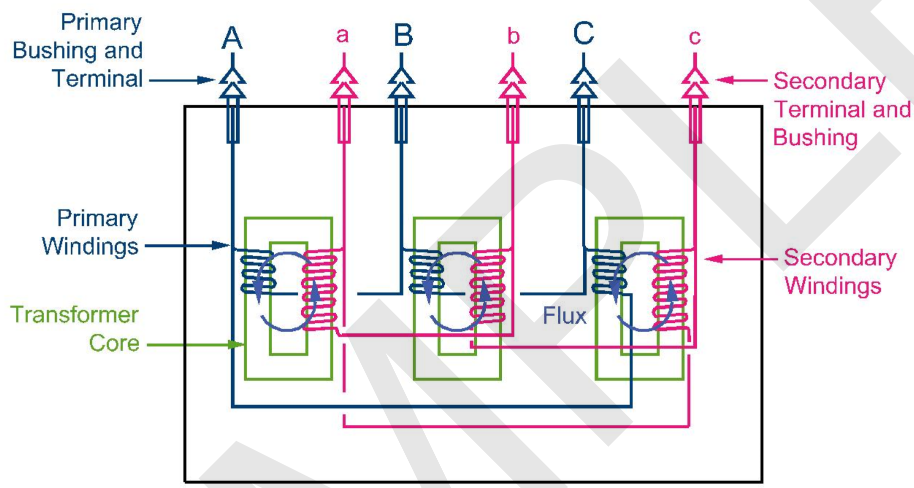


Figure 1: Basic construction of a three-phase transformer, which is made up of three single-phase transformers. The copper windings can be seen on the transformer core. These windings are then wired to connection points at the exterior of the transformer. These points are called terminals. The bushings are located at the terminals. They are used to insulate the wires that pass through the transformer enclosure, preventing the charge in the wires from hitting the grounded enclosure.

2.1.1 Types

There are various types of transformers, which can be seen on any of the popular manufacturers' websites. For the purposes of the exam, you should just be familiar with the names and how the types are different only for context of problems. The exam most likely will not test you on the construction differences of the different types of transformers. The exam will test you on the different transformer arrangements which are discussed later.

http://www.schneider-electric.us/en/product-category/53700-transformers/?filter=business-4-low-voltage-products-and-systems

2nd Designation: The next deciding factor in cooling the windings is how that type of oil is moved over the hot windings. The oil can naturally flow over the hot windings via natural convection or it can be forced through pumps. Fans are used to move air and pumps are used to move oil.

3rd Designation: If the windings are cooled with oil or another liquid, then the heat in the type of oil must be expelled to the outside ambient air. The heat can be transferred from the oil to air or to water.

4th Designation: Once the heat is transferred from oil to either air or water, then the heat can be removed from the air or water and transferred to the ambient air via either natural convection or forced convection (fan).

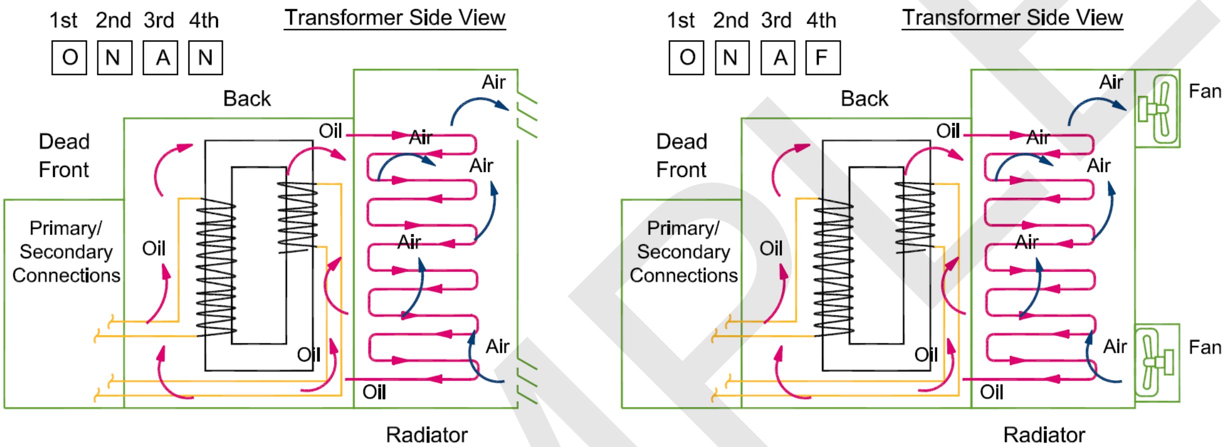


Figure 7: This figure shows coils that are cooled by naturally flowing oil and oil that is cooled via naturally flowing air (ONAN). On the right hand side the cooling method shows coils that are cooled by naturally flowing oil and oil that is cooled via forcefully flowing air (ONAF).

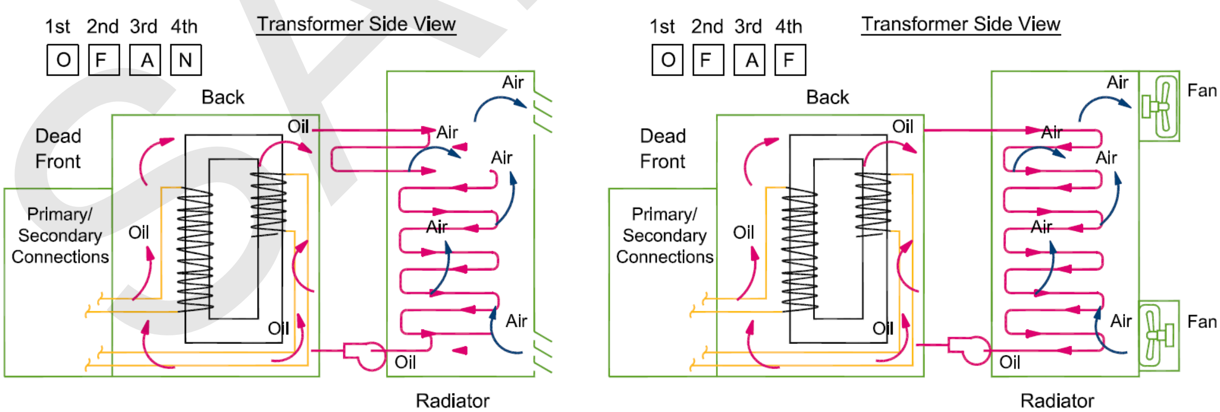


Figure 8: This figure shows coils that are cooled by forcefully flowing oil and oil that is cooled via naturally flowing air (OFAN). On the right hand side the cooling method shows coils that are cooled by forcefully flowing oil and oil that is cooled via forcefully flowing air (OFAF).

operates instantaneously. The last component is the motor, which consumes the real and reactive power.

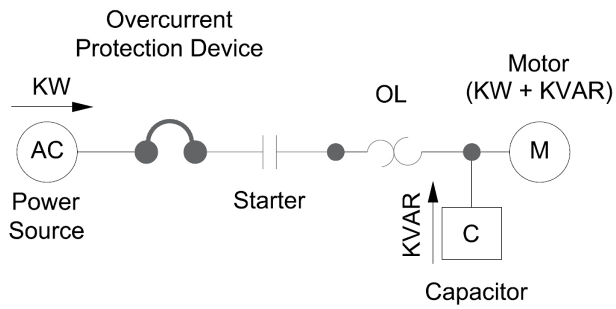


Figure 24: In this figure, a capacitor is installed at the motor, on the load side of the overload device. The capacitor will now be the new source of reactive power and this causes a reduction in the amperage from the power source and through the OCPD (overcurrent protection device), starter and OL (overload device). The overload device will see less current, so its settings must be adjusted or replaced, otherwise it will not accurately detect an overload condition. For example, if the full load current was 10 A and the overload device were to trip at 13 A. The full load current is now 8 A, so the overload condition will occur at a smaller value and if the OL device is still set at the higher value, then it will not accurately protect the motor.

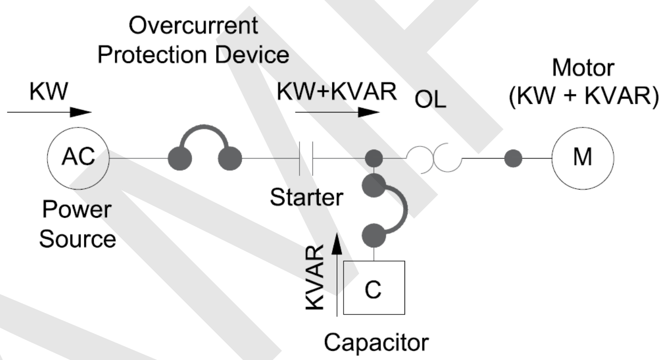


Figure 25: This situation bypasses the problem of changing the settings or replacing an existing overload device. In this scenario the OL device will get both the real and reactive power flows.

7.4 Capacitor Harmonics

Capacitors can cause resonance on a system. Resonance occurs at a frequency where the given inductance and capacitance values feed upon each other and incrementally build up the voltage and current to unsafe values. The changing inductor magnetic field generates current that charges the capacitor and the capacitor discharges current to build the inductor's magnetic field. They continually work together at this resonant frequency and continue to increase the voltage and current.

8.3 Problem 3 - Autotransformer

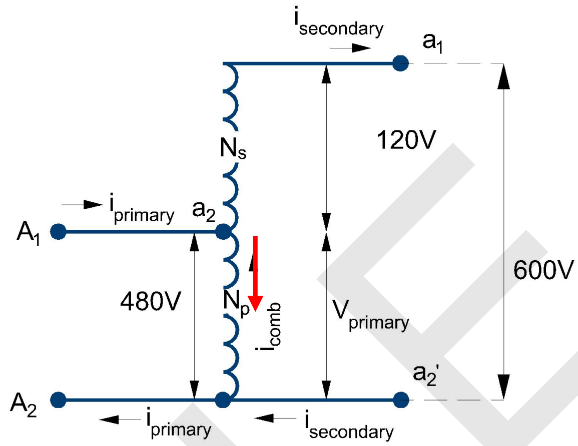
A single-phase, 480V/120V transformer rated at 50 KVA is re-wired as an autotransformer in order to step-up the voltage from 480V to 600V. What is rating of the autotransformer?

(a) 50 KVA

(b) 125 KVA

(c) 200 KVA

(d) 250 KVA



8.4 Problem 4 - Autotransformer

A 3-phase autotransformer has a rating of 100 KVA. The autotransformer transforms line voltages from 13.8KV to 10 KV. What is the KVA rating of $V_{primary}$ and $V_{secondary}$ of the autotransformer as shown below? This figure is one of the three phases and the autotransformer is arranged as a wye-wye transformer.

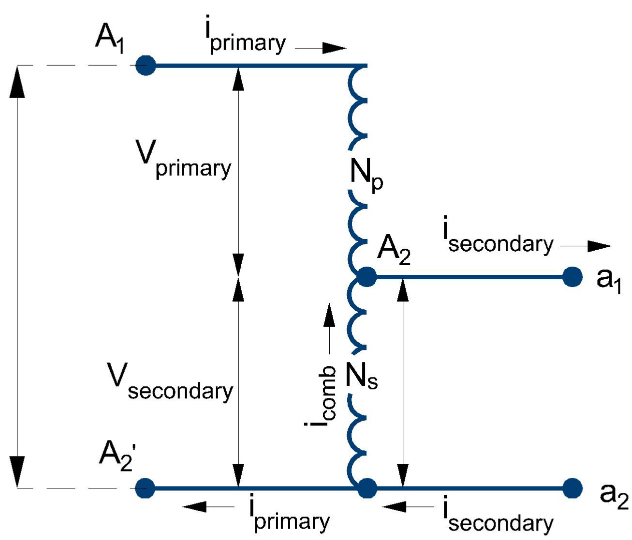
Answers arranged as apparent power through $V_{primary}$ & $V_{secondary}$

(a) 2.2 KVA & 2.2 KVA

(b) 2.2 KVA & 9.2 KVA

(c) 3.9 KVA & 9.2 KVA

(d) 9.2 KVA & 9.2 KVA



$$7.97\ KV = V_{primary} + 5.77\ KV \rightarrow V_{primary} = 2.2\ KV$$

Now find the currents, since you know the voltage and the apparent power.

$$S = 33.33\ KVA = V_{ph,A1-A2'} * I_{primary} \rightarrow I_{primary} = \frac{33.33\ KVA}{7.97\ KV} = 4.18\ A$$

$$S = 33.33\ KVA = V_{ph,a1-a2} * I_{secondary} \rightarrow I_{secondary} = \frac{33.33\ KVA}{5.77\ KV} = 5.78\ A$$

Next find i_{comb}

$$I_{primary} + I_{comb} = I_{secondary} \rightarrow I_{comb} = 5.78\ A - 4.18\ A = 1.6\ A$$

Now use the current and the voltages to find the power through $V_{primary}$ and $V_{secondary}$.

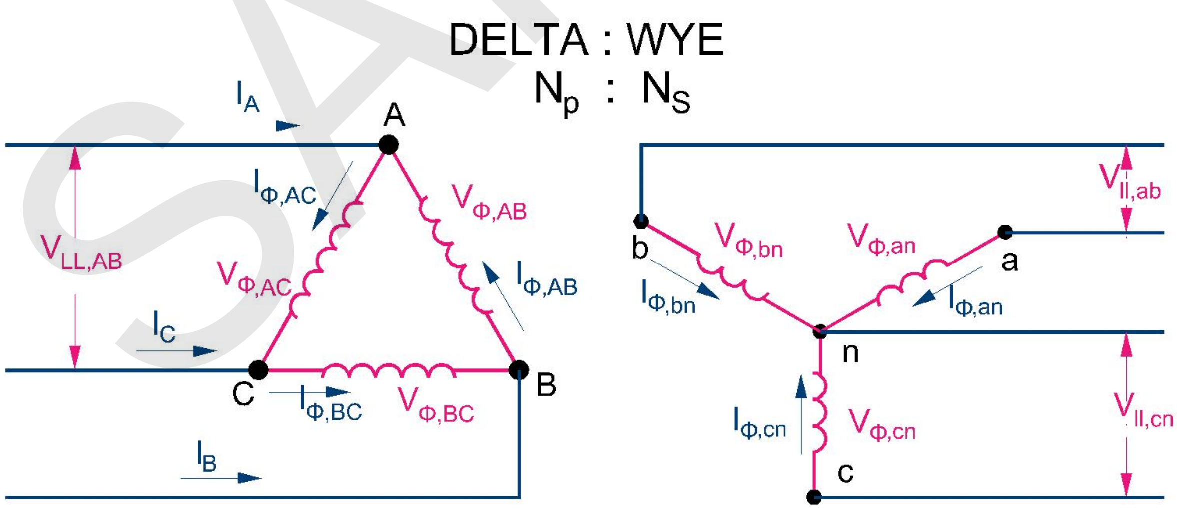
$$S_{V\ primary} = I_{primary} * V_{primary} = 4.18\ A * 2.2\ KV = 9.2\ KVA$$

$$S_{V\ secondary} = I_{comb} * V_{secondary} = 1.6\ A * 5.77\ KV = 9.2\ KVA$$

The correct answer is most nearly, **(d) 9.2 KVA & 9.2 KVA.**

9.5 Solution 5 – Transformer Arrangements

A 3-phase delta-wye transformer is rated at 100 MVA, 13.2 KV-480V. If there is a motor with a load of 500 A, then what is the corresponding current on the high voltage side in one of the phases of the transformer?



The motor load of 500 amps corresponds to the line current on the secondary.

6 – Transmission & Distribution

Voltage drop | Voltage regulation | Power factor correction | Voltage support | Power quality | Fault current analysis | Transformer connections | Transmission line models | Power flow | Power system stability

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SECTION 6.0 – TRANSMISSION & DISTRIBUTION

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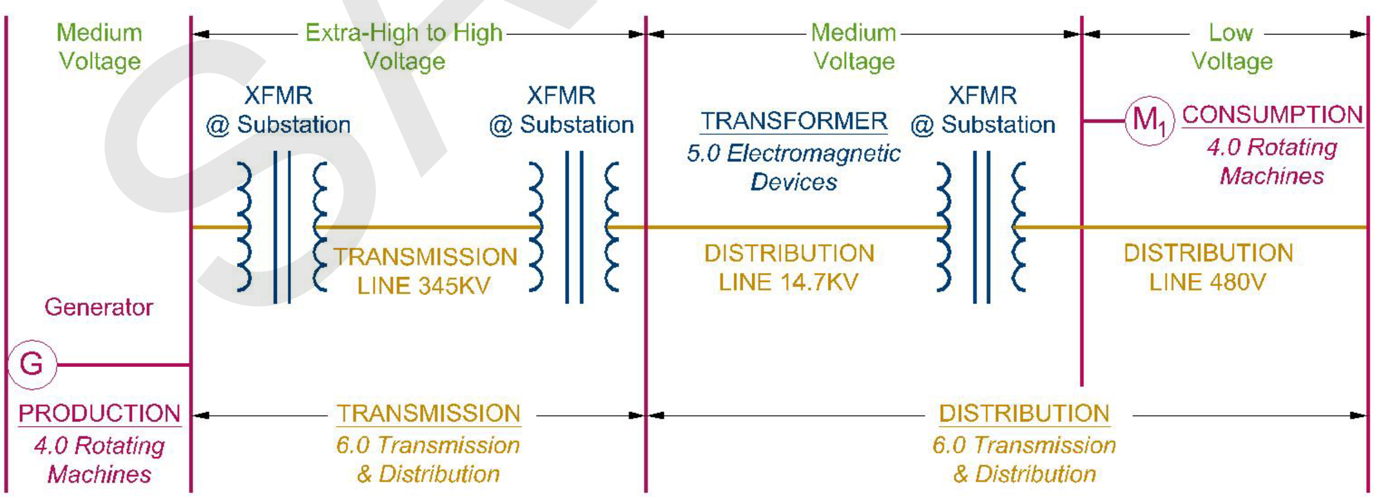
1.0 INTRODUCTION

The section, Transmission & Distribution, accounts for approximately 10-15 questions on the Power Engineering, Electrical PE exam.

Transmission covers the extra-high (>230 kV) and high (115 kV to 230 kV) voltage lines that transport electricity from the electric power plants (generators) to the substations. These lines can travel miles and miles between substations and are typically under the jurisdiction of the electric utility. These transmission lines are also governed by the NES (under *Section 11.0 Codes and Standards*). The distribution system consists of the medium (69 kV to 2.4kV) and low voltage (600V and less) lines that transmit electricity between substations and also transmit electricity to consumers. These consumers can be residential, commercial voltages at 480V and below. But these consumers can also be industrial at medium voltages (69 kV to 2.4kV). Motors and generators are not included under this section, since they are covered under *Rotating Machines*. Transformers are also included in a separate section, but are technically covered under *Transmission and Distribution*. Protection devices are also technically part of *Transmission and Distribution* but are excluded from this section and are included in its own section.



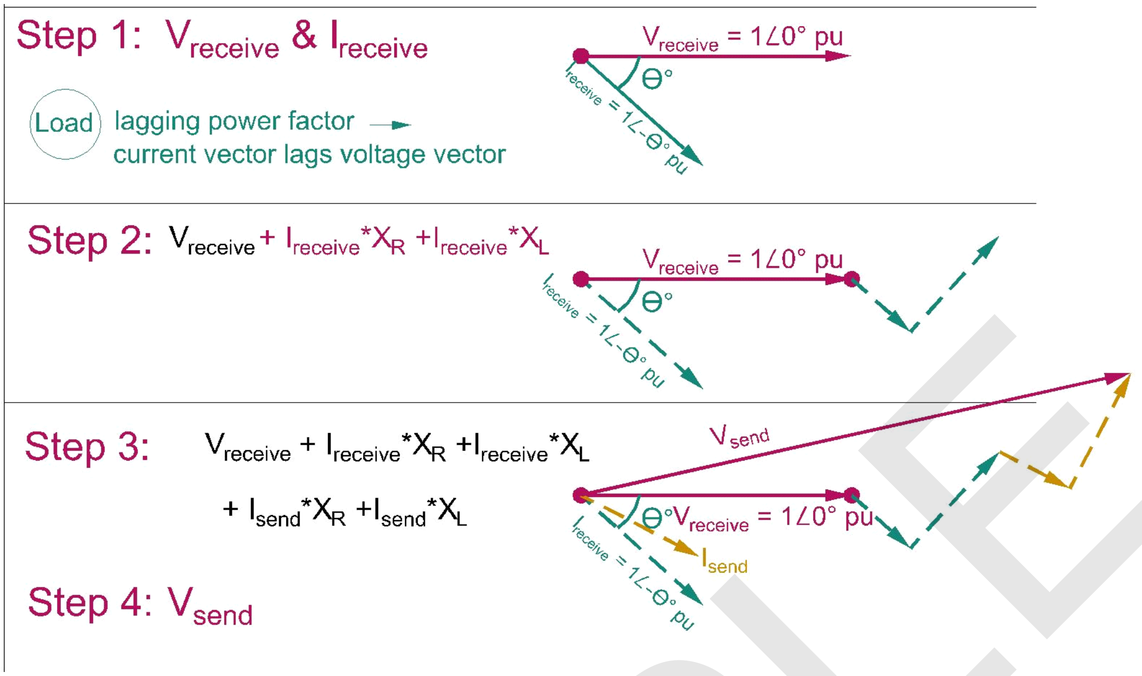


Figure 12: The remaining steps of the medium transmission line are the same as the short transmission line equivalent circuit. The only difference in this explanation is that you start with the receiving end voltage and voltage drops are ADDED onto the receiving voltage phasor, which results in the sending voltage phasor.

2.1.7 Long Transmission Line

The long transmission line is similar to the medium transmission line, except instead of only two capacitance lines or one capacitance line, the long transmission line is assumed to have many capacitance lines. This requires you to integrate throughout the entire length of the transmission line and will require software to complete, or a lot of time. For this reason, the long transmission line is not included in this book.

2.2 VOLTAGE DROP

As you can see in the phasor diagrams for the short transmission line, the voltage drop along a transmission line will be dependent on the impedances AND the power factor of the load. The following equations characterize the voltage drop on a transmission line for the line to line and line to neutral situations.

- Short Transmission Line Voltage Drop Equations

$$V_{drop,line-line} = \left(X_R cos(\theta) + X_L sin(\theta)\right) * I * \sqrt{3}$$

$$V_{drop,line-neutral} = \left(X_R cos(\theta) + X_L sin(\theta)\right) * I$$

$$X_R = resistance\ of\ line\ (\Omega);\ X_L = reactance\ of\ line\ (\Omega);$$

varying frequencies is given an effective value, a.k.a. RMS, but in the figure below the term E is used.

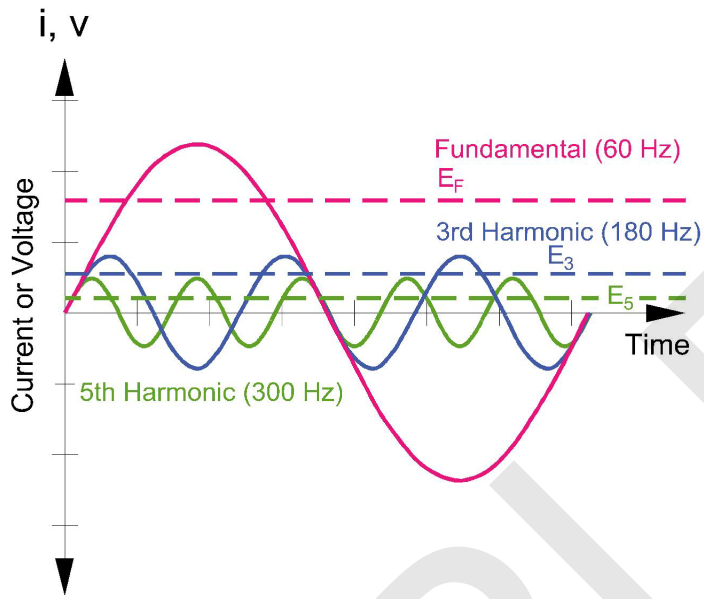


Figure 16: A distorted waveform can be de-constructed into pure sinusoidal waves of varying frequencies.

The process by which the distorted waveform is de-constructed is not relevant to the exam, because it involves complicated Fourier analysis. You should be able to quantify how much harmonics are in a circuit through any one of the following equations.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V^2{}_{n,RMS}}}{V_{RMS}{}_{fundamental}}$$

In the equation above, you must sum up the square of the root mean square values of all nth frequencies. Then you take the square root of this sum. This is equal to the root mean square of the waveform without the fundamental frequency.

$$THD = \frac{V_{RMS}{}_{without\ fundamental}}{V_{RMS}{}_{fundamental}}$$

Next you divide these two numbers to get the total harmonic distortion, which can be multiplied by 100 in order to get the THD in percentage.

The issue with harmonics is that these values will create unbalanced waveforms, which will cause more current to flow through the neutral which will increase the heating in all circuits. The amount that will flow in the neutral can be found through the positive, negative and zero sequences. These sequences correspond to the nth order of harmonics as shown in the following table. You will see that the triplen harmonics (multiples of 3) correspond to the zero

3.2 TRANSFORMER CONNECTIONS

The various transformer connections like delta-wye and wye-wye are covered in *Section 5.0 Electromagnetic Devices*. But now that you know about positive, negative and zero sequence components, you will be able to see how the various transformer connections behave during fault conditions, specifically fault conditions that generate zero sequence currents.

In a three phase or phase to phase fault, then the currents will be balanced and there will be no zero sequence currents. When a phase to ground or double phase to ground fault occurs, zero sequence currents will occur. These zero sequence currents will travel along the phase or phases and then back on the neutral. If a neutral does not exist, then there will be no path for these zero sequences to travel, unless the transformer connection has a ground or a path for the zero sequence to recirculate.

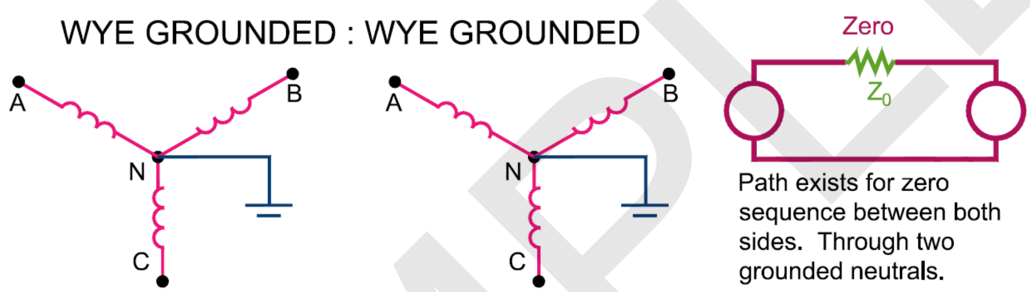


Figure 33: In a wye-wye, both sides grounded, there is a path for the zero sequence currents to flow from on both sides of the transformer. This allows the transformer to transform these zero sequence currents from the secondary line side of the transformer to the primary line side.

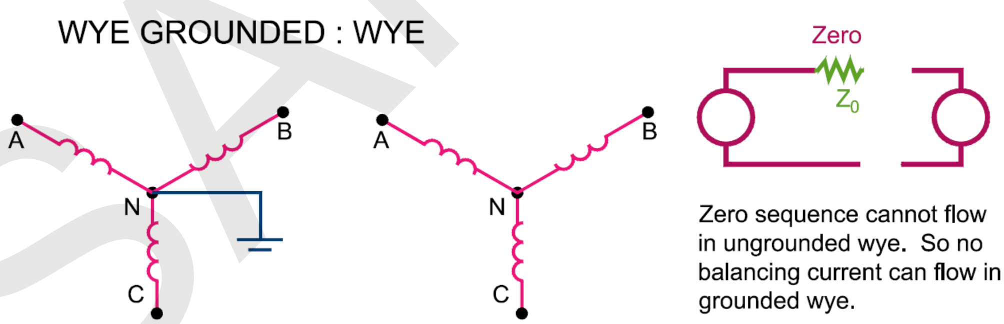


Figure 34: In this arrangement, the zero sequence currents can circulate on the primary side of the transformer, if the fault were to occur on the primary side of the transformer. However, if the fault were to occur on the secondary side, the zero sequence currents would be unable to flow. Thus the zero sequence currents would be unable to be transformed from the secondary line side of the transformer to the primary line side of the transformer.

6.4 Power Flow During Fault Condition with No Load During Fault

This power flow diagram can be used for problems with no load during a fault.

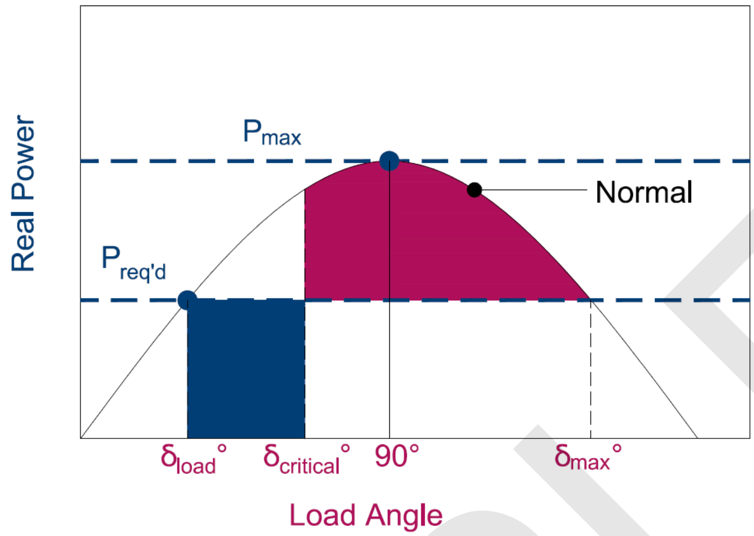


Figure 55: In this diagram, the critical angle must be selected for a given power load, such that the blue area is equal to the red area. The system is stable if the angle is less than the critical angle, meaning that the blue area is less than the red area.

The previous scenario will most likely take too long to test on the PE exam, so this is the most likely scenario that can be tested in the power system stability topic. You can solve for the critical angle, given the other variables. There are many other variations of problems that can be asked with this one graph alone.

$$\cos(\delta_C) = \frac{P_{required}(\pi - 2 * \delta_{load})}{P_{max}} - \cos(\delta_{load})$$

Please be sure to use radians when using the equation.

6.5 Swing Equation for Synchronous Motor – Torque

The torque swing equation can be used to show the relationship between the net accelerating torque and the actual acceleration of the motor's rotor. If the electrical torque provided to the motor is greater than the mechanical torque provided by the motor, then there is a net accelerating torque, which will cause the rotational speed of the rotor to increase.

$$J \frac{d^2\theta_m}{dt^2} = T_a = T_e - T_m$$

$J = polar\ moment\ of\ inertia\ (kg - m^2);\ \theta_m = angular\ displacement\ of\ rotor\ mass\ (radians)$

7.7 PROBLEM 7 – PARALLEL GENERATORS

A 3-phase generator is connected to a very large power distribution system. It is assumed the generator is connected to an infinite bus. The infinite bus is operating at a voltage of 13.2 KV∠0°. The generator is operating at a voltage of 13.0 KV∠0° and 200 A. The internal reactance is X_a and the internal resistance of the generator is negligible. What is the power provided by the generator?

(a) $2{,}680\angle -90° KVA$

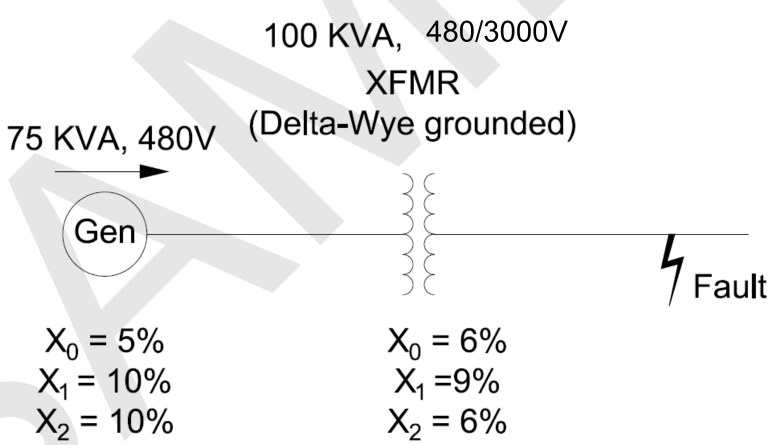
(b) $4{,}503\angle -90° KVA$

(c) $4{,}503\angle +90° KVA$

(d) $2{,}640\angle -90° KVA$

7.8 PROBLEM 8 – FAULT CURRENT ANALYSIS

A three phase bolted fault occurs at the location in the diagram below. What is the short circuit current?



(a) 5 A

(b) 21 A

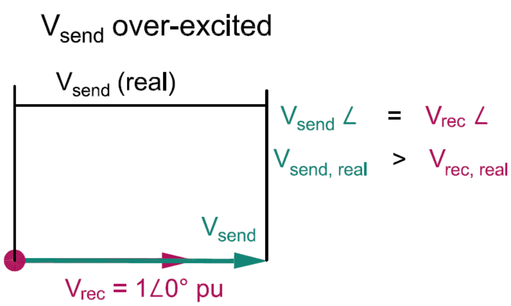
(c) 48 A

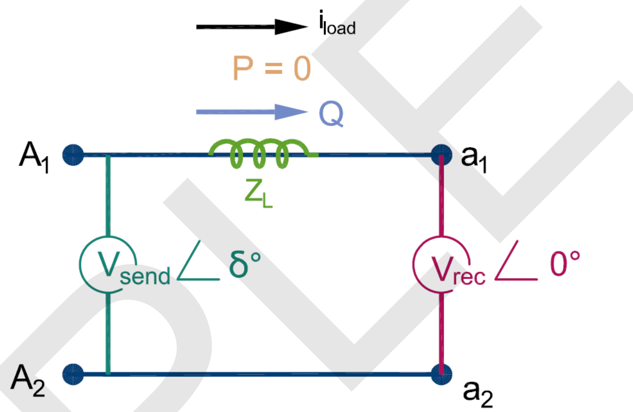
(d) 86 A

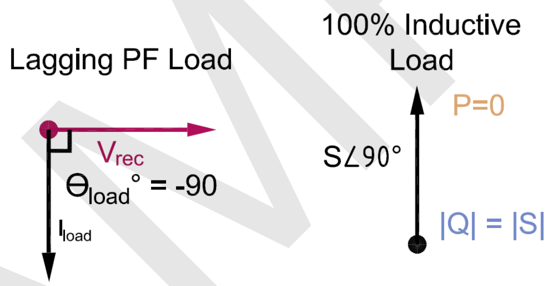
A 3-phase generator is connected to a very large power distribution system. It is assumed the generator is connected to an infinite bus. The infinite bus is operating at a voltage of 13.2 KV∠0°. The generator is operating at a voltage of 13.4 KV∠0° and 200 A. The internal reactance is X_a and the internal resistance of the generator is negligible. What is the power produced by the generator?

$$S = I^{*} x\, V x\, \sqrt{3}$$

The difficulty is finding the angle of the current. Luckily, you know from this section that the angle should be -90 degrees.







$$S = 200A\angle 90° * 13.4kV\angle 0° * \sqrt{3}$$

$$S = 4{,}642\angle 90° KVA$$

The correct answer is most nearly, (c) $4{,}642\angle 90° KVA$

8.7 SOLUTION 7 – PARALLEL GENERATORS

A 3-phase generator is connected to a very large power distribution system. It is assumed the generator is connected to an infinite bus. The infinite bus is operating at a voltage of 13.2 KV∠0°. The generator is operating at a voltage of 13.0 KV∠0° and 200 A. The internal reactance is Xa and the internal resistance of the generator is negligible. What is the power provided by the generator?

7 – Protection

National Electrical Code | National Electrical Safety Code | Standard for Electrical Safety in the Workplace: Shock and Burns | Hazardous area classification

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Section 7.0 – Protection

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1.0 INTRODUCTION

Protection accounts for approximately 11-17 questions on the Power Electrical PE exam.

A protection system in power systems is designed to monitor the power system through voltage, current, phase, power factor and many other measurement devices. These devices are discussed further in the next section, *Measurement and Instrumentation*. This section, *Protection*, focuses on the protective devices that receive the signals from the measurement devices. These protective devices ensure safe and nearly continuous operation of the electrical power supply.

The topic of Protection is vast and some engineers may spend their entire careers as a Protection Engineer for a utility and may never learn all the intricacies of various protection schemes. However, the exam will not test this level of detail and should only cover the main concepts and skills in the topic of Protection. These topics include basic knowledge of the protective devices available, overcurrent protection calculations, protective relaying devices, relay and device coordination and the most common protection schemes for busbars, transformers, transmission lines, motors and generators.

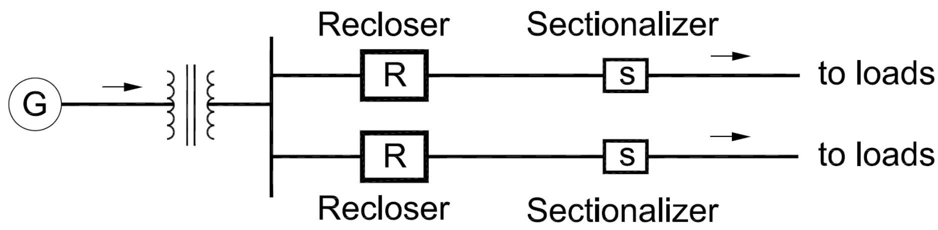


Figure 2: This figure shows two circuits each with a re-closer and a sectionalizer.

If the top re-closer has operated 5 times in the past 5 minutes, then the sectionalizer will switch open and will stop the current from flowing to the loads. The bottom re-closer has only operated 2 times in the past 5 minutes, so its corresponding sectionalizer remains closed.

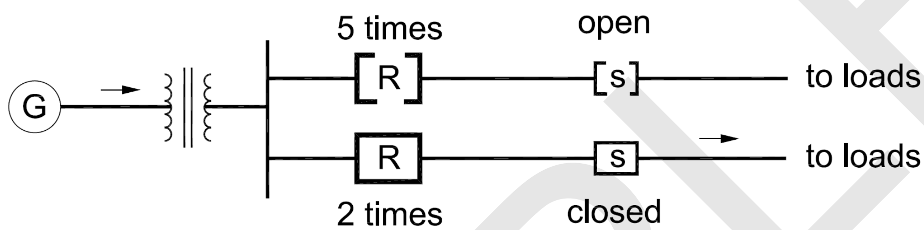


Figure 3: The top re-closer has operated too many times, so when the re-closer has broken the circuit, the corresponding sectionalizer will open. When the re-closer closes the circuit again, the sectionalizer will have already opened the circuit, so no current will flow to the loads in that circuit.

A re-closer must be robust in order to stop a large amount of current, but the sectionalizer only operates when there is no current flowing. The sectionalizer does not need to be robust.

3.0 Overcurrent Protection

In order to protect electrical equipment and to limit the damage of short circuit current, overcurrent protection devices (OCPD) are installed to break the circuit and stop the flow of the current. As an electrical engineer in the power field, you will most likely be required to size an OCPD. These devices must be sized to meet (1) the rated current, (2) the rated voltage and (3) the interrupting current.

- (1) Voltage Rating: The voltage rating is the rated voltage at the location of the overcurrent protection device. If a bus is operating at 240 V then the OCPD must be at least equal to or greater than 240 V.
- (2) Current Rating: The current rating must be less than the rating of the conductor that connects the OCPD. However, conductors are usually rated for very high amperes when compared to the OCPD. In order to get the current rating of the OCPD you should check the NEC section. An OCPD usually has a current rating of 125% of the continuous load current on the conductor.

$$MVA_{SC,total} = 12.5 + 7.53 = 20.03\ MVA$$

Finally, use the voltage at the fault location to find the short circuit current.

$$I_{sc} = \frac{20.03 * 1000\ kVA}{\sqrt{3} * 13.8\ kV} = 837\ A$$

3.2.2 Example 2 – Fault at Transmission Line

In this example, the fault current is found at the end of the transmission line. This is shown as fault location 3.

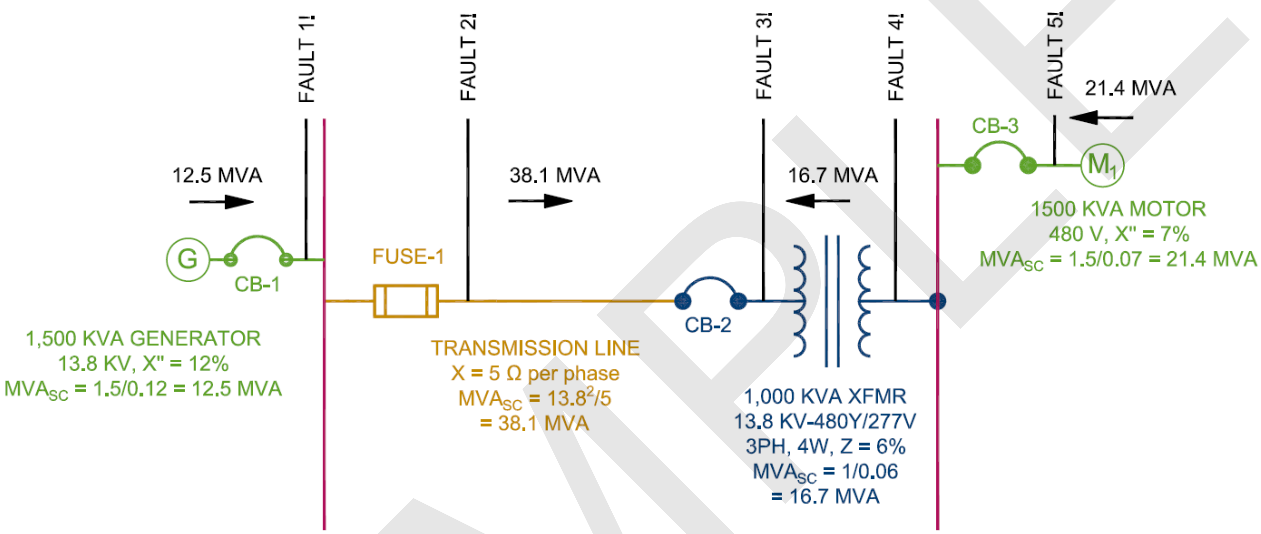


Figure 7: Next, find the MVA short circuit at location 3. Remember that the motor is acting as a generator in this problem. If the motor does not act as a generator, then only the generator and transmission short circuit MVA's will apply.

$$MVA_{SC,upstream} = \left(\frac{1}{12.5} + \frac{1}{38.1}\right)^{-1} = 9.41\ MVA\,;$$

$$MVA_{SC,downstream} = \left(\frac{1}{16.7} + \frac{1}{21.4}\right)^{-1} = 9.38 MVA$$

Next add the MVA short circuit upstream and downstream values in parallel.

$$MVA_{SC,total} = 9.41 + 9.38 = 18.79\ MVA$$

Finally, use the voltage at the fault location to find the short circuit current.

$$I_{sc,location\ 3} = \frac{18.79 * 1000\ kVA}{\sqrt{3} * 13.8\ kV} = 786\ A$$

In the previous figure, a CT-2 measures current through a conductor with a ratio of 1000:1. The current transformer communicates the value to the relay and when the value is over 3A, then the relay trips the circuit breaker. A value of 3A in the relay circuit corresponds to a value of 3000A in the conductor.

4.1.2 Overvoltage/Undervoltage Relays

In an overvoltage or undervoltage relay, a potential (voltage) transformer measures the voltage at a certain spot at a conductor. A relay will take this value and will open the circuit breaker if the voltage is below or above a pre-determined threshold.

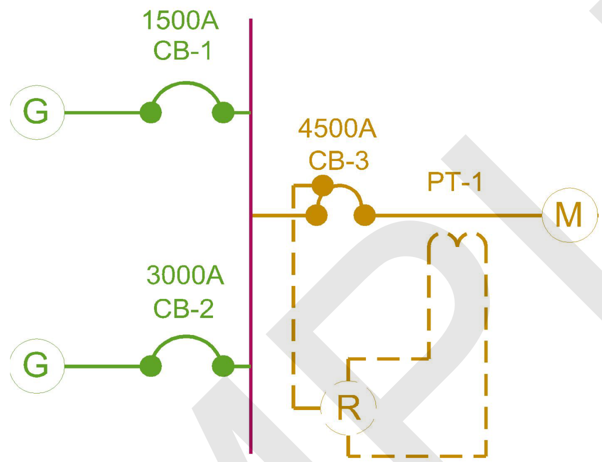


Figure 11: Overvoltage/Undervoltage relay

4.1.3 Directional Relays

A directional relay is used on distribution and transmission lines to distinguish the direction of the fault. There may be multiple overcurrent protection devices in a transmission distribution system. If a fault were to occur, then all of them could potentially trip. By determining the direction of the fault current, the protection devices will know which devices the fault falls in between and the appropriate overcurrent protection devices can be tripped to isolate the fault.

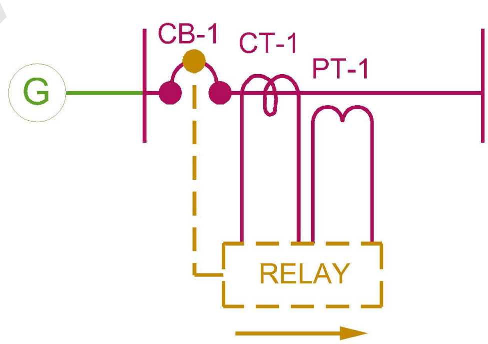


Figure 12: A directional relay is often used to protect a transmission line.

5.5 Definite Time Overcurrent Protection

The next type of relay is the definite time overcurrent protection relay. In this relay the current must reach a certain value but it must maintain that amperage for a certain number of seconds. This type of relay can be used as a backup to the previous relay. If the first relay didn't trip instantaneously, then this relay could be activated after current is maintained for four seconds in the graph below.

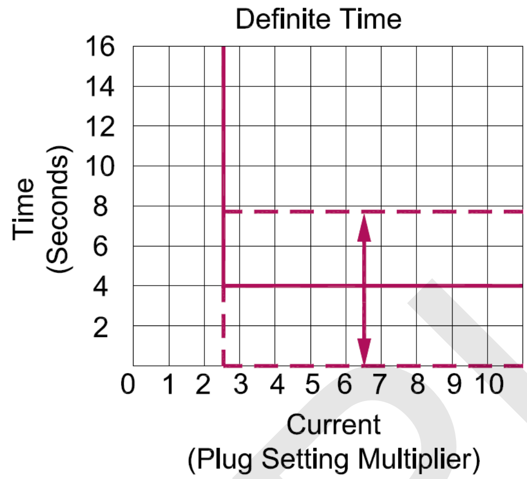


Figure 23: This figure shows a definite time relay that is set at 4 seconds and a PSM of 2.5.

The time can also be adjusted up and down, so this relay can be adjusted to an instantaneous overcurrent protection relay. Historically, the time value was adjusted via a dial, so the time value is often called a time dial setting.

5.6 Inverse Time Overcurrent Protection (51)

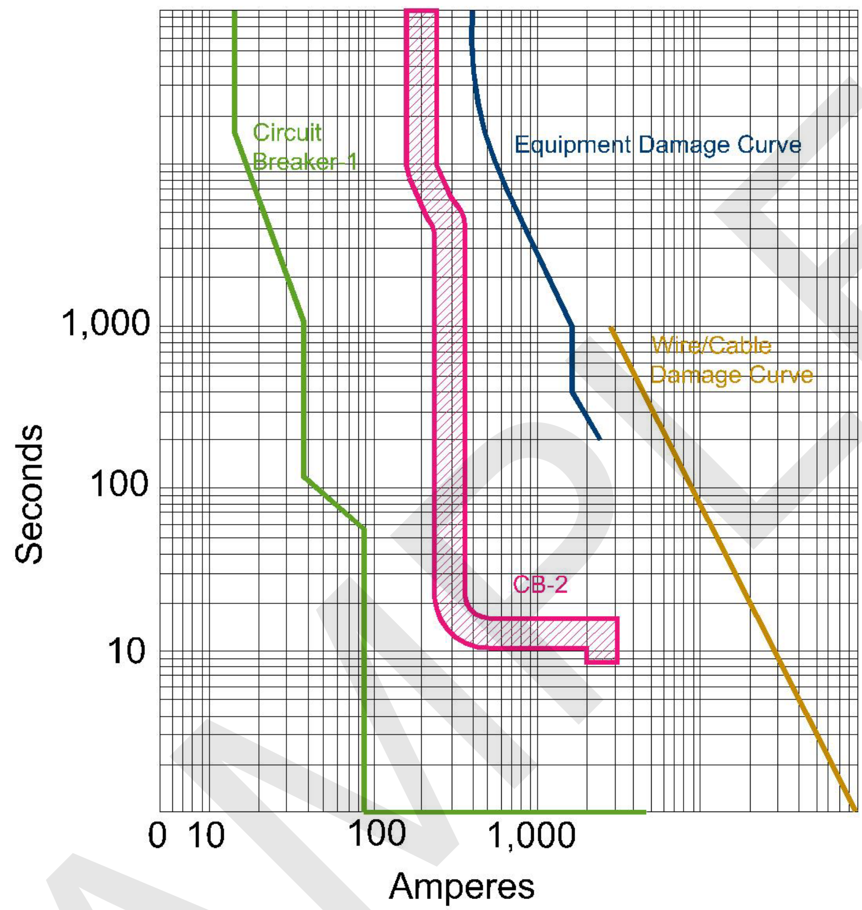
An inverse time overcurrent protection relay has a curve on the time current coordination graph. It is downward sloping, thus at higher currents, the time to trip is much smaller than it is at lower currents. The degree of inversion of this curve can be adjusted or different types of circuit breakers can be selected with varying degrees of inversion. The common types are moderately inverse, inverse, very inverse and extremely inverse. The difference in time to trip between smaller and larger currents is much greater for the extremely inverse curve. For the moderately inverse curves, the difference in time is much smaller.

An inverse time relay follows the ANSI device number 51. This relay trips when the alternating current exceeds a pre-determined value, which is the same as the previous relay 50. Except, the operating time is inversely related to the magnitude of the current.

The following graphs show the inverse relationship between time and current.

6.3 PROBLEM 3 – TCC

A short circuit calculation indicates that a phase to phase fault will cause a short circuit current of 500 A. When will circuit breaker-1 trip, if it has the following characteristics shown in the below graph?



The answer is most nearly?

(a) Instantaneous

(b) 1 second

(c) 10 seconds

(d) 100 seconds

7.15 Solution 15 – Protective Relays

One of the best ways to solve this problem is to first graph the mho circle, line impedance and the load impedance on an X/R graph.

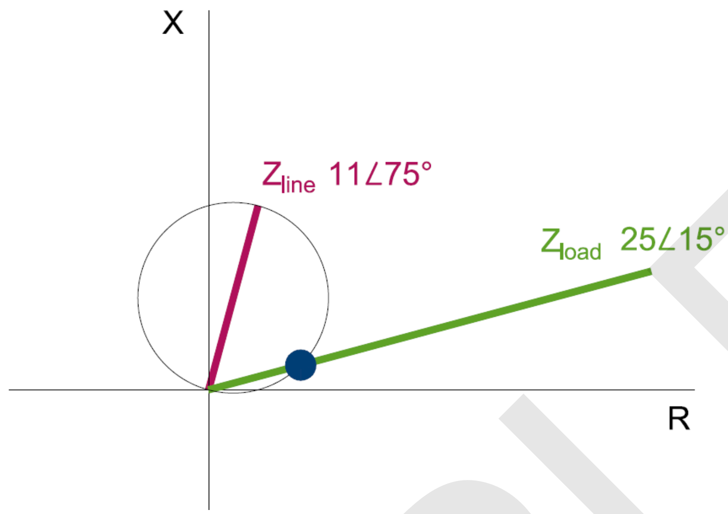


Figure 28: This figure was graphed by first drawing the line impedance line at 110% of the line impedance. This value is equal to 11 angle 75 degrees. This line serves as the diameter of the mho circle. Next, you can draw the circle from the midpoint of the mho circle's diameter. Next, draw the load impedance line as 25 angle 15 degrees. The intersection of the load impedance line and the mho circle is the answer to this problem.

You will need some geometry to find out that the angle between the red and green line is 60 degrees and that a right triangle can be formed with the diameter of the circle and the lines connecting the ends of that specific diameter.

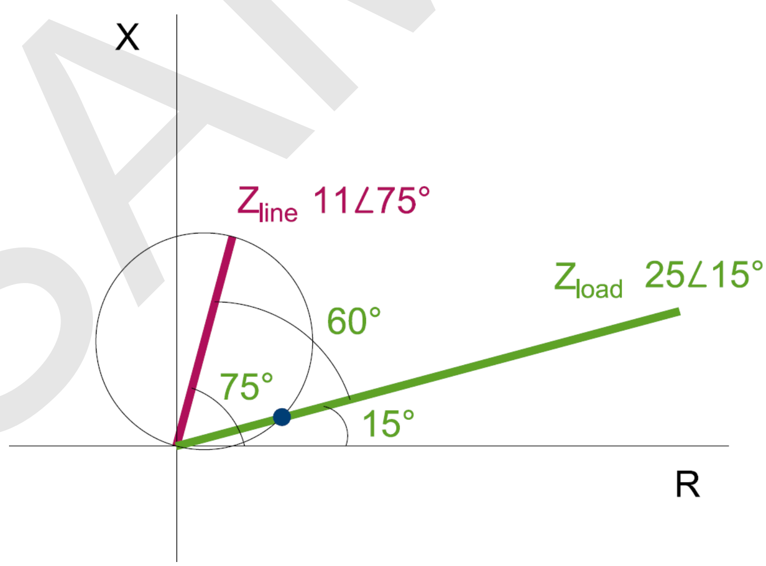


Figure 29: This shows how the angle between the two lines is found.

8 – Measurement & Instrumentation

Instrument transformers | Insulation testing | Ground resistance testing

Section 8.0 – Measurement & Instrumentation

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1.0 INTRODUCTION

The section, Measurement & Instrumentation, accounts for approximately 4-6 questions on the Power Engineering, Electrical PE exam.

Measurement and Instrumentation is focused on the equipment and the use of the equipment to measure current, voltage, resistance, power and power factor. This topic is a good example of how the exam focuses on the application of electrical concepts rather than on theory. In this

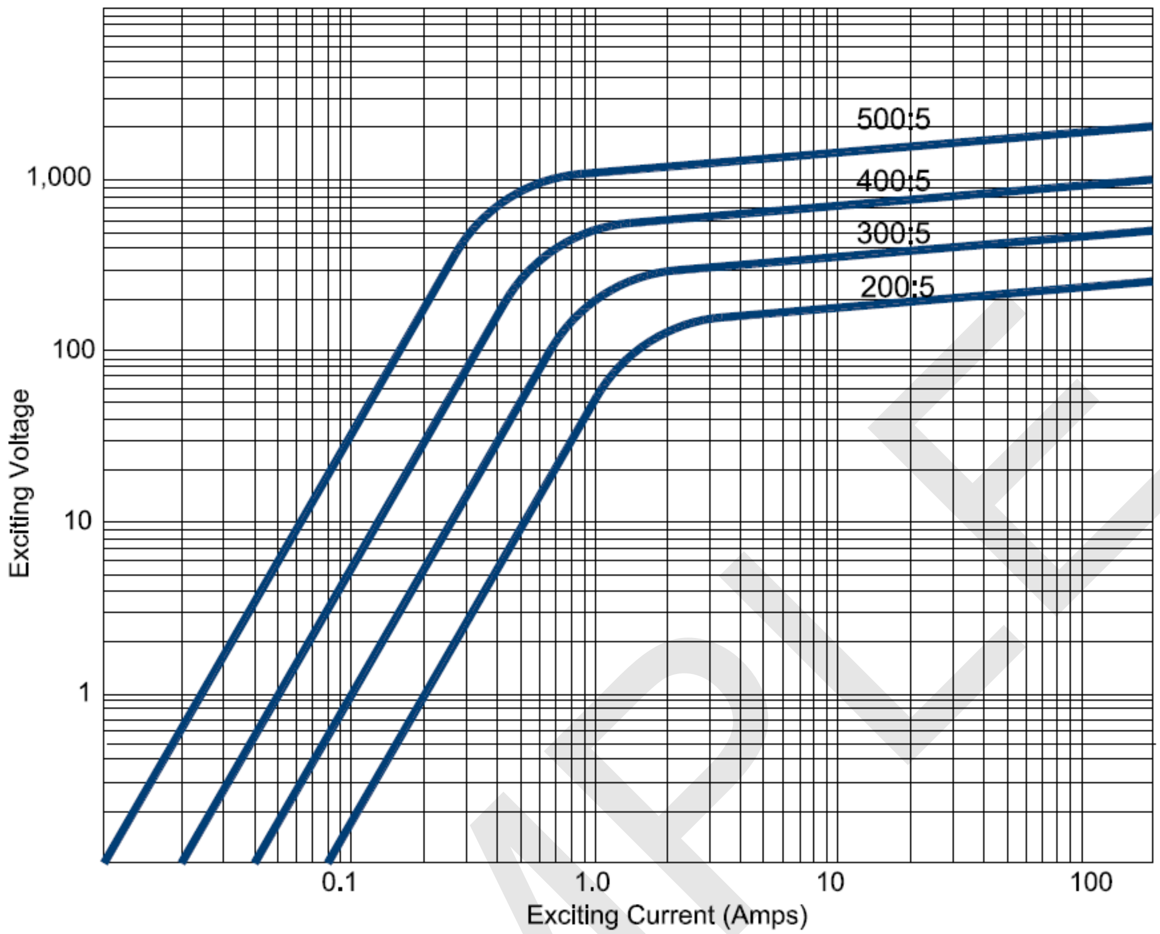


Figure 4: This figure shows the relationship between the exciting voltage and exciting current for various CT ratios.

As an example, assume a 500:5 CT with a current of 500 A and a burden of 6.12 ohms. The corresponding excitation voltage is 30 V.

$$I_{excitation} = 0.1\ A\ (from\ figure\ above); I_s = \frac{30\ V}{6.12\ \Omega} = 4.9\ A$$

$$I_{total} = 4.9 + 0.1 = 5\ A$$

Remember that the primary current causes the excitation voltage, which will then cause the secondary current. You want to make sure that the primary current is only causing secondary current.

Now, let's see if the exciting voltage is increased to 1,100 V. The excitation current can be found from the graph and the secondary current can be found from Ohm's law.

$$I_{excitation} = 100\ A\ (from\ figure\ above); I_s = \frac{1{,}100\ V}{6.12\ \Omega} = 180\ A$$

$$I_{total} = 100 + 180 = 280\ A$$

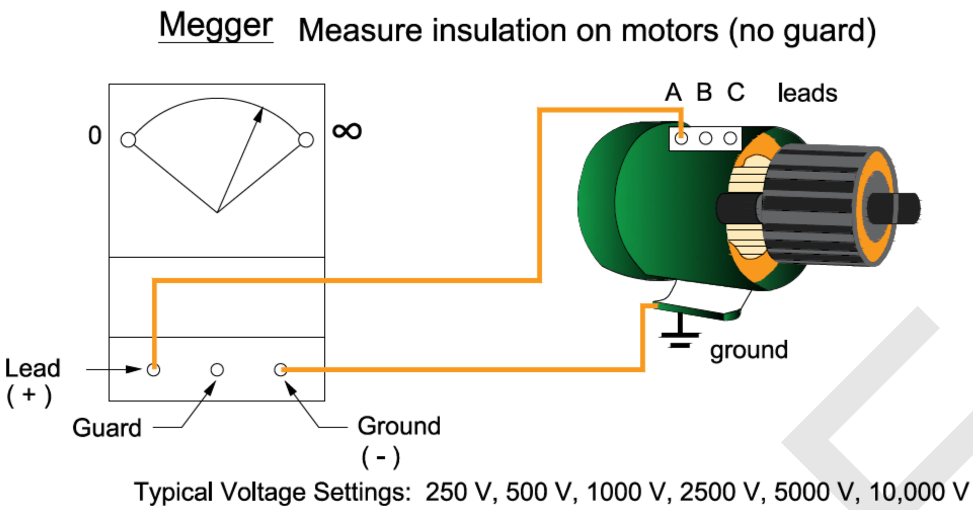


Figure 16: This figure shows the testing of the insulation of conductor A.

Although you are intending on testing the insulation around conductor A, you may also indirectly test the insulation between conductors A & B. Some of the current may travel through the insulation of A & B and to the conductor of B, where a parallel path would be created to the ground. This will change the resistance measured by the megger.

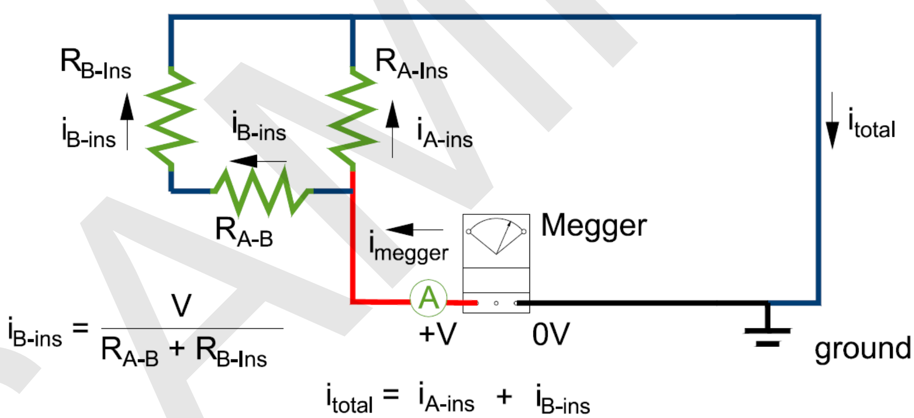


Figure 17: This figure shows the equivalent circuit of the previous figure. Current travels from the 1st lead of the megger and through the insulation of both A & B and then to the ground connection, where it is picked up by the second lead of the megger.

If the resistance between A & B is sufficiently large, then the extra current traveling through the parallel circuit may be minimal. But if the current is large, then you will get lower resistance measurements. If this is the case, then you should use the guard mode.

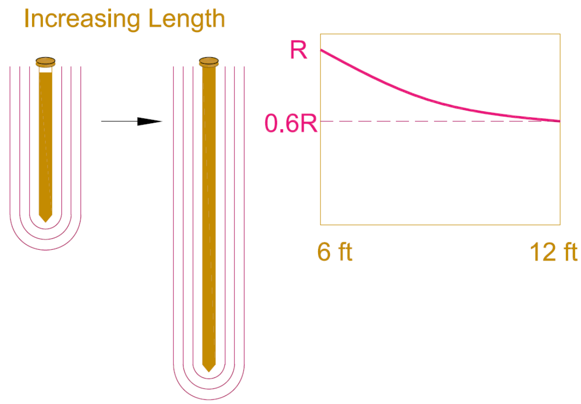


Figure 22: Increasing the length of the ground rod will increase the surface area and thus lower the resistance. As a rule of thumb, doubling the length will decrease the resistance to 60% of its original value.

The complex governing equation is shown below. You shouldn't need this equation, you just need to know that the length has a bigger effect on the resistance than the diameter.

$$R = \frac{\rho(t_{shell\ 1})}{\pi(D + 2t_{shell\ 1})(L + t_{shell\ 1})} + \frac{\rho(t_{shell\ 2})}{\pi(D + 2t_{shell\ 2})(L + t_{shell\ 2})} + \cdots \frac{\rho(t_{shell\ n})}{\pi(D + 2t_{shell\ n})(L + t_{shell\ n})};$$

$$R = \frac{\rho}{2\pi L} \ln\left(\frac{8L}{D} - 1\right)$$

6.2.2 Soil Properties

The type of soil will affect the resistivity of the soil. First, the size of the individual soil particles will affect the resistivity. If the soil has smaller particles, then the resistivity will be less. The more air gaps there are between pieces of soil, the higher the resistivity. Rocky soil will have a higher resistivity and fine gravel will have a lower resistivity. Second, the amount of dissolved salts will increase the conductivity and thus reduce the resistivity.

Type of Soil	Average Soil Resistivity (ohm-m)	Type of Soil	Average Soil Resistivity (ohm-m)
Moist gravel	500	Moist sandy soil	150
Dry gravel	1,000	Dry sandy soil	300

6.2.3 Season and Weather

The season and weather will also affect the ground resistivity. As moisture increases, the conductivity of the soil will increase and thus the resistivity will decrease. If there is significant moisture in the soil, then the temperature will also affect the soil resistivity. As the temperature increases, the water resistivity will decrease and thus cause the soil resistivity to decrease.

7.5 Practice Problem 5 – Ground Resistance Testing

The fall of potential method is used to test the grounding electrode resistance. The testing results in the following values. The test used a test current of 2 A. The current electrode is placed at a distance of 200 feet. What is the effective ground resistance?

Distance (ft.)	Voltage
20	1V
40	6V
60	10V
80	13V
100	15V
120	16V
140	16.5
160	N/A
180	N/A
200	N/A

The answer is most nearly,

(a) 3.5 Ω

(b) 8 Ω

(c) 11 Ω

(d) 16 Ω

8.0 SOLUTIONS

8.1 SOLUTION 1 – CURRENT TRANSFORMER

A current transformer with a current ratio of 100:1A is used to monitor a 480V, 1 PH system with a maximum current of 400A. If the CT is reading 2.5A, then what is the current in the system?

You are given the current ratio which is always in terms of Primary: Secondary.

$$100:1 \rightarrow I_{primary}:I_{secondary}$$

You should convert the ratios to fractions as shown below and solve for the primary current which will equal the current in the system.

$$\frac{100\ A}{1\ A} = \frac{I_{primary}}{2.5\ A}$$

$$I_{primary} = 250\ A$$

The correct answer is most nearly, (c) 250 A.

8.2 SOLUTION 2 – POTENTIAL TRANSFORMER

A potential transformer with a turns ratio of 100:1 is used to monitor the line to line voltage of the secondary feeds of a 480/120V wye-wye transformer. What is the phase voltage of the transformer secondary when the PT reads 1V?

$$\frac{V_{primary}}{V_{secondary}} = \frac{100}{1}$$

Therefore the primary voltage is 100V (line to line). You just need to convert the voltage to phase voltage. Since the transformer has a wye secondary, there will be a root3 conversion.

$$V_{primary,line\ to\ line} = 100V$$

$$V_{primary,phase} = \frac{100V}{\sqrt{3}} = 57.8V$$

(a) 1V

(b) 58V

(c) 100V

(d) 120V

9 – Applications

Lightning protection| Surge protection | Reliability | Illumination/lighting and energy efficiency | Demand calculations | Energy management | Engineering economics | Grounding

Section 9.0 – Applications

Table of Contents

Actual Lightning Frequency N_D (Describes the building's possible lightning frequency)	Tolerable Lightning Frequency N_C (Describes the building's resistance and avoidance of lightning)
$N_D = (N_G)(Area)(C_D)(10^{-6})$	$N_C = \frac{1.5\ x\ 10^{-3}}{(C_2)(C_3)(C_4)(C_5)}$

$$If\ N_D > N_C, then\ install\ a\ lightning\ protection\ system.$$

$$If\ N_D < N_C, then\ a\ lightning\ protection\ system\ is\ not\ required.$$

2.3 Lightning Protection Systems

The fundamental principle in the protection of life and property against lightning is to provide a means by which a lightning discharge can enter or leave the earth without resulting damage or loss. A low-impedance path that the discharge current will follow in preference to all alternative high-impedance paths offered by building materials such as wood, brick, tile, stone, or concrete should be offered. When lightning follows the higher impedance paths, damage can be caused by the heat and mechanical forces generated during the passage of the discharge. Most metals, being good electrical conductors, are virtually unaffected by either the heat or the mechanical forces if they are of sufficient size to carry the current that can be expected. The metallic path should be continuous from the grounding electrode to the strike termination device. Care should be exercised in the selection of metal conductors to ensure the integrity of the lightning conductor for an extended period. A nonferrous metal such as copper or aluminum will provide, in most atmospheres, a lasting conductor free of the effects of rust or corrosion.

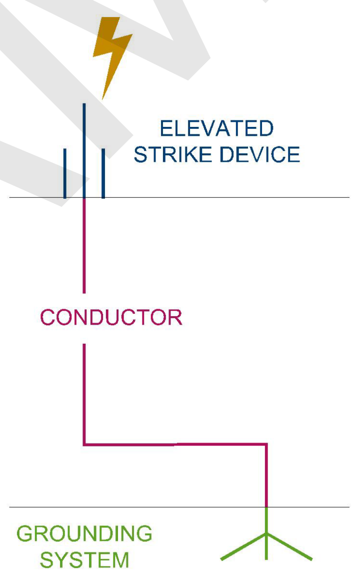


Figure 2: An overall view of a lightning protection system

Reflectance values are provided in the IES and below are a sample of some of the most common room surfaces. Reflectance values are provided in percentages, which indicate how much of the light that hits the surface is reflected and the inverse of these values represents how much of that same light is absorbed.

Roof Surface	**Reflectance Value**	**Surface**	**Reflectance Value**
White ACT	70% – 80%	Reflective Aluminum	85% – 95%
Carpet	10% – 30%	White Walls	40% – 60%

4.2.3 Select Coefficient of Utilization

Now that you have the reflectance values of the room and you have the shape of the room with the cavity ratios, you can now find the coefficient of utilization. This value is found on IES tables and indicates the percentage of the lighting levels that reach the work space.

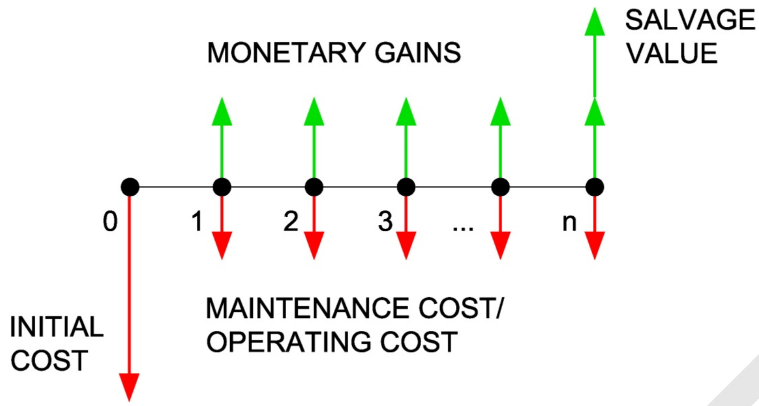
The table below is an example of a coefficient of utilization table for a specific light fixture type. In the table, ρ is the effective reflectance for the ceiling cavity (cc), floor cavity (fc), and wall (w). You can interpolate between the values in this table to match your exact conditions.

% ρ_{cc}	80%				70%			
% ρ_{w}	70%	50%	30%	10%	70%	50%	30%	10%
For 30% ρ_{fc}								
RCR								
1	1.092	1.082	1.075	1.068	1.077	1.070	1.064	1.059
2	1.079	1.066	1.055	1.047	1.068	1.057	1.048	1.039
3	1.070	1.054	1.042	1.033	1.061	1.048	1.037	1.028
4	1.062	1.045	1.033	1.024	1.055	1.040	1.029	1.021
5	1.056	1.038	1.026	1.018	1.050	1.034	1.024	1.015
6	1.052	1.033	1.021	1.014	1.047	1.030	1.020	1.012
7	1.047	1.029	1.018	1.011	1.043	1.026	1.017	1.009
8	1.044	1.026	1.015	1.009	1.040	1.024	1.015	1.007
9	1.040	1.024	1.014	1.007	1.037	1.022	1.014	1.006
10	1.037	1.022	1.012	1.006	1.034	1.020	1.012	1.005

4.2.4 Compute Average Illuminance Level

Once you have the coefficient of utilization, then you apply a light loss factor based on the previously mentioned factors. Finally, take the values and input them into the equation below. Typically, you are given a foot-candle value that you must meet in accordance with IES. You will also have your area, CU and LLF. This will result in the total amount of lumens required for the space. You can use these total lumens and calculate how many lights you need and what lumens per lamp will be required.

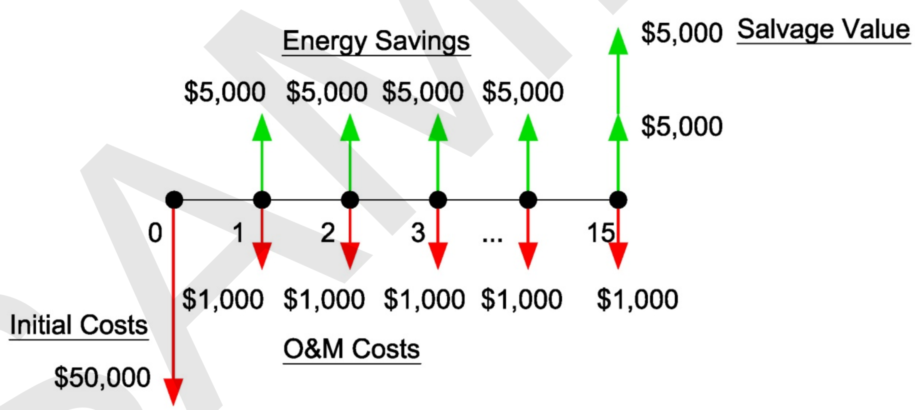
$$Foot-candles = \frac{(\#\ of\ fixtures)(lamps\ per\ fixture)(lumens\ per\ lamp) * CU * LLF}{area\ (ft^2)}$$



As previously stated, the most important thing in engineering economic analysis is to *convert all monetary gains and costs to like terms*, whether it is present value, future value, annual value or rate of return. Each specific conversion will be discussed in the following sections.

Each of the sections will use the same example in order to illustrate the difference in converting between each of the different terms.

Example: A new chiller has an initial cost of \$50,000 and a yearly maintenance cost of \$1,000. At the end of its 15 year lifetime, the chiller will have a salvage value of \$5,000. It is estimated that by installing this new chiller, there will be an energy savings of \$5,000 per year. The interest rate is 4%.



6.4 Convert to Present Value

What is the Present Value (Present Worth) of this chiller?

The first term, initial cost is already in present value.

$$PV_{initial\ cost} = -\$50{,}000$$

8.0 PRACTICE PROBLEMS

8.1 PROBLEM 1 - LIGHTING

A room has dimensions 20' x 20' x 10'. The lights in the room are located 1' below the ceiling. The room is a conference room, which requires 40 FC at a desk height of 3' above the floor. You previously calculated a coefficient of utilization as 0.8 and a ballast factor is 0.95 for the light fixtures to be used. What are the total lumens required in the room by the light fixtures?

(a) 2,000 lumens

(b) 10,000 lumens

(c) 20,000 lumens

(d) 21,050 lumens

8.2 PROBLEM 2 - LIGHTING

A walkway shall be lit by an exterior wall-mounted light. The walkway extends from 0 ft to 5' away from the wall. You must provide a minimum of 10 FC at all points along the walkway. The wall mounted light is located 10' above the walkway. The light cut sheet indicates 1,500 candela at all angles. What are the foot-candle values at 0' from the wall and 5' from the wall?

(a) 8 fc and 10 fc

(b) 12 fc and 15 fc

(c) 12 fc and 60 fc

(d) 60 fc and 60 fc

S

T

U

Z

10 – Codes & Standards

National Electrical Code | National Electrical Safety Code | Standard for Electrical Safety in the Workplace: Shock and Burns | Hazardous area classification

STUDY GUIDE
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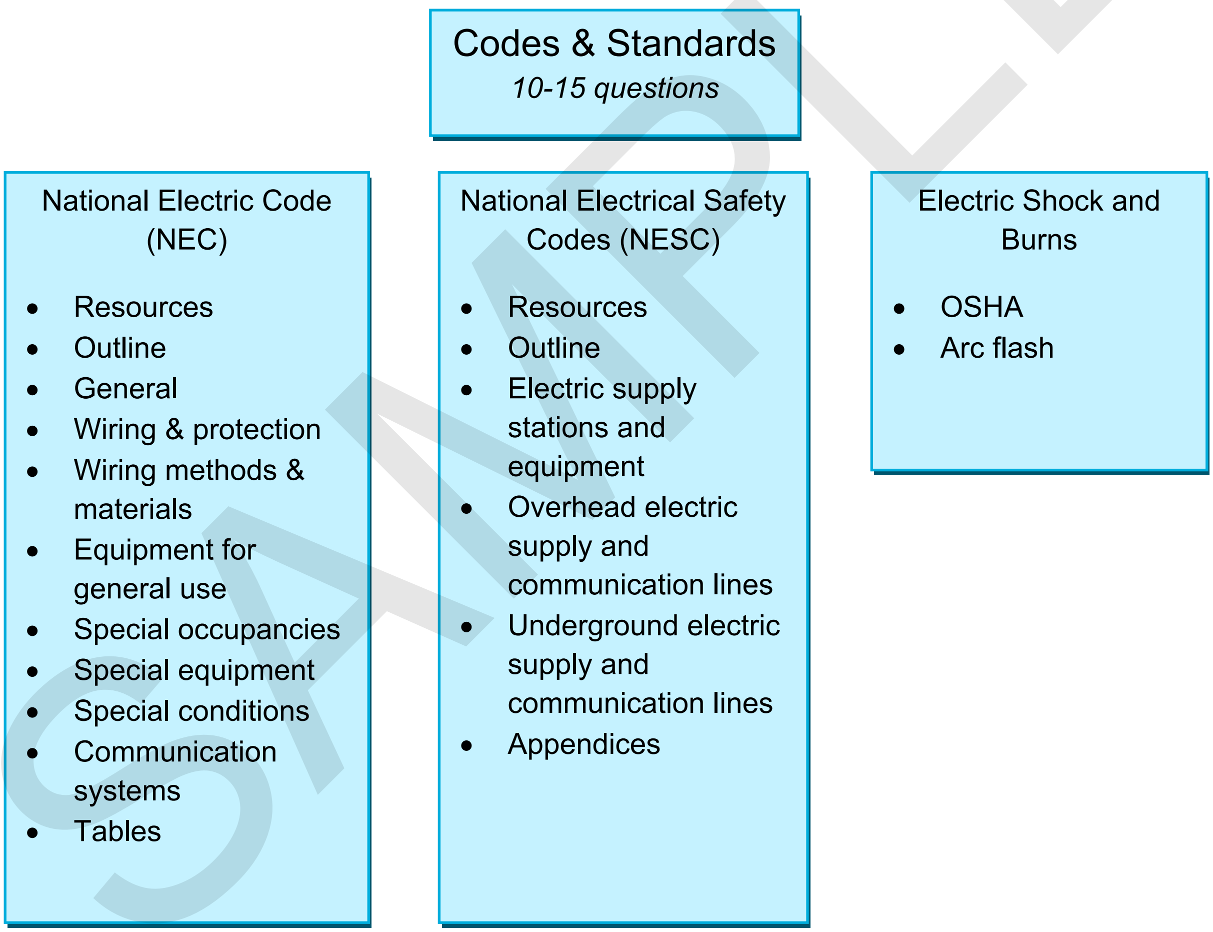
Section 10.0 – Codes & Standards

Table of Contents

1.0 INTRODUCTION

Codes & Standards accounts for approximately 10-15 questions on the Electrical & Computer Power PE exam.

The codes and standards section of the exam is the section where most people do well on the exam. Many of these questions simply test your familiarity with the NEC and NESC. You should be well prepared to go to any section in the book, although some sections of the codes are more used than others. The most common questions are highlighted in this section of the book. Also included in this section is a technique that you can use to quickly navigate to the correct part of the code to answer a question on the exam. This technique involves memorizing the format of the book, such that if you are given a certain type of code question, you will know exactly what section to look at in the book.



2.5.1 Article 430 Motors, Motor Circuits and Controllers

This article shows you how to size all electrical components serving motors. This includes the feeder, conductor, disconnect, circuit breaker, starter and overload device.

Motor Feeder - Short-Circuit and Ground Fault Protection: 430.61 - 430.63

Motor Disconnect: 430.101 – 430.113. The ampere rating of the disconnecting shall not be less than 115 percent of the sum of all currents at the full load condition. Small motors use locked rotor current as 6X the full load current.

Stationary Motors (<1/8 HP)	Use branch circuit OCPD
Stationary Motors (<2 HP)	2X FLC or FLC/0.8 or HP rating of motor
Motors (<1,000 V)	115% of FLC rating of motor
Horsepower Rating	FLC Rating (430.248, 249 or 250) and LRC Rating (430.251A & B)
Ampere Rating	115% of FLC

A disconnect for a motor branch circuit must be capable of interrupting the locked-rotor current of the motor. This disconnecting means it must disconnect both the motor and the controller from all ungrounded supply conductors, NEC Section 430-103.

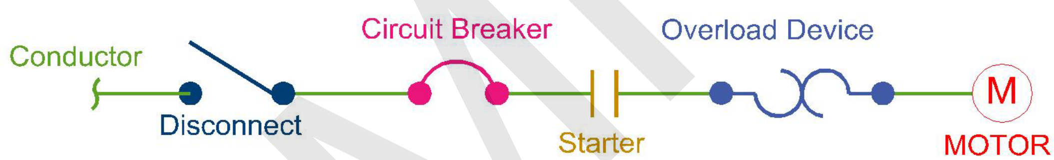


Figure 2: Motor one-line diagram

Motor Branch - Short-Circuit and Ground Fault Protection: These devices are quick reacting devices that are sized based on a percentage of full load current. The values for the percentages are found in Table 430.52. More information on branch circuit short-circuit and ground fault protection can be found in the following sections, 430.51 through 430.58.

Motor Overload Protection: These devices are slow reacting devices that protect motors from overheating due to motor overloads and failure to start. The sections that cover motor overload protection are 430.31 through 430.44. There are two main types of overload protection that are provided, (1) Separate Overload Device and (2) Thermal Protector. The sizing for these devices is described in the tables below based on various scenarios.

Separate Overload Device Sizing	
Motors with service factor 1.15 or greater	125% nameplate full load current rating
Motors with a marked temperature rise 40 C or less	125% nameplate full load current rating
All other motors	115% nameplate full load current rating

• Article 620 - Elevators, Dumbwaiters, Escalators, Moving Walks, Platform Lifts and Stairway Chairlifts	• Article 670 - Industrial Machinery
• Article 625 - Electric Vehicle Charging System	• Article 675 - Electrically Driven or Controlled Irrigation Machines
• Article 626 - Electrified Truck Parking Spaces	• Article 680 - Swimming Pools, Fountains and Similar Installations
• **Article 630 - Electric Welders**	• Article 682 - Natural and Artificially Made Bodies of Water
• Article 640 - Audio Signal Processing, Amplification and Reproduction Equipment	• Article 685 - Integrated Electrical Systems
• Article 645 - Information Technology Equipment	• Article 690 - PV Systems
• Article 646 - Modular Data Centers	• Article 692 - Fuel Cell Systems
• Article 647 - Sensitive Electronic Equipment	• Article 694 - Wind Electric Systems
• Article 650 - Pipe Organs	• **Article 695 - Fire Pumps**

2.8 Chapter 7: Special Conditions

This chapter covers the requirements for the electrical systems under these special conditions. The requirements cover areas, like grounding, fault protections, testing/maintenance, overcurrent protection, listing, controls and sizing/rating.

The special conditions, which are shown below, describe scenarios where additional safety requirements are necessary beyond the normal requirements which are included in Chapters 1, 2, 3 and 4. Please remember that the requirements in these earlier chapters will apply, unless overridden by the requirements in Chapter 7.

The special conditions include the installation of generators and other standby power systems, healthcare systems, fire alarm systems and low voltage systems.

• Article 700 Emergency Systems	• Article 725 Class 1, Class 2 and Class 3 Remote Control, Signaling and Power-Limited Circuits
• Article 701 Legally Required Standby Systems	• Article 727 Instrumentation Tray Cable: Type ITC
• Article 702 Optional Standby Systems	• Article 728 Fire Resistive Cable Systems
• Article 705 Interconnected Electric Power Production Sources	• Article 750 Energy Management Systems
• Article 708 Critical Operations Power Systems	• Article 760 Fire Alarm Systems

4.1 NFPA 70E – Standard for Electrical Safety in the Workplace

By NFPA

The Standard for Electrical Safety in the Workplace includes requirements to prevent accidents from electrical systems in the field. Included in the appendix are the arc flash boundary calculations, used to determine safe distances during an arc flash. There are two safety terms that you should be familiar with for the exam, (1) Electric Shock and (2) Arc Flash.

Electric Shock: Electric shock is also known as electrocution. This occurs when an electric current passes through the body. Electric shock can occur through either direct contact with a conductor or indirect contact (no touching). A human can feel approximately 1 mA (AC) or 5 mA (DC). The minimum amount of current that can seriously injure a person is around 1 amp.

Arc Flash: In an arc flash, electricity is conducted from a high voltage point to a low voltage point, like ground through the air. The energy released in this arc is huge. The temperatures of the arc can exceed tens of thousands of degrees Celsius and can also result in an explosive blast. An arc most commonly occurs when a circuit breaker is opened. The sudden break in electricity will cause high voltage on one side of the circuit and no voltage on the other side, with air in-between. This potential difference causes an arc to occur, which is typically contained within the circuit breaker device.

You may want to purchase the PDF version, so that you can simulate the actual exam conditions.

Amazon Link[1]: NFPA 70E

5.0 Hazardous Area Classifications

Hazardous area classifications are generally defined in the NEC (NFPA 70). Additional detailed recommended practices or requirements for electrical installations in flammable and combustible areas are provided in NFPA 497, 499, and 30B. These three codes are specifically referenced in the NCEES exam specifications and it is recommended that you bring all three to the exam.

5.1 NFPA 497 – Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas

By NFPA

This document provides recommendations, and not code requirements, for hazardous classifications in chemical process areas. It is intended to be used in conjunction with Article 500 of the NEC (NFPA 70E) to assist in identifying more specific hazardous classifications.

6.5 Problem 5: Disconnect Switch

A 20-hp, three-phase, induction motor is operated at 230 V. The motor has a service factor of 1.15 and is a code letter B. What is the minimum size of a separate motor disconnect switch? Assume that there is already a circuit breaker and this is a separate motor disconnect switch.

a) 50 A

b) 54 A

c) 63 A

d) 108 A

6.6 Problem 6: Junction Box

Four #10 conductors enter a junction box. Three conductors are spliced with #12 conductors. The remaining #10 conductor is terminated in the junction box. What is the minimum volume of the junction box?

a) 16.75 in^3

b) 17.75 in^3

c) 18.75 in^3

d) 19.00 in^3

6.11 Problem 11: Motor Conductor

A passenger elevator is served by a continuous rated, 10 HP, 3 PH, 460 V induction motor. The nameplate current is 12 A. What is the minimum rating of the conductor serving this motor?

a) 12.1 A

b) 16.8 A

c) 17.5 A

d) 21.1 A

6.12 Problem 12: Conductor Serving Multiple Motors

A conductor feeds two identical motors, each motor is rated at 10 HP, 3 PH, 460 V induction motor. What is the minimum current rating of the conductor serving these motors?

a) 14 A

b) 17.1 A

c) 28.6 A

d) 31.5 A

The correct answer is most nearly, (d) 4 V.

7.4 SOLUTION 4: OVERLOAD DEVICE

A 1-hp, single-phase motor is operated at 208 V and has a nameplate full load current of 7.1 A. The motor has a service factor of 1.15 and is a code letter B. What is the maximum size separate overload device allowed for this motor?

Separate Overload Device Sizing	
Motors with service factor 1.15 or greater	**125% nameplate full load current rating**
Motors with a marked temperature rise 40 C or less	125% nameplate full load current rating
All other motors	115% nameplate full load current rating

Thermal Protector Sizing	
Motors full load current 9 A or less	170% nameplate full load current rating
Motor full load current from 9.1 to 20 A	156% nameplate full load current rating
Motor full load current greater than 20 A.	140% nameplate full load current rating

Although the answer is in the above table, you should read the code to make yourself familiar with this information.

$$Overload\ Device = 125\% * 7.1\ A = 8.9\ A$$

a) 7.1 A

b) 8.8 A

c) 10.2 A

d) 14.5 A

The correct answer is most nearly, (b) 8.8 A.

7.5 SOLUTION 5: DISCONNECT SWITCH

A 20-hp, three-phase, induction motor is operated at 230 V. The motor has a service factor of 1.15 and is a code letter B. What is the minimum size of a separate motor disconnect switch? Assume that there is already a circuit breaker and this is a separate motor disconnect switch.

11 - Conclusion

11.0 Conclusion

If you have any questions on this book or any other Engineering Pro Guides product, then please contact me at my email below. Also if you are looking for more Power PE products, then please visit the website and purchase the complete set of Power PE products. The website also has a bunch of free information that you can use to facilitate your studying. Finally, each webpage also has a section for you to ask questions on the product and to leave comments, in addition the errata for each product is located on their respective webpages.

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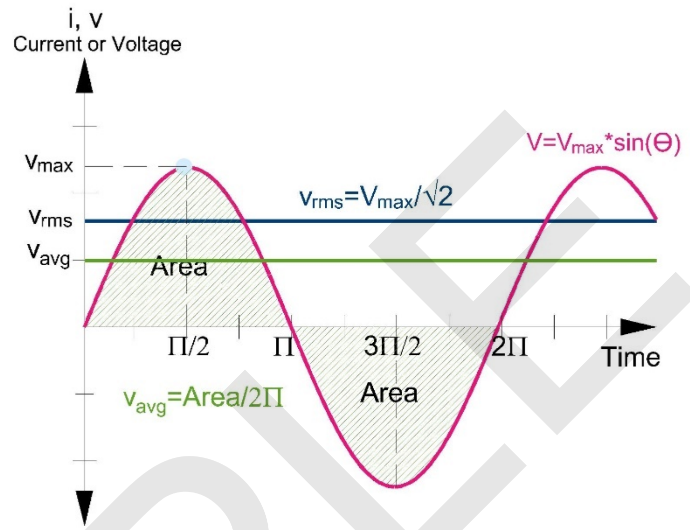
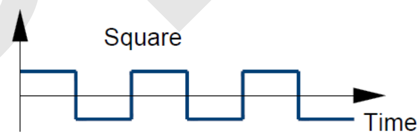
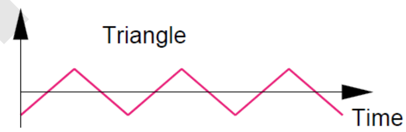
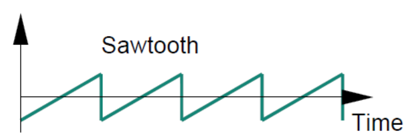
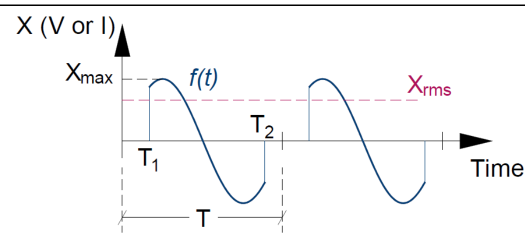
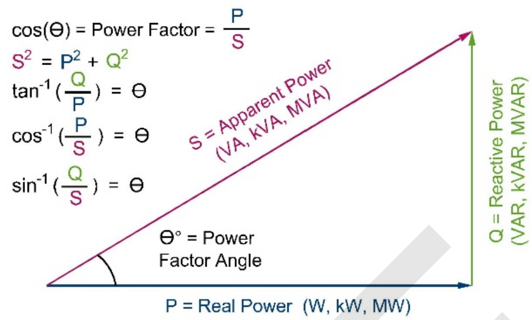
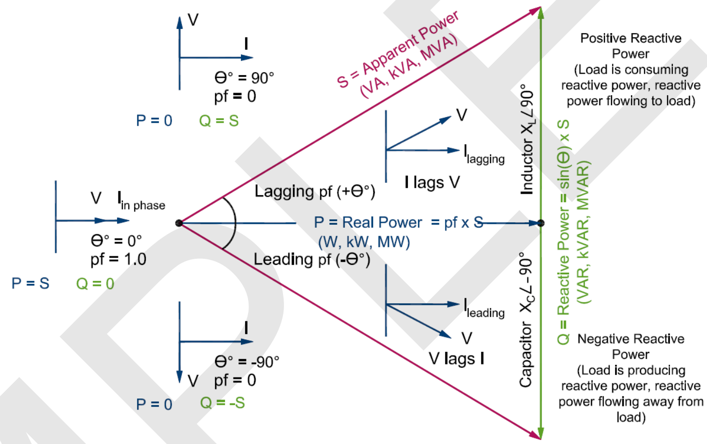
If you have any questions, please email me Justin Kauwale at contact@engproguides.com

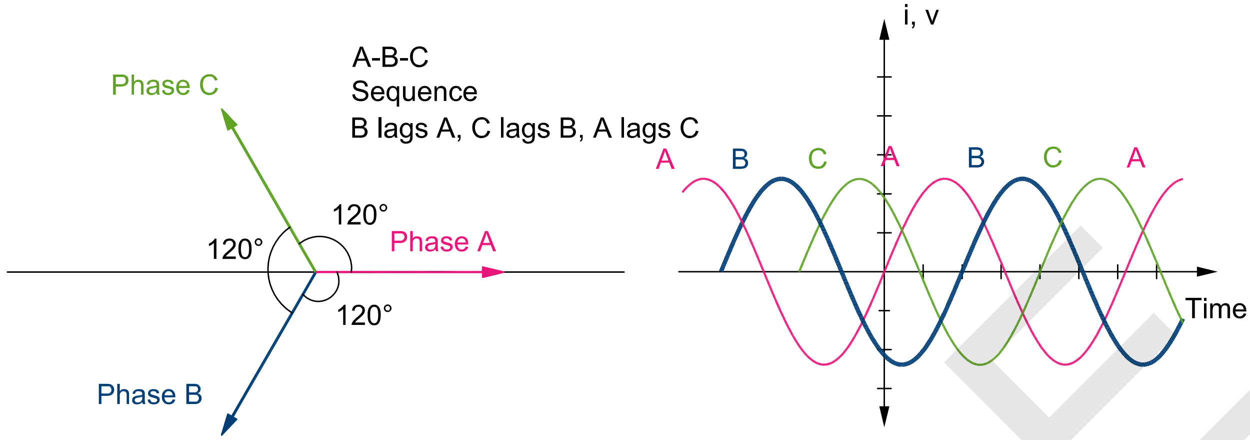
Hi. My name is Justin Kauwale, the creator of Engineering Pro Guides. I will be happy to answer any questions you may have about the PE exam. Good luck on your studying! I hope you pass the exam and I wish you the best in your career. Thank you for your purchase!

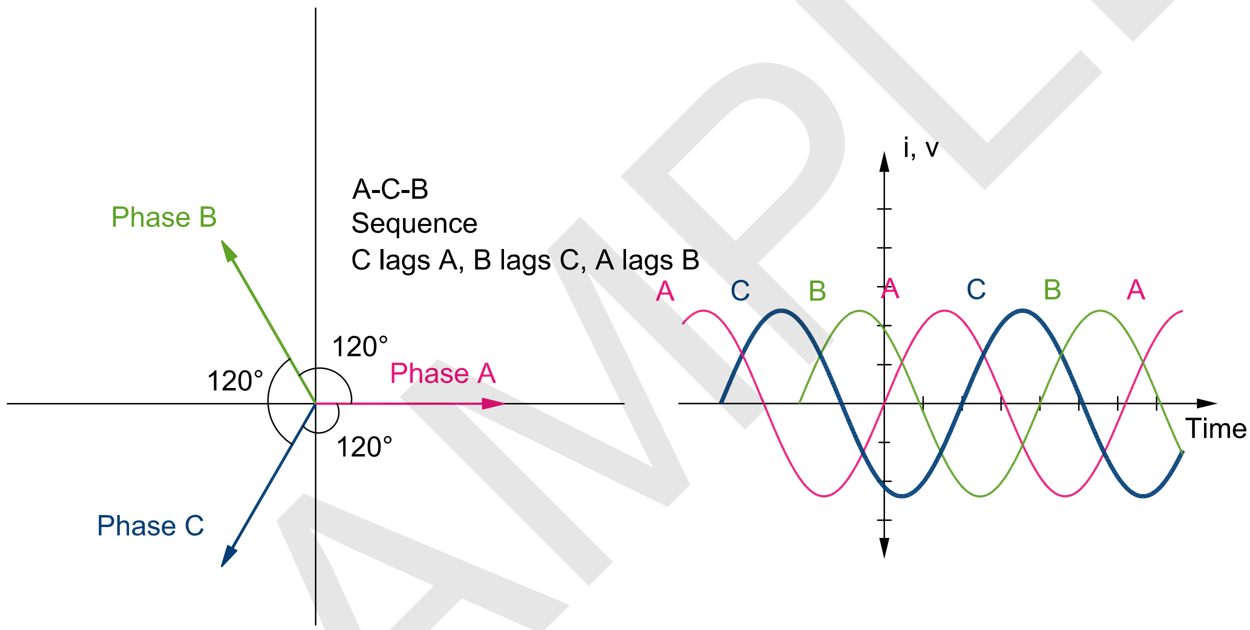
12 – Cheat Sheets

Section 1.0 - Basic/Common Equations

Term	Equation	Description
Waveforms		
Max Voltage	V_{max}	
Root Mean Square Voltage	$V_{rms} = \frac{V_{max}}{\sqrt{2}}$	
Average Voltage	$V_{avg} = \frac{2 * V_{max}}{\pi}$	
Square Wave RMS	$V_{rms} = V_{max}$	
Triangle/Sawtooth Wave RMS	$V_{rms} = \frac{V_{max}}{\sqrt{3}}$	 
Waveform RMS	$X_{rms} = \sqrt{\frac{1}{T}\int_{T_1}^{T_2} f(t)^2 dt}$	

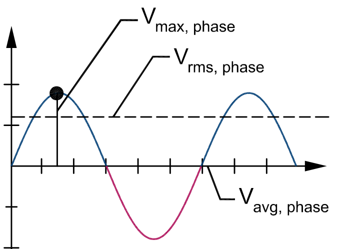
Power, Circuits		
Apparent Power	$S = P + jQ$ $I = \angle\theta;\ I^* = \angle -\theta;$ $S_{1ph} = \frac{V^2}{Z} = I^*V$ $= I^2Z$	
Power Factor	$PF = cos\theta$ $+\theta = lagging$ $-\theta = leading$	
Power Factor Adjustment	$\frac{kVAR_1}{kVAR_2} = \frac{V_1^2}{V_2^2}$	Power factor corrections where Reactive Power (Q) changes and Real Power (P) remains the same
Real Power	$P = S * PF$ $P = S * \cos(\theta)$	Real power represents real results (heat, mechanical work, light, etc.)
Reactive Power	$Q = S * \sin(\theta)$	Reactive power represents power that oscillates back and forth. Produces AC magnetic field that is used by inductive devices (transformers, ballasts, induction motors, etc.)
Voltage	$V = IZ = \frac{S}{I} = \sqrt{SZ}$	
Current	$I = \sqrt{\frac{S}{Z}} = \frac{S}{V} = \frac{V}{R}$ $I_{rms} = \frac{I_{max}}{\sqrt{2}}$	
Impedance	$Z = \frac{V^2}{S} = \frac{S}{I^2} = \frac{V}{I}$ $Z\angle\theta° = R + jX$	
Admittance	$Y = \frac{1}{Z}$	
Resistance [Ω]	$R = \frac{\rho L}{A}$	Where ρ = resistivity [Ω-circ mil/ft], L = length [ft], A = cross sectional area [circular mils]. An inductor is a consumer of


A-B-C
Sequence
B lags A, C lags B, A lags C
Phase C
Phase A
Phase B
120°
120°
120°
i, v
A
B
C
A
B
C
A
Time

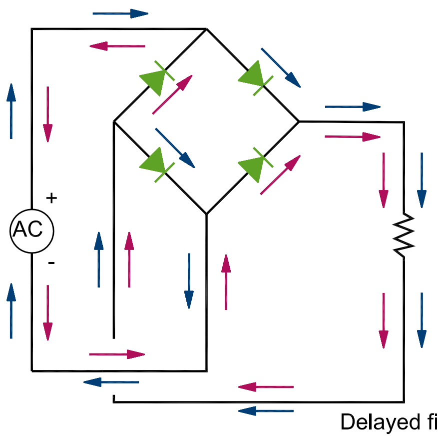

A-C-B
Sequence
C lags A, B lags C, A lags B
Phase B
Phase A
Phase C
120°
120°
120°
i, v
A
C
B
A
C
B
A
Time

Single Phase - Full Wave Rectifier (No capacitor)

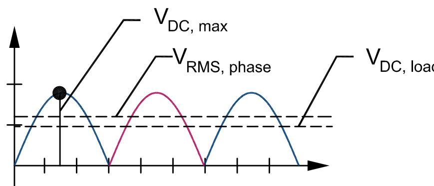
SOURCE



$V_{max, phase} = \sqrt{2} \times V_{RMS, phase}$



DC LOAD



Ripple Factor $r = \sqrt{(V_{rms}/V_{avg})^2 - 1}$

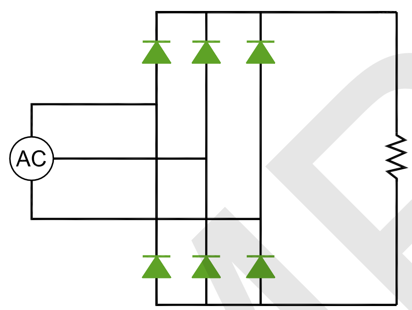
$V_{DC, max} = \sqrt{2} \times V_{RMS, phase}$

$V_{DC, load} = 0.9 \times V_{RMS, phase}$

Delayed firing angle -> $V_{DC, load} = \frac{1}{pi} \times (1+\cos(\delta°)) \times V_{AC, Max}$

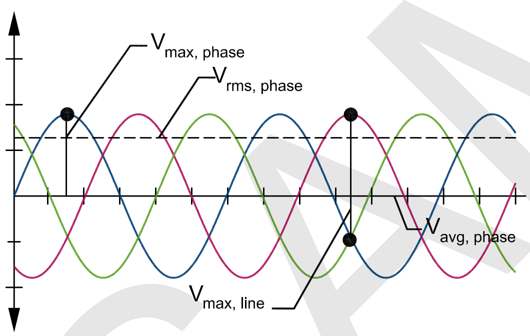
Three Phase - Full Wave Rectifier (No capacitor)

SOURCE

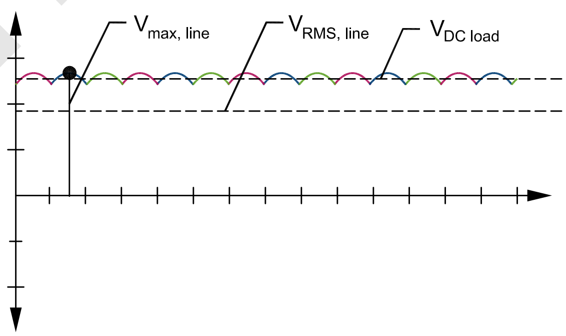


DC LOAD

SOURCE



DC LOAD



$V_{max, phase} = \sqrt{2} \times V_{RMS, phase}$

$V_{max, line} = \sqrt{2} \times V_{RMS, line}$

$V_{line} = \sqrt{3} \times V_{phase}$

$V_{DC, load} = 1.35 \times V_{RMS, line}$

Ripple Factor $r = \sqrt{(V_{rms}/V_{avg})^2 - 1}$

$V_{DC, max} = \sqrt{2} \times V_{RMS, line}$

Delayed firing angle -> $V_{DC load} = 6 \times \frac{1}{2pi} \times (0.5 + \cos(\delta°))V_{AC, MAX}$

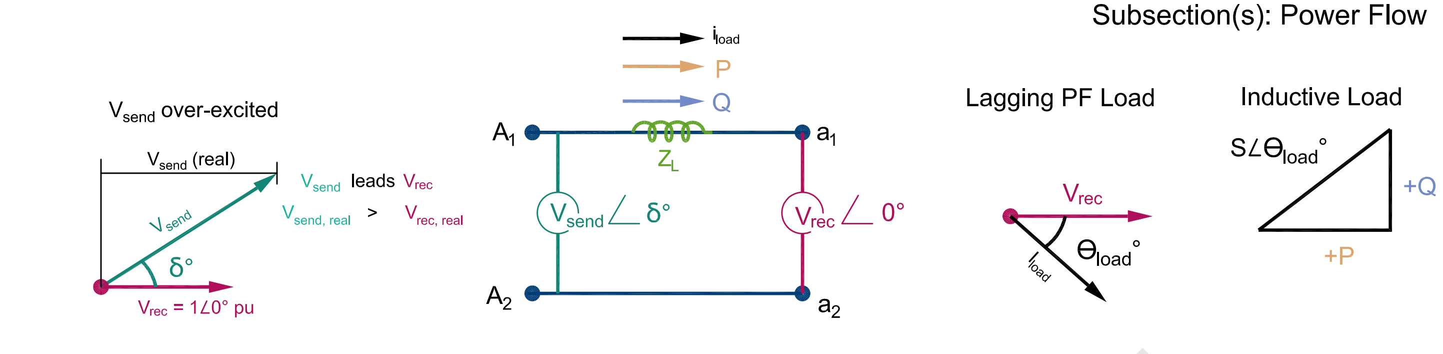
<u>3-Phase Full Wave Rectifier</u>

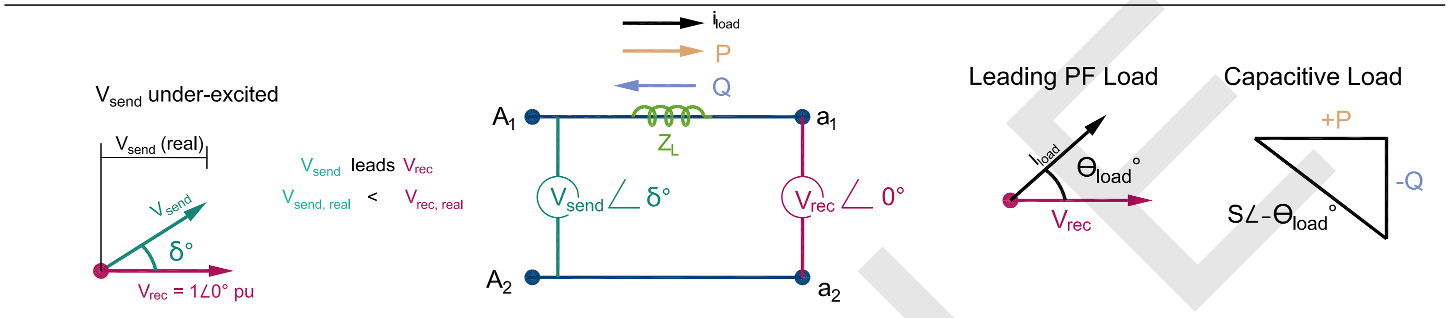
$V_{DC, load} = 1.35 \times V_{RMS, line}$

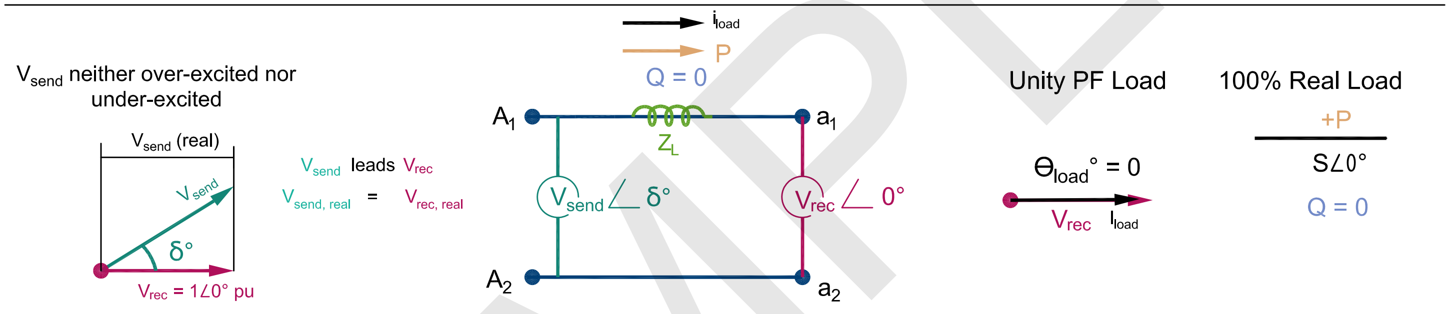
$V_{DC, load} = 2.33 \times V_{RMS, phase}$

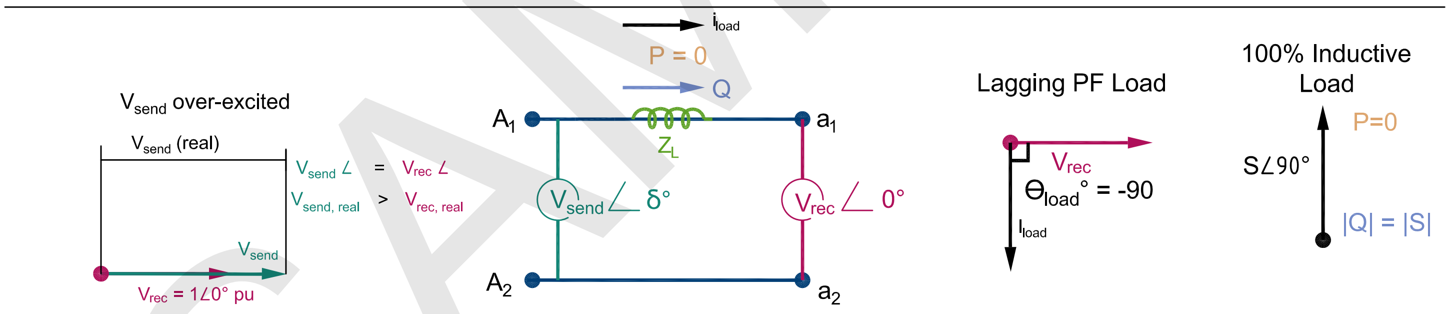
$V_{DC, load} = 0.95 \times V_{max, line}$

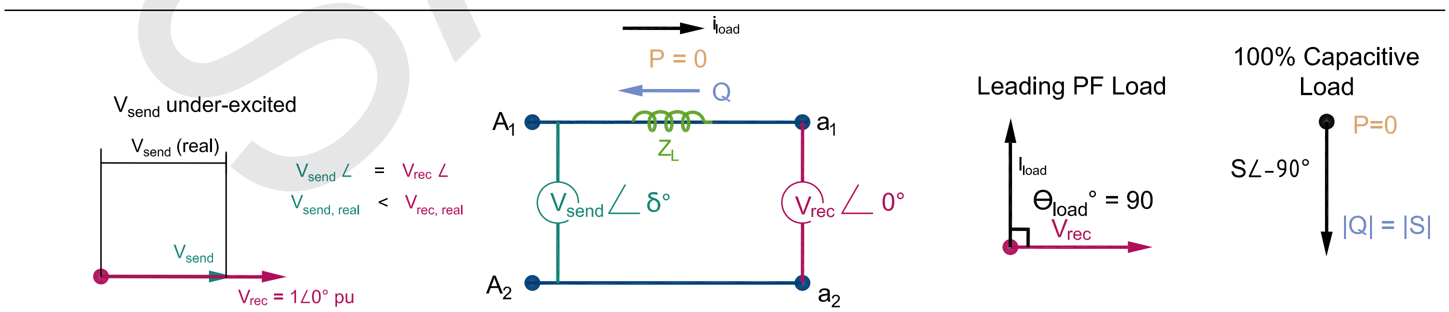
$V_{DC, load} = 1.65 \times V_{max, phase}$

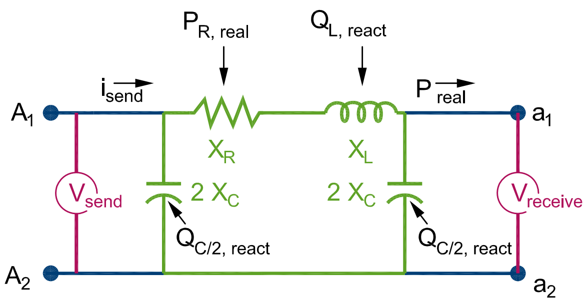

V_send over-excited
V_send (real)
V_send
δ°
V_rec = 1∠0° pu
V_send leads V_rec
V_send, real > V_rec, real
i_load
P
Q
A1
a1
Z_L
V_send ∠ δ°
V_rec ∠ 0°
A2
a2
Lagging PF Load
V_rec
Θ_load°
I_load
Inductive Load
S∠Θ_load°
+Q
+P


V_send under-excited
V_send (real)
V_send
δ°
V_rec = 1∠0° pu
V_send leads V_rec
V_send, real < V_rec, real
i_load
P
Q
A1
a1
Z_L
V_send ∠ δ°
V_rec ∠ 0°
A2
a2
Leading PF Load
I_load
Θ_load°
V_rec
Capacitive Load
+P
-Q
S∠-Θ_load°


V_send neither over-excited nor under-excited
V_send (real)
V_send
δ°
V_rec = 1∠0° pu
V_send leads V_rec
V_send, real = V_rec, real
i_load
P
Q = 0
A1
a1
Z_L
V_send ∠ δ°
V_rec ∠ 0°
A2
a2
Unity PF Load
Θ_load° = 0
V_rec
I_load
100% Real Load
+P
S∠0°
Q = 0


V_send over-excited
V_send (real)
V_send
V_rec = 1∠0° pu
V_send ∠ = V_rec ∠
V_send, real > V_rec, real
i_load
P = 0
Q
A1
a1
Z_L
V_send ∠ δ°
V_rec ∠ 0°
A2
a2
Lagging PF Load
V_rec
Θ_load° = -90
I_load
100% Inductive Load
P=0
S∠90°
|Q| = |S|


V_send under-excited
V_send (real)
V_send
V_rec = 1∠0° pu
V_send ∠ = V_rec ∠
V_send, real < V_rec, real
i_load
P = 0
Q
A1
a1
Z_L
V_send ∠ δ°
V_rec ∠ 0°
A2
a2
Leading PF Load
I_load
Θ_load° = 90
V_rec
100% Capacitive Load
P=0
S∠-90°
|Q| = |S|

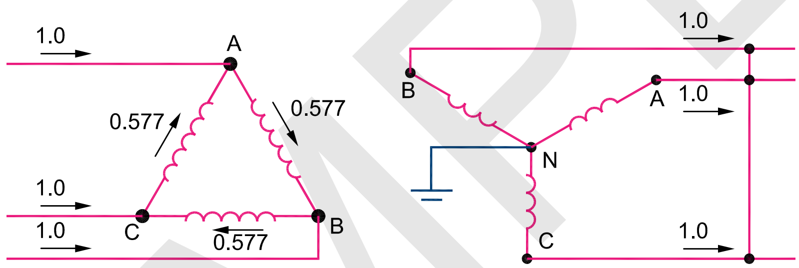


Causes of Faults

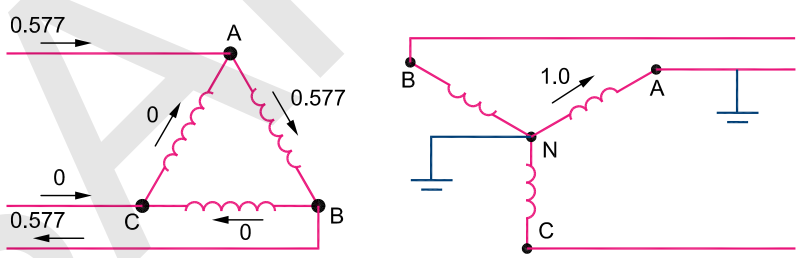
Overhead transmission lines: Lightning and wind cause damage to poles, supports. Other environmental conditions like, corrosion freezing, snow, rain can also erode insulation and supports. Human or animal damage, fallen trees.

Underground transmission lines: Lightning, corrosion, freezing, rain, age, animals, humans.

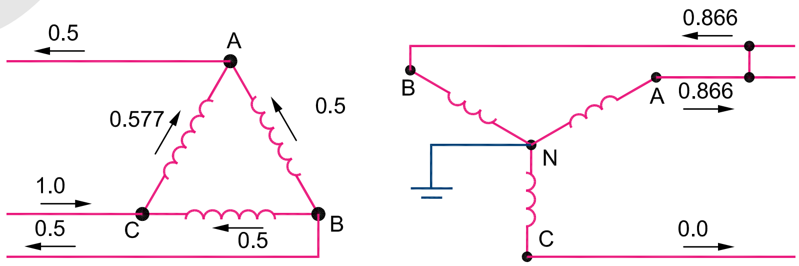
THREE PHASE FAULT



PHASE TO GROUND FAULT



PHASE TO PHASE FAULT



ARTICLE 430- MOTORS

BASED ON NEC 2017

PART I: GENERAL

430.6 Determine Amp & Motor Rating

Find Motor FLA

230.6(A) Typical Motors
(not used for low speed <1200rpm, high torque, or multispeed motors)

1) **Size conductors, switches, branch-circuit short circuit, and ground fault protection**: Use Tables 430.247 thru 430.250 to find amps (FLA), not the nameplate amp.

2) **Size individual motor overload protection**: Use motor nameplate amps (FLA).

230.6(B) Torque Motors

1) **Size branch circuit conductors**: Use nameplate locked-rotor current (LRC)

230.6(C) A/C Adjustable Voltage Motors

1) **Size conductors, switches, branch-circuit short circuit, and ground fault protection**: Use nameplate Maximum Operating Current or Control Nameplate. If MOC is not given, use 150% of Tatbles 430.249 and 430.350.

230.6(D) Valve Actuator Motor Assemblies

2) **Size conductors, branch-circuit short circuit, and ground fault protection**: Use nameplate FLA.

430.7 Locked-Rotor Current (LRC) Code Letters (A, B, C, thru V)
Current during startup. Typically 300%-600% of the FLA

Locked Rotor KVA = Motor HP * Code Letter Value (KVA/HP)
Locked Rotor Current, 3ph (A) = Locked Rotor kVA/[√(3)*kV]

ARTICLE 215- FEEDERS

Feeders supply Branch Circuit Loads

215.2(A)(1) Feeders ≤ 600V
Find FLA from branch circuit (multiple conductors). Calculated from Parts III, IV, V from Article 220. Use larger of the two requirements below.

a. $Feeder\ Amp\ (A) \geq 125\% * \sum Amp_{Continuous\ Load} + \sum Amp_{Non-Continuous\ Load}$
b. **Feeder Amp (A) ≥ Max Load * Adjustment/Correction Factors**

Feeders are conductors that supply power from service equipment to branch circuit panels. Branch circuit conductors supply power from the panel to the load, such as motors and receptacles.

PART II: CONDUCTORS

430.22 Single Motor

Find Conductor FLA

Continuous Duty
Conductor (A) = 125%*FLA

Or not less than others listed in 430.22 (A)-(G): For DC, Multispeed, Y-Δ, Part Winding, Separate Terminal Enclosures, Small Motors

Non-Continuous Duty
Conductor (A) = Nameplate FLA*% from Table 430.22(E)

430.24 Multiple Motors

Find Conductor FLA

$$Conductor\ Amp\ (A) = 125\% * Motor\ FLA_{largest\ rated\ motor\ (430.6A)} + \sum Motor\ FLA_{other\ motor\ (430.6A)} + 100\% * Non-\ Motor\ Amp_{noncontinuous} + 125\% * Non-motor\ Amp_{continuous}$$

ARTICLE 310 - CONDUCTORS

Find Wire Size

Article 310.15
Lookup wire sizes based on motor FLA

Table 310.15(B)(16) – Conductor sizes based on temperature, wire type/material, FLA rating
Insulated wires, up to 3 current carrying conductors, 60°-90°C, ≤2000V

Table 310.15(B)(17)-(21) – Other wire conditions

Adjust for Temperature and # of Wires

310.15(B)(2) Temperature Correction Factor
Multiply FLA rating based on correction factor for different ambient temperatures.

$$New\ FLA = Old\ FLA * Correction\ Factor$$

- **Table 310.15(B)(2)(a) - Based on 30°C (86°F)**
- Table 310.15(B)(2)(b) - Based on 40°C (104°F)

310.15(B)(3) Conductor Quantity Correction Factor
Multiply FLA rating based on correction factor for conductor qty.

$$New\ FLA = Old\ FLA * Correction\ Factor\ (\%)$$

- **Table 310.15(B)(3)(a) – More than 3 Conductors**

13 – Index