ELTR 115 (AC 2), section 2

Recommended schedule

Day 1

Topics: *Power in AC circuits*
Questions: *1 through 20*
Lab Exercise: *Lissajous figures for phase shift measurement (question 71)*

Day 2

Topics: *Power factor correction*
Questions: *21 through 40*
Lab Exercise: *Power factor correction for AC motor (question 72)*

Day 3

Topics: *Alternator construction and introduction to polyphase AC*
Questions: *41 through 55*
Lab Exercise: *Power factor correction for AC motor (question 72, continued)*

Day 4

Topics: *AC motor construction and polyphase AC circuits*
Questions: *56 through 70*
Lab Exercise: *work on project*

Day 5

Exam 2: *includes Lissajous figure phase shift measurement performance assessment*

Practice and challenge problems

Questions: *74 through the end of the worksheet*

Impending deadlines

Project due at end of ELTR115, Section 3
Question 73: Sample project grading criteria

Skill standards addressed by this course section

EIA *Raising the Standard; Electronics Technician Skills for Today and Tomorrow*, June 1994

C Technical Skills – AC circuits
C.01 Demonstrate an understanding of sources of electricity in AC circuits.
C.04 Demonstrate an understanding of basic motor/generator theory and operation.
C.05 Demonstrate an understanding of measurement of power in AC circuits.
C.30 Understand principles and operations of AC polyphase circuits.

B Basic and Practical Skills – Communicating on the Job
B.01 Use effective written and other communication skills. *Met by group discussion and completion of labwork.*
B.03 Employ appropriate skills for gathering and retaining information. *Met by research and preparation prior to group discussion.*
B.04 Interpret written, graphic, and oral instructions. *Met by completion of labwork.*
B.06 Use language appropriate to the situation. *Met by group discussion and in explaining completed labwork.*
B.07 Participate in meetings in a positive and constructive manner. *Met by group discussion.*
B.08 Use job-related terminology. *Met by group discussion and in explaining completed labwork.*
B.10 Document work projects, procedures, tests, and equipment failures. *Met by project construction and/or troubleshooting assessments.*
C Basic and Practical Skills – Solving Problems and Critical Thinking
C.01 Identify the problem. *Met by research and preparation prior to group discussion.*
C.03 Identify available solutions and their impact including evaluating credibility of information, and locating information. *Met by research and preparation prior to group discussion.*
C.07 Organize personal workloads. *Met by daily labwork, preparatory research, and project management.*
C.08 Participate in brainstorming sessions to generate new ideas and solve problems. *Met by group discussion.*
D Basic and Practical Skills – Reading
D.01 Read and apply various sources of technical information (e.g. manufacturer literature, codes, and regulations). *Met by research and preparation prior to group discussion.*
E Basic and Practical Skills – Proficiency in Mathematics
E.01 Determine if a solution is reasonable.
E.02 Demonstrate ability to use a simple electronic calculator.
E.05 Solve problems and [sic] make applications involving integers, fractions, decimals, percentages, and ratios using order of operations.
E.06 Translate written and/or verbal statements into mathematical expressions.
E.09 Read scale on measurement device(s) and make interpolations where appropriate. *Met by oscilloscope usage.*
E.12 Interpret and use tables, charts, maps, and/or graphs.
E.13 Identify patterns, note trends, and/or draw conclusions from tables, charts, maps, and/or graphs.
E.15 Simplify and solve algebraic expressions and formulas.
E.16 Select and use formulas appropriately.
E.17 Understand and use scientific notation.
E.26 Apply Pythagorean theorem.
E.27 Identify basic functions of sine, cosine, and tangent.
E.28 Compute and solve problems using basic trigonometric functions.

F Additional Skills – Electromechanics
B.01e Types of motors.

Common areas of confusion for students

Difficult concept: *Power factor.*

The very idea of such a thing as "imaginary power" (reactive power) is hard to grasp. Basically, what we're talking about here is current in an AC circuit that is not contributing to work being done because it is out of phase with the voltage waveform. Instead of contributing to useful work (energy leaving the circuit), it merely stores and releases energy from reactive components. In a purely reactive circuit, *all* power in the circuit is "imaginary" and does no useful work. In a purely resistive circuit, *all* power is "real" and is dissipated from the circuit by the resistance (this is also true of motor circuits operating at 100% efficiency, where energy leaves not in the form of heat but in the form of mechanical work). In all realistic circuits, power is some combination of "real" and "imaginary;" true and reactive.

Difficult concept: *Measuring phase shift with an oscilloscope.*

Phase shift is not as easy to measure with an oscilloscope as is amplitude or frequency, and it takes practice to learn. Some students have a tendency to look for memorizable formulae or step-by-step procedures for doing this rather than to figure out how and why it works. As I am fond of telling my students, *memory will fail you! Understand, don't memorize!* Phase shift measurement is not as difficult as it may look. Once you figure out the relationship between horizontal divisions on the oscilloscope screen and the period (360^o) of the waveforms, figuring phase shift is merely a matter of ratio: x divisions of shift is to the number of divisions per cycle as y degrees of shift is to 360^o.

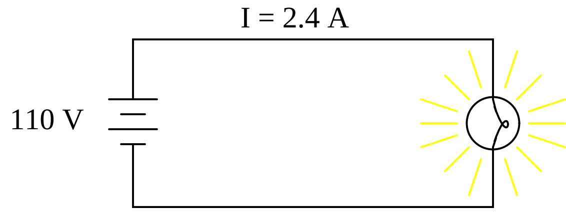
Difficult concept: *Polyphase electric power.*

Electrical systems having more than one phase (*poly*-phase) are tremendously useful and prevalent in modern industry. The idea of having multiple voltages and currents in a system all out of phase with each other may seem a little weird and confusing, but it is very necessary to know. Perhaps the best way to grasp what is going on in these systems is to see a video animation of three-phase power being generated, or a three-phase motor in action. As I teacher, I like to use blinking Christmas lights or the motion of crowds in grandstands sequentially waving ("The Wave") as an illustration of the large-scale "motion" one may create with out-of-phase sequences.

When it comes to mathematically analyzing what is happening in polyphase systems, phasor diagrams are most useful. Try to apply a phasor diagram to polyphase problems which you know the solution(s) to, and then see how the same types of diagrams may apply to problems you are currently trying to solve.

Question 1

Power is easy to calculate in DC circuits. Take for example this DC light bulb circuit:

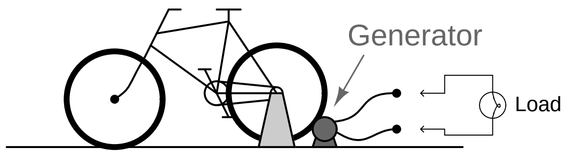


Calculate the power dissipation in this circuit, and describe the transfer of energy from source to load: where does the energy come from and where does it go to?

file 02171

Question 2

A generator is coupled to a bicycle mechanism, so that a person can generate their own electricity:

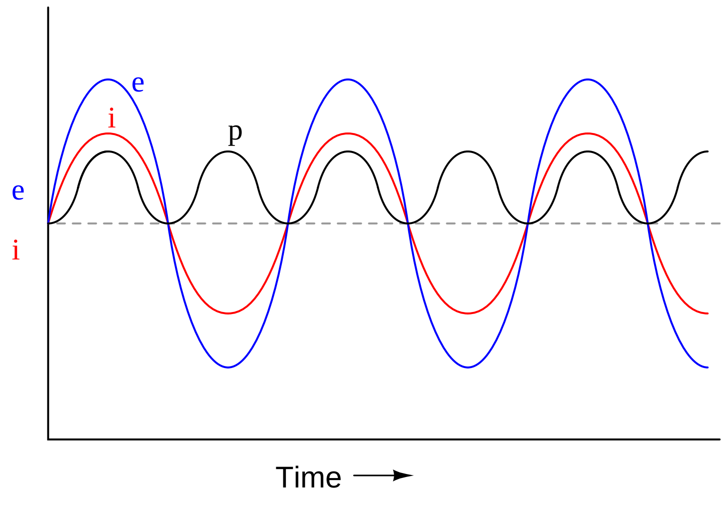


The person pedaling this bicycle/generator notices that it becomes more difficult to pedal when the generator is connected to a load such as a light bulb, or when it is charging a battery. When the generator is open-circuited, however, it is very easy to spin. Explain why this is, in terms of *work* and energy transfer.

file 02172

Question 3

If the power waveform is plotted for a resistive AC circuit, it will look like this:

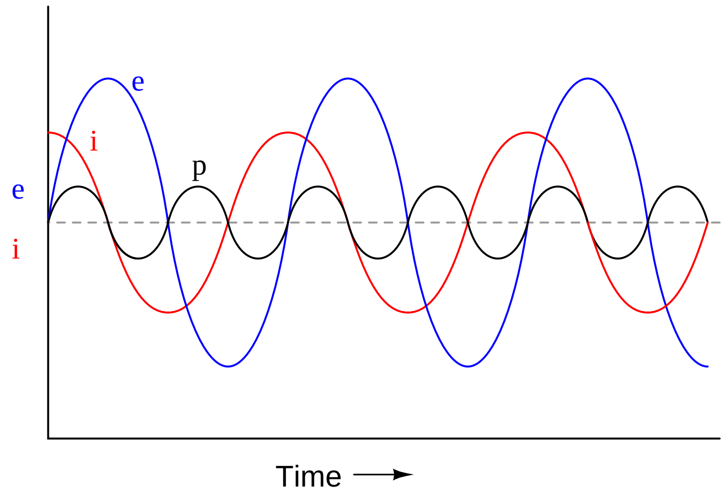


What is the significance of the power value always being *positive* (above the zero line) and never negative (below the zero line)?

file 02174

Question 4

If the power waveform is plotted for an AC circuit with a 90 degree phase shift between voltage and current, it will look something like this:

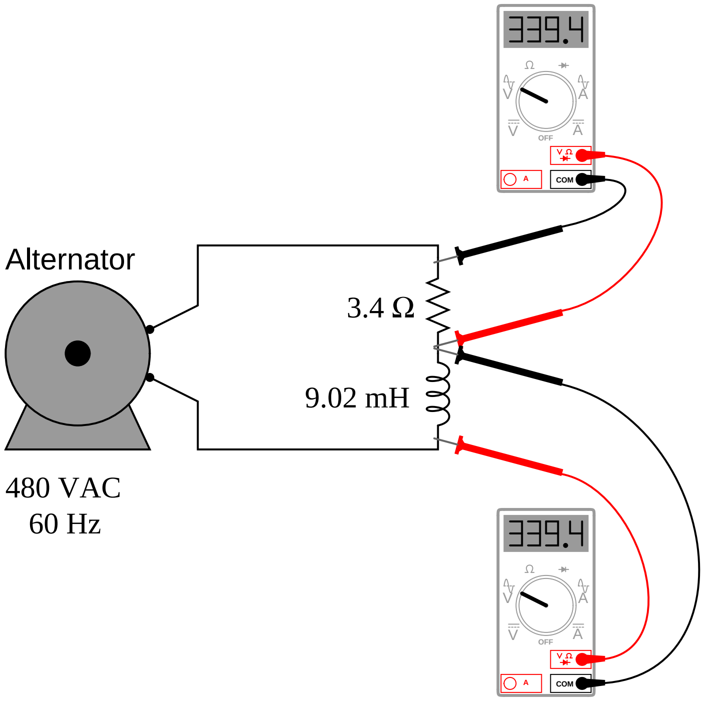


What is the significance of the power value oscillating equally between positive (above the zero line) and negative (below the zero line)? How does this differ from a scenario where there is zero phase shift between voltage and current?

file 02175

Question 5

If this circuit is built and operated, it will be found that the resistor becomes much hotter than the inductor, even though both components drop the exact same amount of voltage and carry the exact same amount of current:

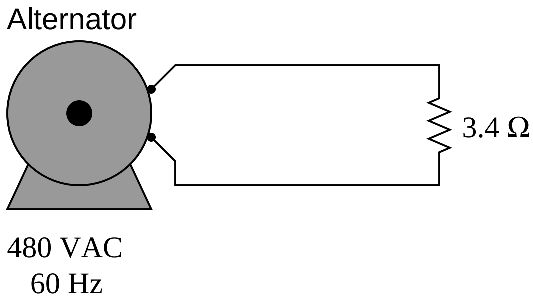


Explain why there is such a remarkable difference in heat output between these two components, given their identical voltage drops and currents.

file 02177

Question 6

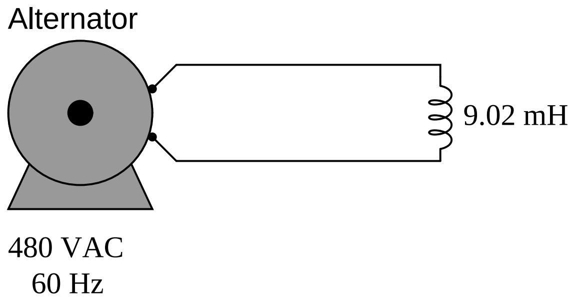
Calculate the current in this circuit, and also the amount of mechanical power (in units of "horsepower") required to turn this alternator (assume 100% efficiency):



file 00767

Question 7

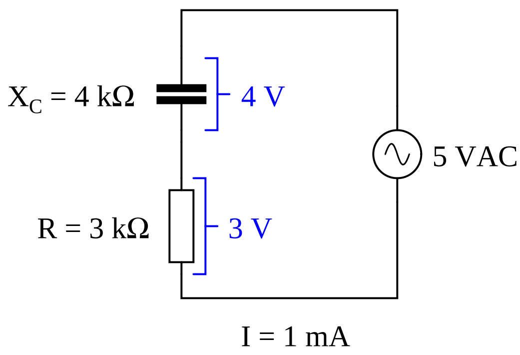
Calculate the current in this circuit, and also the amount of mechanical power (in units of "horsepower") required to turn this alternator (assume 100% efficiency):



file 00768

Question 8

A student is pondering the behavior of a simple series RC circuit:



It is clear by now that the 4 kΩ capacitive reactance does not directly add to the 3 kΩ resistance to make 7 kΩ total. Instead, the addition of impedances is *vectorial*:

$$\sqrt{{X_C}^2 + R^2} = Z_{total}$$

$$\mathbf{Z_C} + \mathbf{Z_R} = \mathbf{Z_{total}}$$

$$(4\text{k}\Omega \angle -90^o) + (3\text{k}\Omega \angle 0^o) = (5\text{k}\Omega \angle -53.13^o)$$

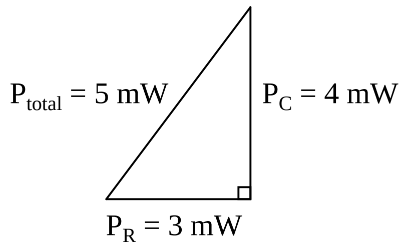
It is also clear to this student that the component voltage drops form a vectorial sum as well, so that 4 volts dropped across the capacitor in series with 3 volts dropped across the resistor really does add up to 5 volts total source voltage:

$$\mathbf{V_C} + \mathbf{V_R} = \mathbf{V_{total}}$$

$$(4\text{V} \angle -90^o) + (3\text{V} \angle 0^o) = (5\text{V} \angle -53.13^o)$$

What surprises the student, though, is power. In calculating power for each component, the student arrives at 4 mW for the capacitor (4 volts times 1 milliamp) and 3 mW for the resistor (3 volts times 1 milliamp), but only 5 mW for the total circuit power (5 volts times 1 milliamp). In DC circuits, component power dissipations *always* added, no matter how strangely their voltages and currents might be related. The student honestly expected the total power to be 7 mW, but that doesn't make sense with 5 volts total voltage and 1 mA total current.

Then it occurs to the student that power might add vectorially just like impedances and voltage drops. In fact, this seems to be the only way the numbers make any sense:



However, after plotting this triangle the student is once again beset with doubt. According to the Law of Energy Conservation, total power in must equal total power out. If the source is inputting 5 mW of power total to this circuit, there should be no possible way that the resistor is dissipating 3 mW *and* the capacitor is dissipating 4 mW. That would constitute more energy leaving the circuit than what is entering!

What is wrong with this student's power triangle diagram? How may we make sense of the figures obtained by multiplying voltage by current for each component, and for the total circuit?

file 02176

Question 9

The three different types of power in AC circuits are as follows:

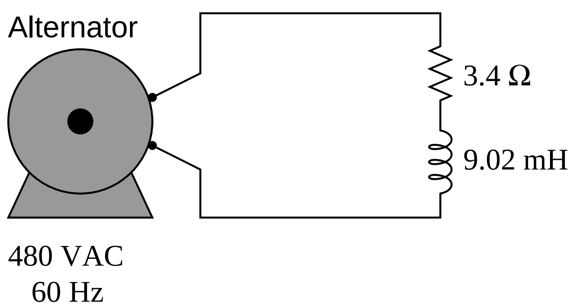
- S = apparent power, measured in Volt-Amps (VA)
- P = true power, measured in Watts (W)
- Q = reactive power, measured in Volt-Amps reactive (VAR)

Explain the names of each of these power types. Why are they called "apparent," "true," and "reactive"?

file 02178

Question 10

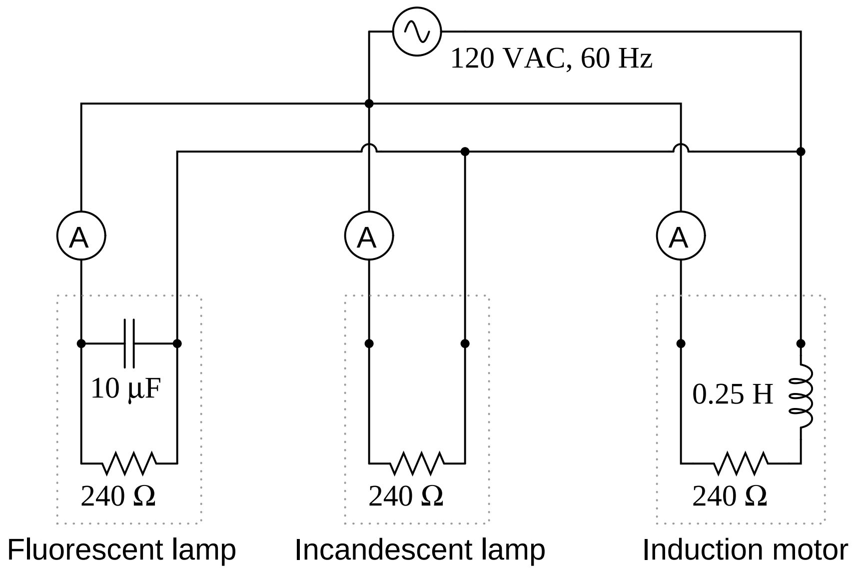
Calculate the current in this circuit, and also the amount of mechanical power (in units of "horsepower") required to turn this alternator (assume 100% efficiency):



file 00769

Question 11

In this circuit, three common AC loads are modeled as resistances, combined with reactive components in two out of the three cases. Calculate the amount of current registered by each ammeter, and also the amount of power *dissipated* by each of the loads:



If someone were to read each of the ammeters' indications and multiply the respective currents by the figure of 120 volts, would the resulting power figures ($P = IE$) agree with the actual power dissipations? Explain why or why not, for each load.

file 00770

Question 12

A very important parameter in AC power circuits is *power factor*. Explain what "power factor" is, and define its numerical range.

file 02173

Question 13

Power calculation in DC circuits is simple. There are three formulae that may be used to calculate power:

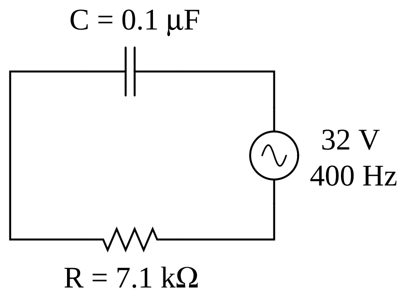
$$P = IV \qquad P = I^2 R \qquad P = \frac{V^2}{R} \qquad \text{Power in DC circuits}$$

Calculating power in AC circuits is much more complex, because there are three different types of power: *apparent* power (S), *true* power (P), and *reactive* power (Q). Write equations for calculating each of these types of power in an AC circuit:

file 02181

Question 14

Calculate the power factor of this circuit:



file 02179

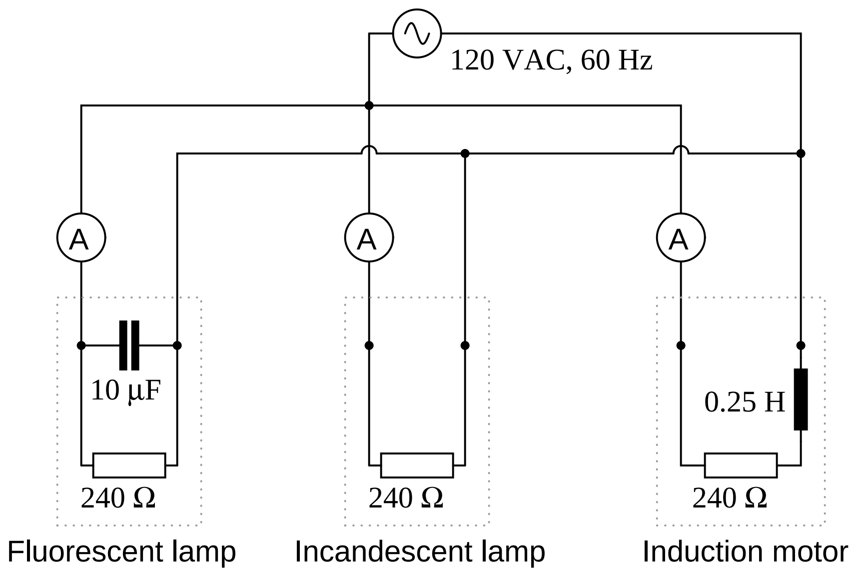
Question 15

Explain the difference between a *leading* power factor and a *lagging* power factor.

file 00774

Question 16

In this circuit, three common AC loads are represented as resistances, combined with reactive components in two out of the three cases. Calculate the amount of true power (P), apparent power (S), reactive power (Q), and power factor (PF) for each of the loads:



Also, draw power triangle diagrams for each circuit, showing how the true, apparent, and reactive powers trigonometrically relate.

file 00772

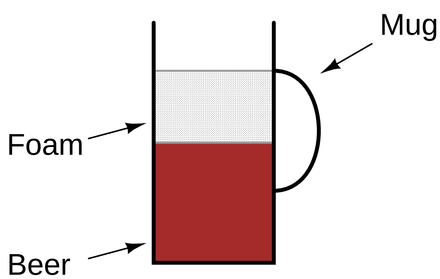
Question 17

Calculate the amount of phase shift between voltage and current in an AC circuit with a power factor of 0.97 (lagging), and an apparent power of 3.5 kVA. Also, write the equation solving for phase shift, in degrees.

file 00775

Question 18

A common analogy used to describe the different types of power in AC circuits is a mug of beer that also contains foam:

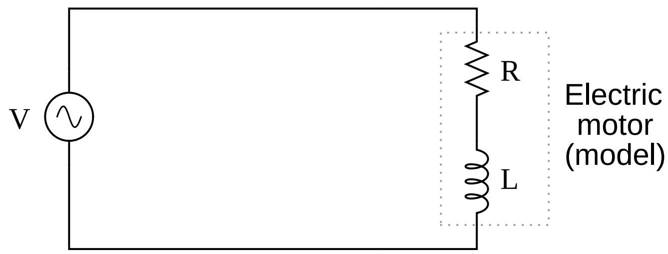


Explain this analogy, relating the quantities of beer and foam to the different types of power in an AC circuit, and also why this analogy is often employed to describe the "desirability" of each power type in a circuit.

file 00771

Question 19

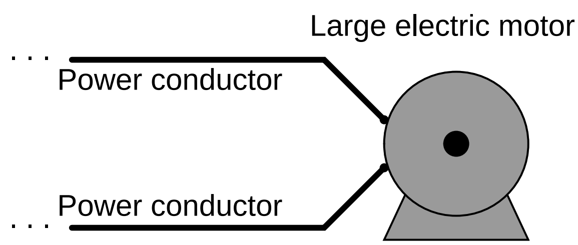
If an electrical device is modeled by fixed values of resistance, inductance, and/or capacitance, it is not difficult to calculate its power factor:



$$\text{P.F.} = \frac{R}{\sqrt{R^2 + (\omega L)^2}}$$

In real life, though, things are not so simple. An electric motor will not come labeled with an ideal-component model expressed in terms of R and L. In fact, that would be impossible, as the resistance R in the circuit model represents the sum total of mechanical work being done by the motor in addition to the energy losses. These variables change depending on how heavily loaded the motor is, meaning that the motor's power factor will also change with mechanical loading.

However, it may be very important to calculate power factor for electrical loads such as multi-thousand horsepower electric motors. How is this possible to do when we do not know the equivalent circuit configuration or values for such a load? In other words, how do we determine the power factor of a *real* electrical device as it operates?



Of course, there do exist special meters to measure true power (wattmeters) and reactive power ("var" meters), as well as power factor directly. Unfortunately, these instruments may not be readily available for our use. What we need is a way to measure power factor using nothing more than standard electrical/electronic test equipment such as multimeters and oscilloscopes. How may we do this?

Hint: remember that the angle Θ of the S-Q-P "power triangle" is the same as the angle in a circuit's Z-X-R impedance triangle, and also the same as the phase shift angle between total voltage and total current.

file 02180

Question 20

Suppose that a single-phase AC electric motor is performing mechanical work at a rate of 45 horsepower. This equates to 33.57 kW of power, given the equivalence of watts to horsepower (1 HP $\approx$ 746 W).

Calculate the amount of line current necessary to power this motor if the line voltage is 460 volts, assuming 100% motor efficiency and a power factor of 1.

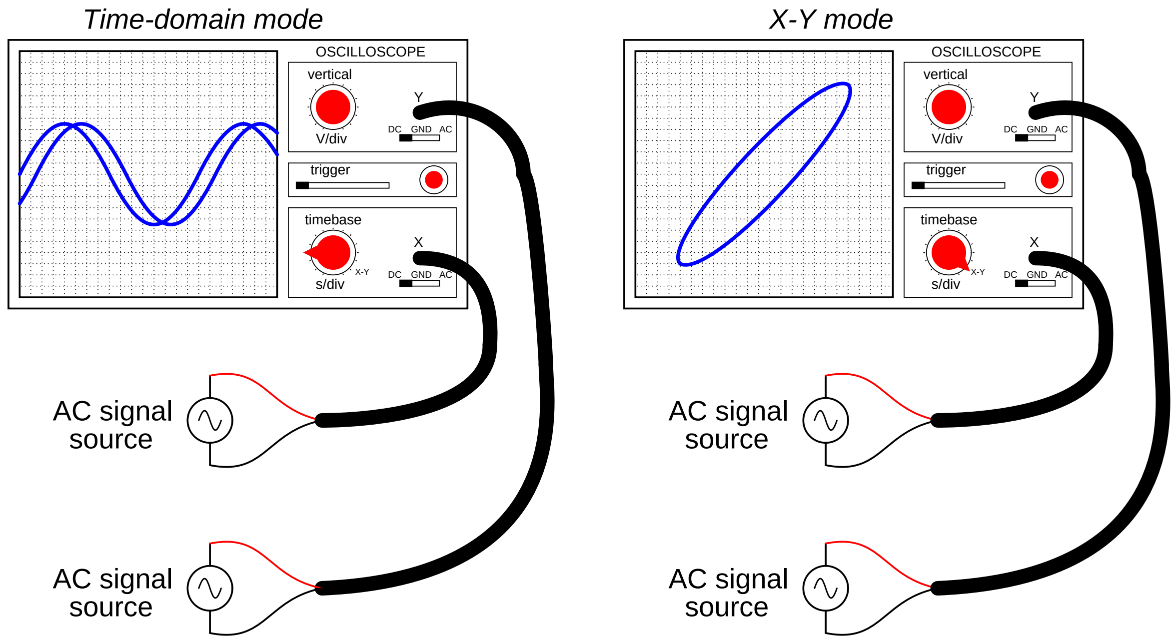
Now re-calculate the necessary line current for this motor if its power factor drops to 0.65. Assume the same efficiency (100%) and the same amount of mechanical power (45 HP).

What do these calculations indicate about the importance of maintaining a high power factor value in an AC circuit?

file 02182

Question 21

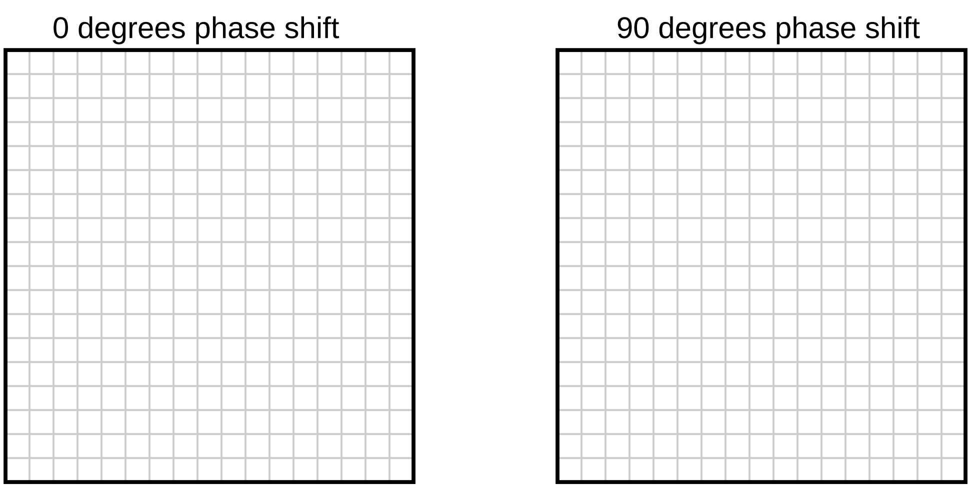
A common feature of oscilloscopes is the $X - Y$ mode, where the vertical and horizontal plot directions are driven by external signals, rather than only the vertical direction being driven by a measured signal and the horizontal being driven by the oscilloscope's internal sweep circuitry:



The oval pattern shown in the right-hand oscilloscope display of the above illustration is typical for two sinusoidal waveforms of the same frequency, but slightly out of phase with one another. The technical name for this type of $X - Y$ plot is a *Lissajous figure*.

What should the Lissajous figure look like for two sinusoidal waveforms that are at exactly the same frequency, and exactly the same phase (0 degrees phase shift between the two)? What should the Lissajous figure look like for two sinusoidal waveforms that are exactly 90 degrees out of phase?

A good way to answer each of these questions is to plot the specified waveforms over time on graph paper, then determine their instantaneous amplitudes at equal time intervals, and then determine where that would place the "dot" on the oscilloscope screen at those points in time, in $X - Y$ mode. To help you, I'll provide two blank oscilloscope displays for you to draw the Lissajous figures on:

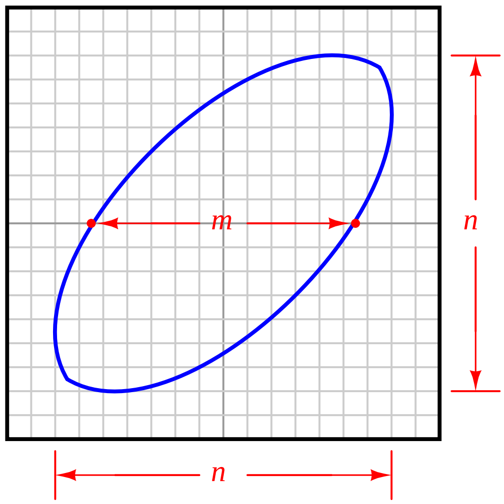


file 01480

Question 22

Lissajous figures, drawn by an oscilloscope, are a powerful tool for visualizing the phase relationship between two waveforms. In fact, there is a mathematical formula for calculating the amount of phase shift between two sinusoidal signals, given a couple of dimensional measurements of the figure on the oscilloscope screen.

The procedure begins with adjusting the vertical and horizontal amplitude controls so that the Lissajous figure is proportional: just as tall as it is wide on the screen (n). Then, we make sure the figure is centered on the screen and we take a measurement of the distance between the x-axis intercept points (m), as such:

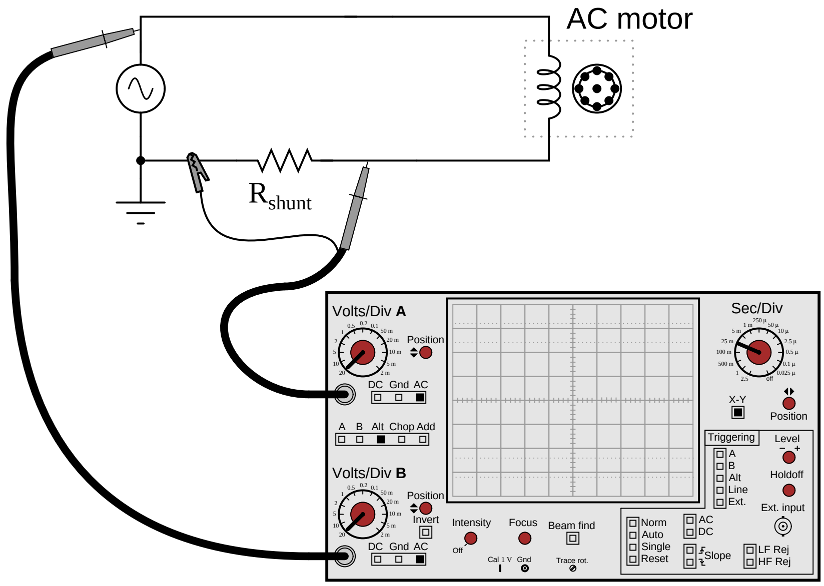


Determine what the formula is for calculating the phase shift angle for this circuit, given these dimensions. Hint: the formula is trigonometric! If you don't know where to begin, recall what the respective Lissajous figures look like for a 0^o phase shift and for a 90^o phase shift, and work from there.

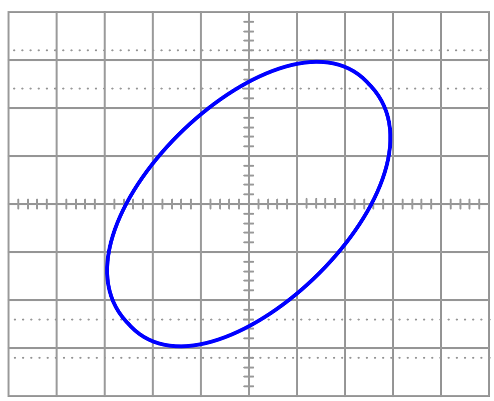
file 01481

Question 23

An oscilloscope is connected to a low-current AC motor circuit to measure both voltage and current, and plot them against one another as a Lissajous figure:



The following Lissajous figure is obtained from this measurement:

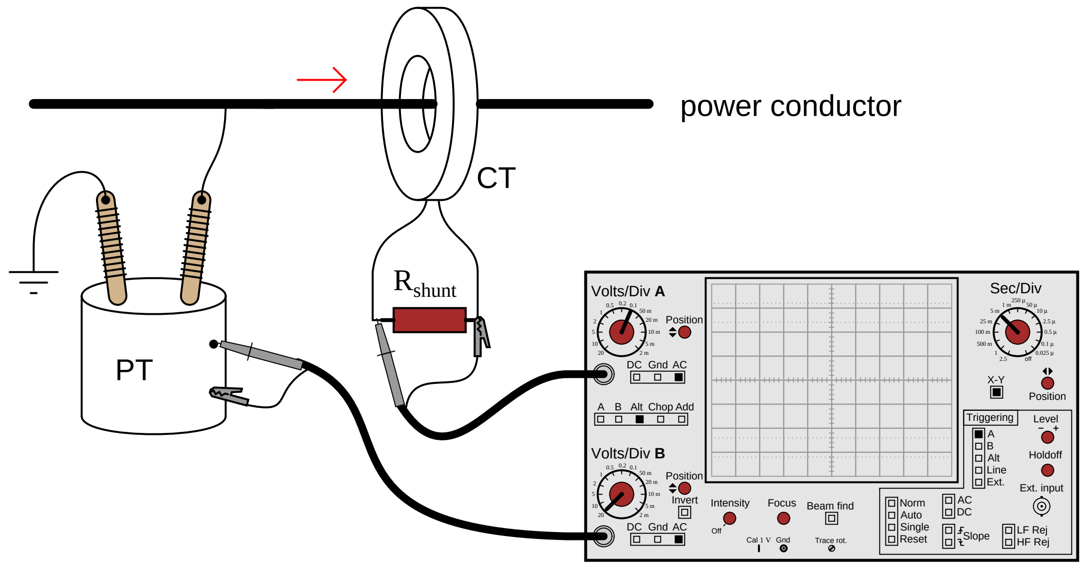


From this figure, calculate the phase angle (Θ) and the power factor for this motor circuit.
file 02183

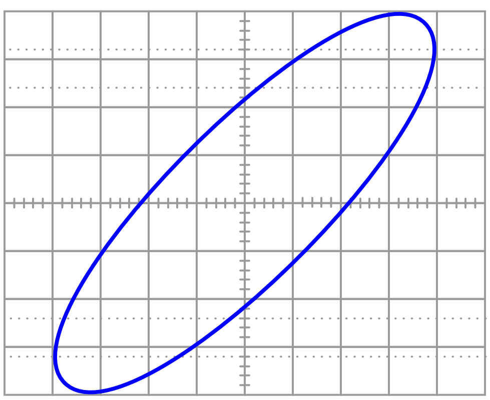
Question 24

A very high-power AC electric motor needs to have its power factor measured. You and an electrician are asked to perform this measurement using an oscilloscope. The electrician understands what must be done to measure voltage and current in this dangerous circuit, and you understand how to interpret the oscilloscope's image to calculate power factor.

It would be impractical to directly measure voltage and current, seeing as how the voltage is 4160 volts AC and the current is in excess of 200 amps. Fortunately, PT (”potential transformer”) and CT (”current transformer”) units are already installed in the motor circuit to facilitate measurements:



After the electrician helps you safely connect to the PT and CT units, you obtain a Lissajous figure that looks like this:



Calculate the power factor of the AC motor from this oscilloscope display.

file 02185

Question 25

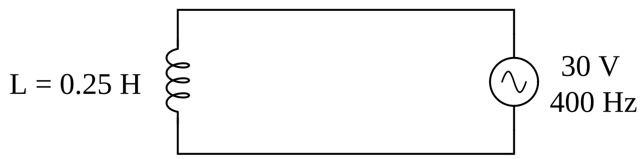
A large electrical load is outfitted with a wattmeter to measure its true power. If the load voltage is 7.2 kV and the load current is 24 amps, calculate the load's apparent power (S). Calculate the power factor and also the phase angle between voltage and current in the circuit if the wattmeter registers 155 kW at those same voltage and current values.

Draw a "power triangle" for this circuit, graphically showing the relationships between apparent power, true power, and phase angle.

file 02187

Question 26

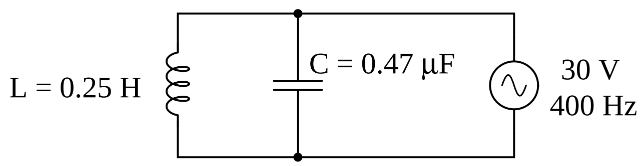
The power factor of this circuit is as low as it can possibly be, 0:



Calculate the apparent, true, and reactive power for this circuit:

- $S =$
- $P =$
- $Q =$

Now, suppose a capacitor is added in parallel with the inductor:



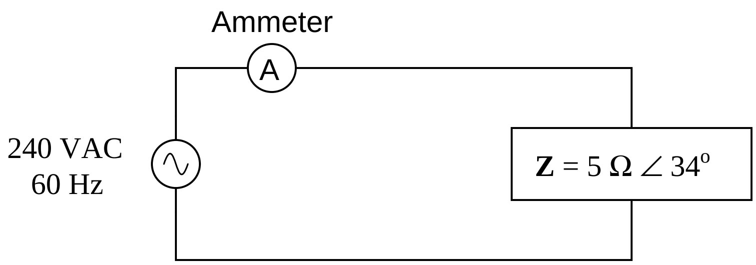
Re-calculate the apparent, true, and reactive power for this circuit with the capacitor connected:

- $S =$
- $P =$
- $Q =$

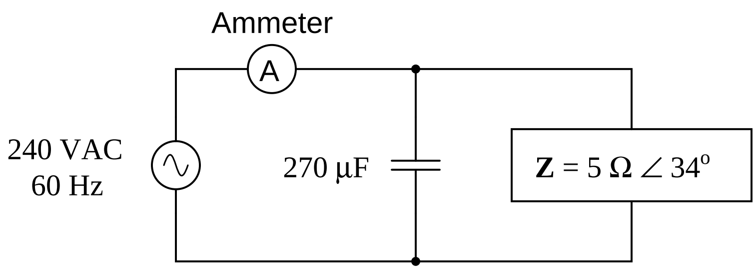
file 02186

Question 27

Calculate the line current and power factor in this AC power system:



Now, calculate the line current and power factor for the same circuit after the addition of a capacitor in parallel with the load:



file 00643

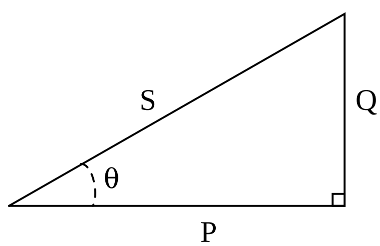
Question 28

It is in the best interest of power distribution systems to maintain the power factors of distant loads as close to unity (1) as possible. Explain why.

file 01885

Question 29

The "power triangle" is a very useful model for understanding the mathematical relationship between apparent power (S), true power (P), and reactive power (Q):



Explain what happens to the triangle if power factor correction components are added to a circuit. What side(s) change length on the triangle, and what happens to the angle Θ?

file 02184

Question 30

When a capacitor is to be connected in parallel with an inductive AC load to correct for lagging power factor, it is important to be able to calculate the reactive power of the capacitor (Q_C). Write at least one equation for calculating the reactive power of a capacitor (in VARs) given the capacitor's reactance (X_C) at the line frequency.

file 02189

Question 31

An inductive AC load draws 13.4 amps of current at a voltage of 208 volts. The phase shift between line voltage and line current is measured with an oscilloscope, and determined to be 23^o. Calculate the following:

- Apparent power (S) =
- True power (P) =
- Reactive power (Q) =
- Power factor =

An electrician suggests to you that the lagging power factor may be corrected by connecting a capacitor in parallel with this load. If the capacitor is sized just right, it will exactly offset the reactive power of the inductive load, resulting in zero total reactive power and a power factor of unity (1). Calculate the size of the necessary capacitor in Farads, assuming a line frequency of 60 Hz.

file 02168

Question 32

An AC load exhibits a lagging power factor of 0.73 at 230 VAC and 315 amps. If the system frequency is 60 Hz, calculate the following:

- Apparent power (S) =
- True power (P) =
- Reactive power (Q) =
- Θ =
- Necessary parallel C size to correct power factor to unity =

file 02191

Question 33

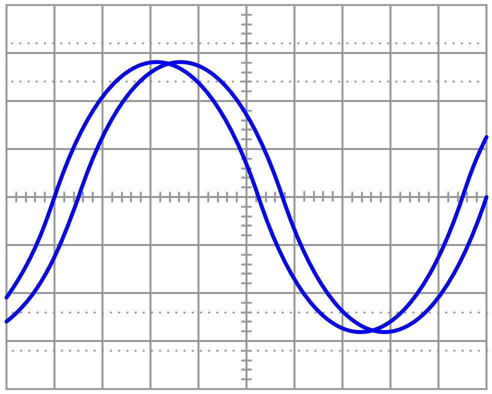
An inductive AC load consumes 15.2 MW of true power at a voltage of 115 kV and 149.8 amps. If the system frequency is 50 Hz, calculate the following:

- Apparent power (S) =
- Reactive power (Q) =
- Power factor =
- Θ =
- Necessary parallel C size to correct power factor to unity =

file 02190

Question 34

A dual-trace oscilloscope is used to measure the phase shift between voltage and current for an inductive AC load:



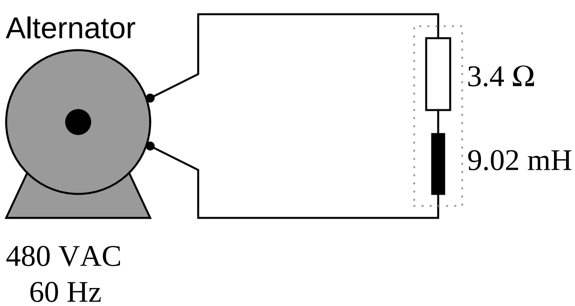
Calculate the following, given a load voltage of 110 volts, a load current of 3.2 amps, and a frequency of 60 Hz:

- Apparent power (S) =
- True power (P) =
- Reactive power (Q) =
- Θ =
- Power factor =
- Necessary parallel C size to correct power factor to unity =

file 02192

Question 35

Calculate the power factor of this circuit:

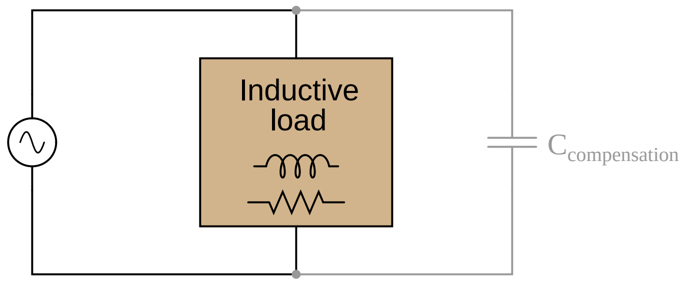


Then, calculate the size of the capacitor necessary to "correct" the power factor to a value of 1.0, showing the best location of the capacitor in the circuit.

file 00776

Question 36

If an AC circuit has a lagging power factor, the way to correct for that power factor is to add a capacitor to the circuit to create *leading* reactive power. This leading reactive power will cancel the lagging reactive power of the load, ideally negating one another so that there is no reactive power demands placed on the source (zero net reactive power in the circuit):

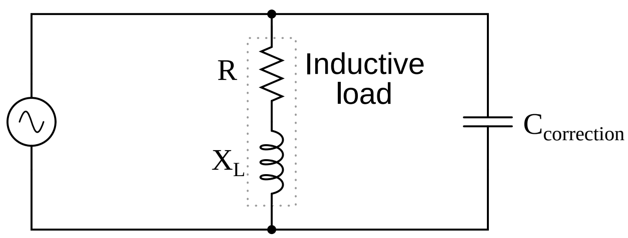


Define a step-by-step procedure for calculating the size of compensating capacitor needed (in Farads) in order to correct any lagging power factor to a value of unity. Make your procedure general enough that it may apply to any scenario.

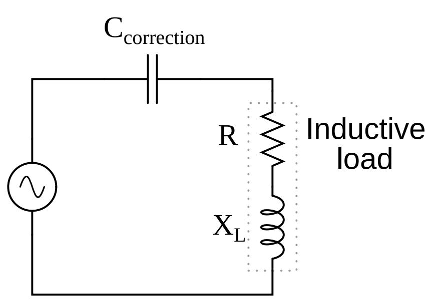
file 02188

Question 37

Most methods of power factor correction involve the connection of a parallel capacitance to an inductive load:



It is technically possible to correct for lagging power factor by connecting a capacitor in *series* with an inductive load as well, but this is rarely done:



Explain why series capacitance is not considered a practical solution for power factor correction in most applications.

file 02195

Question 38

Although most high-power AC loads are inductive in nature, some are capacitive. Explain what you would have to do to correct for the *leading* power factor of a large capacitive load, provided the power factor were low enough to warrant the expense of equipment to correct it.

file 02193

Question 39

In AC power systems, a common way of thinking about reactive power among engineers is in terms of production and consumption. Inductive loads, it is said, *consume* reactive power. Conversely, capacitive loads *produce* reactive power.

Explain how the models of "production" and "consumption" relate to reactive power in capacitors and inductors, respectively. Being that neither type of component actually dissipates or generates electrical energy, how can these terms be appropriate in describing their behavior?

file 00773

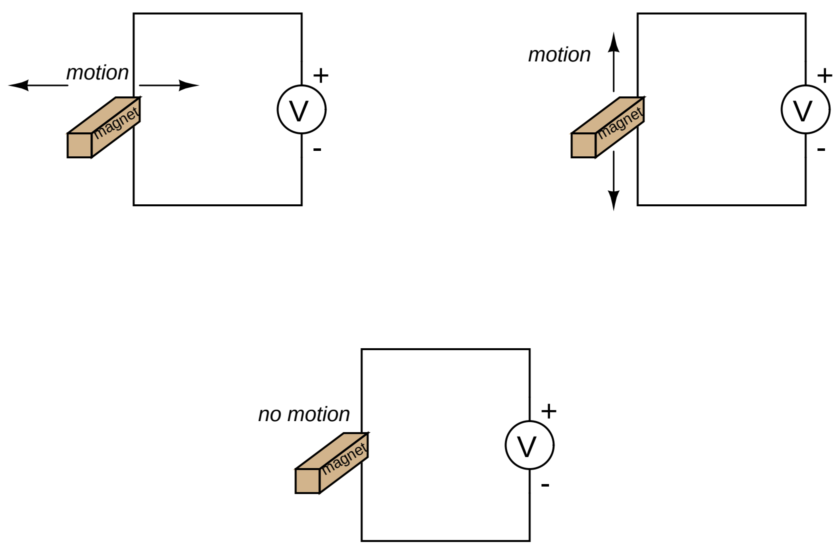
Question 40

Another name for "capacitor" is *condenser*. Explain what a *synchronous condenser* is, and how it is used to correct power factor in AC power systems.

file 02194

Question 41

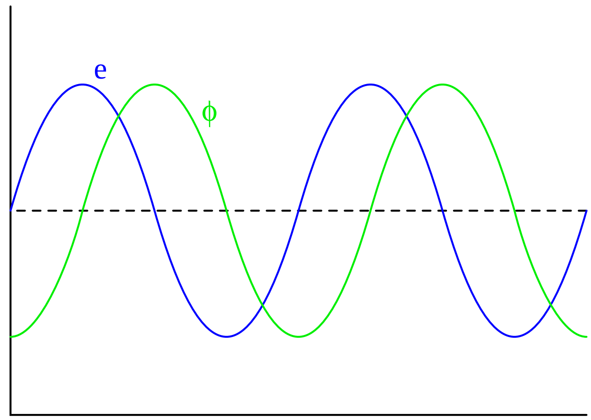
Which magnet motion past the wire will produce the greatest voltmeter indication: perpendicular, parallel, or no motion at all?



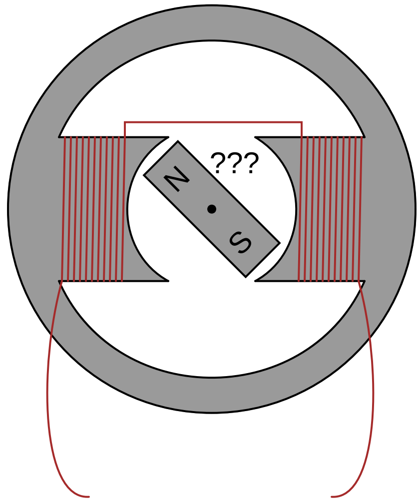
file 00174

Question 42

We know that in order to induce a sinusoidal voltage in a wire coil, the magnetic flux linking the turns of wire in the coil must follow a sinusoidal path over time, phase-shifted 90^o from the voltage waveform. This relationship between flux and induced voltage is expressed in Faraday's equation $v = N\frac{d\phi}{dt}$:



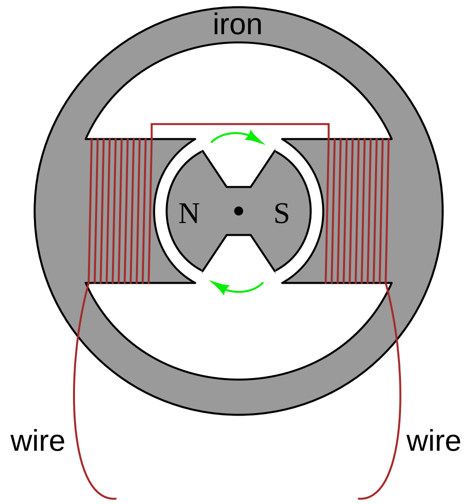
Based on this fact, draw the position of the magnetic rotor in this alternator when the voltage is at one of its peaks:



file 00818

Question 43

Describe the nature of the voltage induced in the stationary ("stator") windings, as the permanent magnet rotor rotates in this machine:



What factors determine the magnitude of this voltage? According to Faraday's Law, what factors can we alter to increase the voltage output by this generator?

Is the induced voltage AC or DC? How can you tell?

file 00816

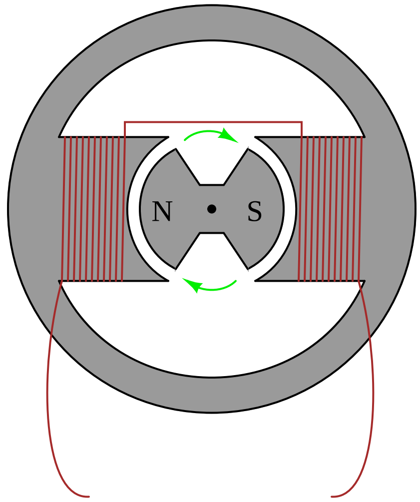
Question 44

In order to make the most practical AC generator (or *alternator*, as it is also known), which design makes more sense: a stationary permanent magnet with a rotating wire coil, or a rotating permanent magnet with a stationary wire coil? Explain your choice.

file 00817

Question 45

If this alternator is spun at 4500 RPM (revolutions per minute), what will be the frequency of its output voltage?



Hint: how many cycles of AC are produced for every revolution of the rotor?

file 00819

Question 46

How fast must a 12-pole alternator spin in order to produce 60 Hz AC power? Write a mathematical equation solving for speed (S) in terms of frequency (f) and the number of poles (N).

file 00821

Question 47

How many poles does an alternator have if it generates 400 Hz power at a shaft speed of 6000 RPM?

file 02196

Question 48

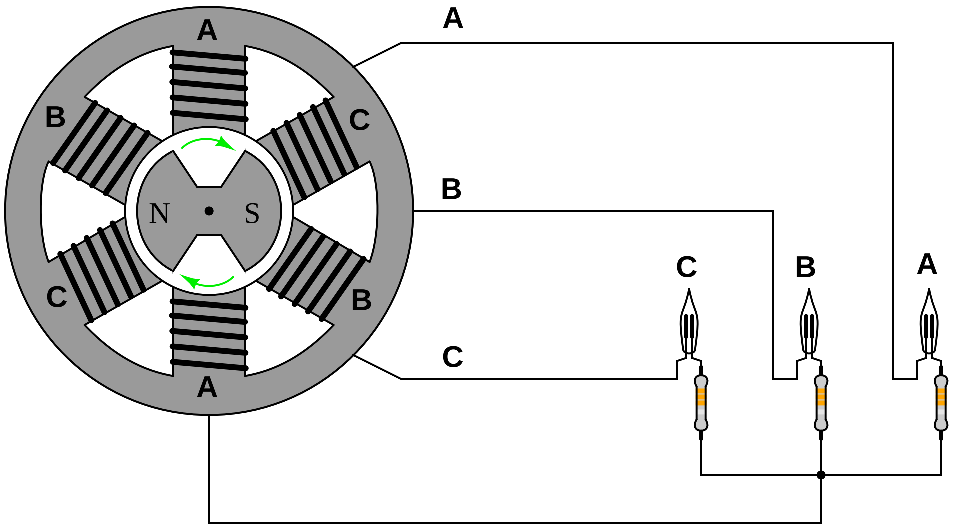
Assuming that the output frequency of an alternator must remain constant (as is the case in national power systems, where the frequency of all power plants must be the same), how may its output voltage be regulated? In other words, since we do not have the luxury of increasing or decreasing its rotational speed to control voltage, since that would change the frequency, how can we coax the alternator to produce more or less voltage on demand?

Hint: automotive alternators are manufactured with this feature, though the purpose in that application is to maintain constant voltage despite changes in engine speed. In automotive electrical systems, the frequency of the alternator's output is irrelevant because the AC is "rectified" into DC (frequency = 0 Hz) to charge the battery.

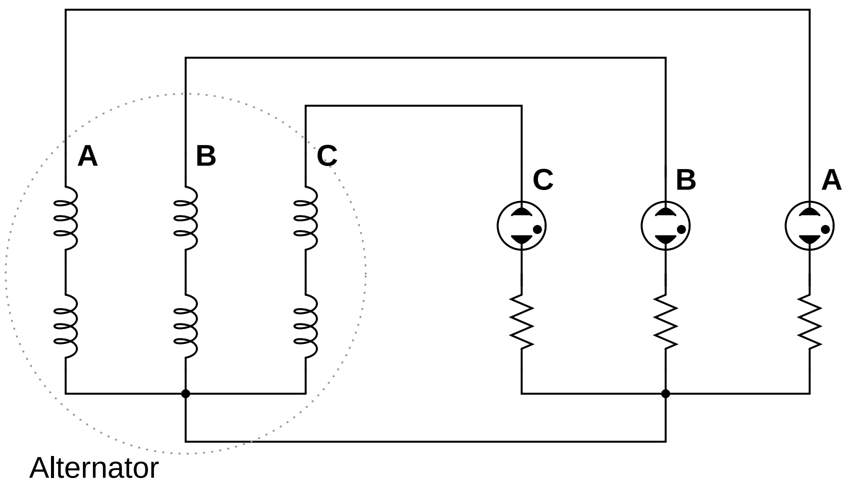
file 00820

Question 49

Suppose a set of three neon light bulbs were connected to an alternator with three sets of windings labeled **A**, **B**, and **C**:



The schematic diagram for this alternator/lamp system is as follows:



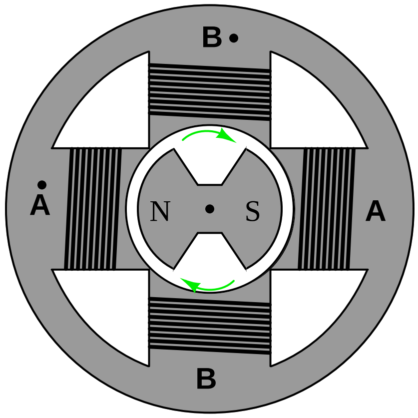
If the alternator spins fast enough (clockwise, as shown), the AC voltage induced in its windings will be enough to cause the neon lamps to "blink" (neon bulbs have very fast reaction times and thus cannot maintain a glow for very long without current, unlike incandescent lamps which operate on the principle of a glowing-hot metal filament). Most likely this blinking will be too fast to discern with the naked eye.

However, if we were to videorecord the blinking and play back the recording at a slow speed, we should be able to see the sequence of light flashes. Determine the apparent "direction" of the lamps' blinking (from right-to-left or from left-to-right), and relate that sequence to the voltage peaks of each alternator coil pair.

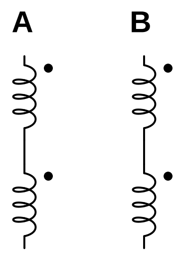
file 02198

Question 50

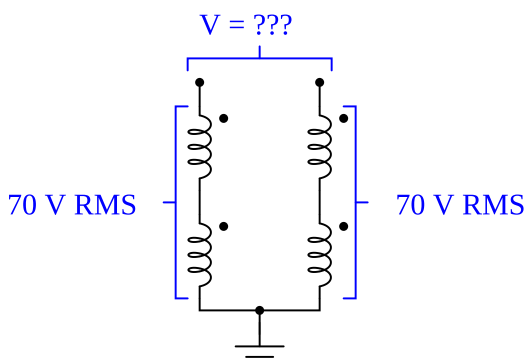
Suppose we have an alternator with two sets of windings, **A** and **B**:



Each pair of windings in each set is series-connected, so they act as just two separate windings:



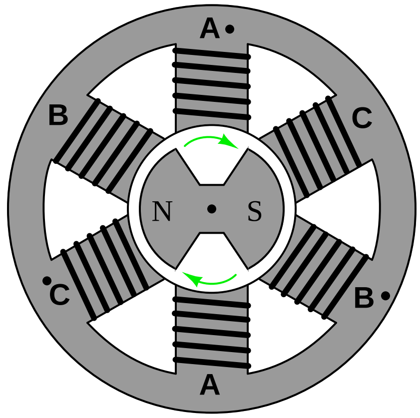
If one end of each winding pair were connected together at a common ground point, and each winding pair output 70 volts RMS, how much voltage would be measured between the open winding pair ends?



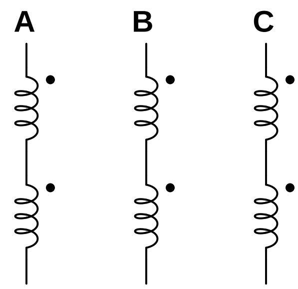
file 01886

Question 51

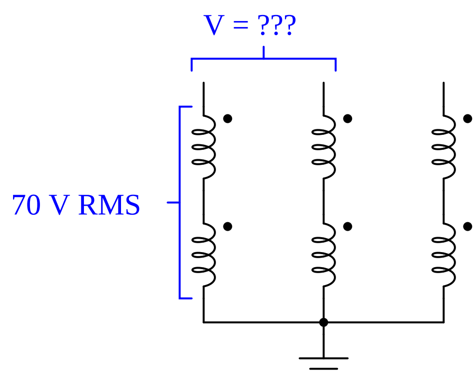
Suppose we have an alternator with three sets of windings, **A**, **B**, and **C**:



Each pair of windings in each set is series-connected, so they act as just three separate windings (pay close attention to the phase-marking dots!):



If one end of each winding pair were connected together at a common ground point, and each winding pair output 70 volts RMS, how much voltage would be measured between any two open wires?



file 01887

Question 52

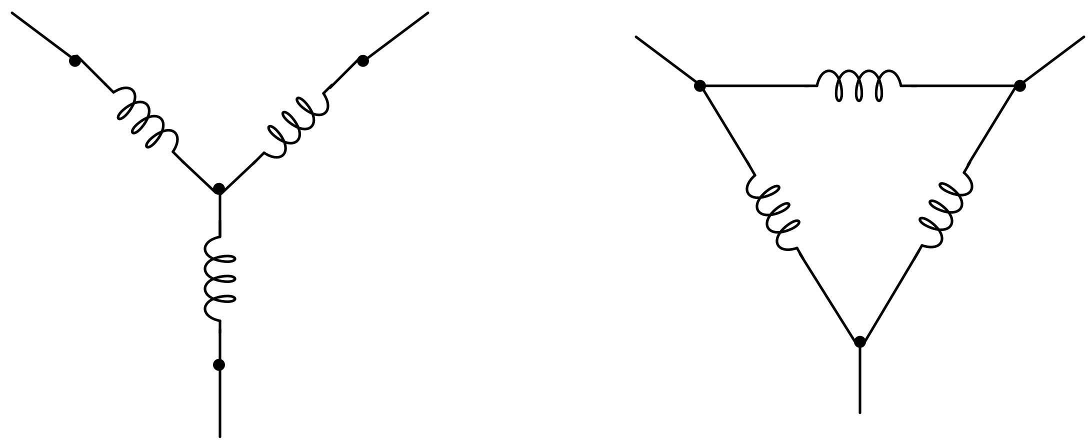
What is *polyphase* electric power, and how does it differ from *single-phase* power?

file 02197

Question 53

Label where each of the following electrical quantities would be found in both the "Y" and "Delta" three-phase configurations:

- Phase voltage
- Line voltage
- Phase current
- Line current



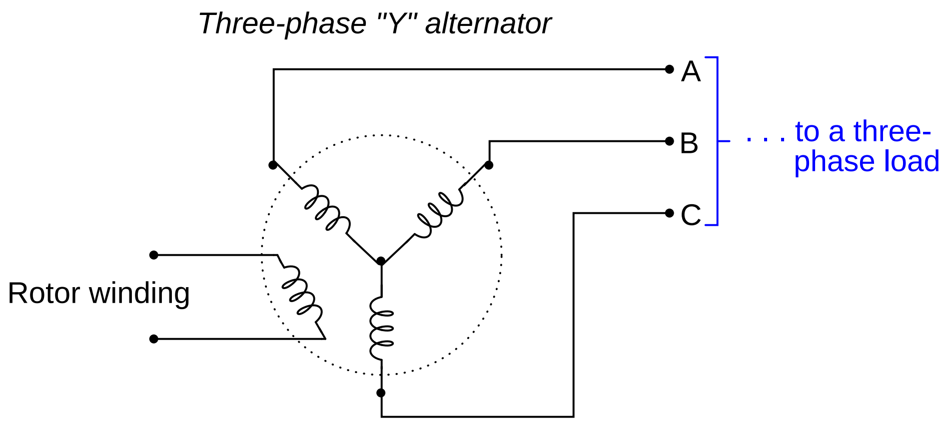
In which circuit (Y or Delta) are the phase and line currents equal? In which circuit (Y or Delta) are the phase and line voltages equal? Explain both answers, in terms that anyone with a basic knowledge of electricity could understand.

Where phase and line quantities are *un*equal, determine which is larger.

file 02201

Question 54

This is a schematic diagram of a *Y-connected* three-phase generator (with the rotor winding shown):

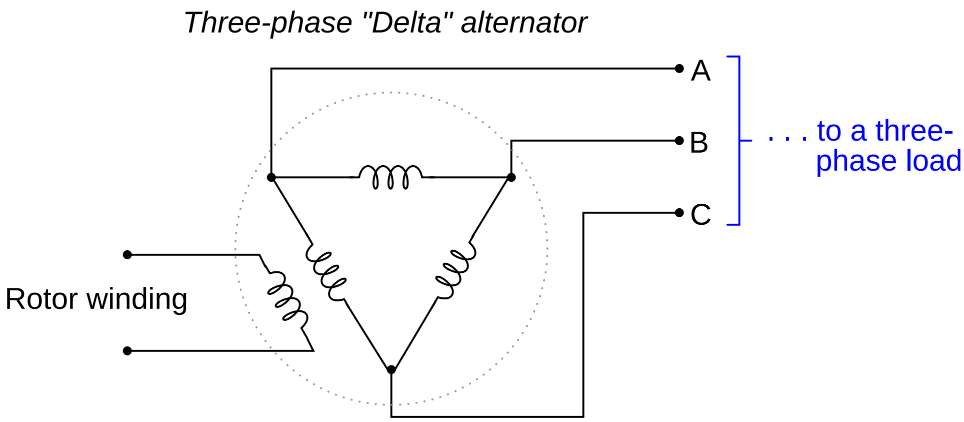


How much AC voltage will appear between any two of the lines (V_{AB}, V_{BC}, or V_{AC}) if each stator coil inside the alternator outputs 277 volts? Draw a phasor diagram showing how the phase (winding) and line voltages relate.

file 02199

Question 55

This is a schematic diagram of a *Delta-connected* three-phase generator (with the rotor winding shown):

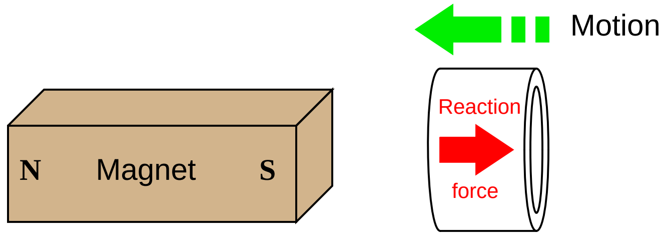


How much AC current will each of the lines (I_A, I_B, or I_C) conduct to a load (not shown) if each stator coil inside the alternator outputs 17 amps of current?

file 02200

Question 56

If a copper ring is brought closer to the end of a permanent magnet, a repulsive force will develop between the magnet and the ring. This force will cease, however, when the ring stops moving. What is this effect called?

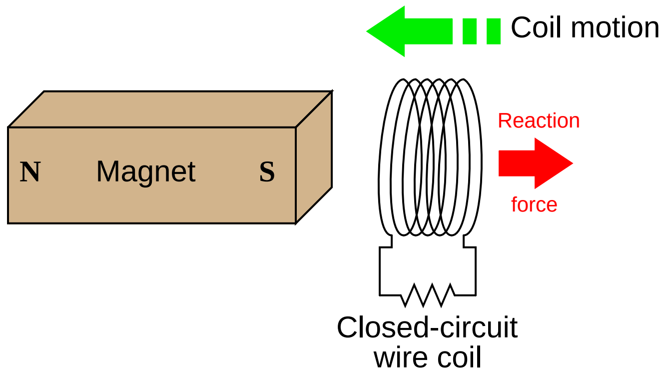


Also, describe what will happen if the copper ring is moved *away* from the end of the permanent magnet.

file 00254

Question 57

If a closed-circuit wire coil is brought closer to the end of a permanent magnet, a repulsive force will develop between the magnet and the coil. This force will cease, however, when the coil stops moving. What is this effect called?

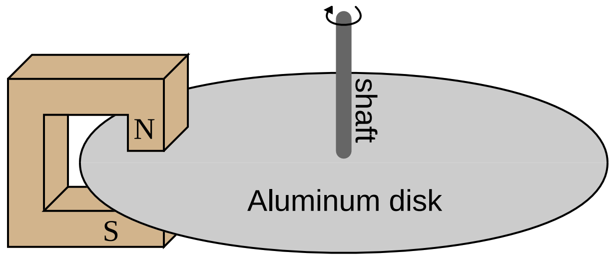


Also, describe what will happen if the wire coil fails open. Does the same effect persist? Why or why not?

file 00735

Question 58

Electromechanical watt-hour meters use an aluminum disk that is spun by an electric motor. To generate a constant "drag" on the disk necessary to limit its rotational speed, a strong magnet is placed in such a way that its lines of magnetic flux pass perpendicularly through the disk's thickness:



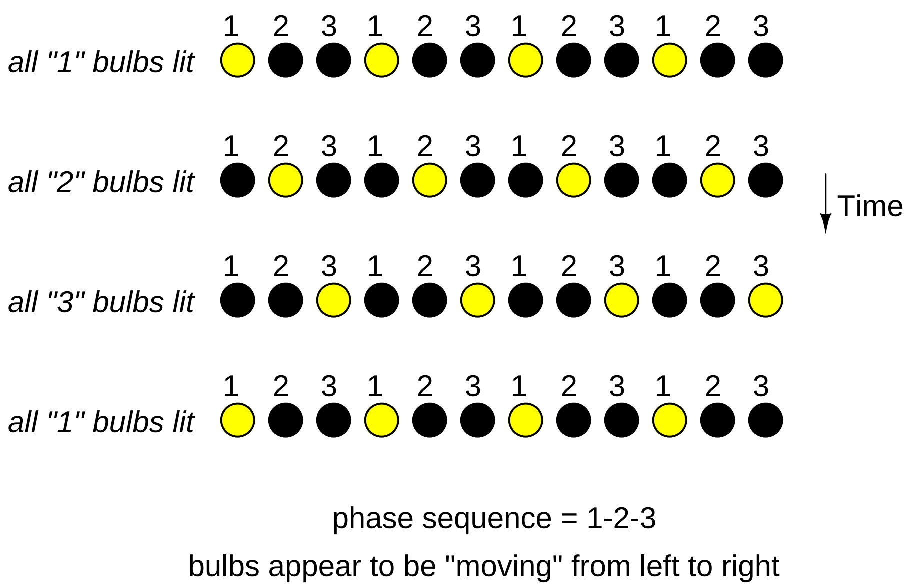
The disk itself need not be made of a ferromagnetic material in order for the magnet to create a "drag" force. It simply needs to be a good conductor of electricity.

Explain the phenomenon accounting for the drag effect, and also explain what would happen if the roles of magnet and disk were reversed: if the magnet were moved in a circle around the periphery of a stationary disk.

file 00745

Question 59

A technique commonly used in special-effects lighting is to sequence the on/off blinking of a string of light bulbs, to produce the effect of motion without any moving objects:

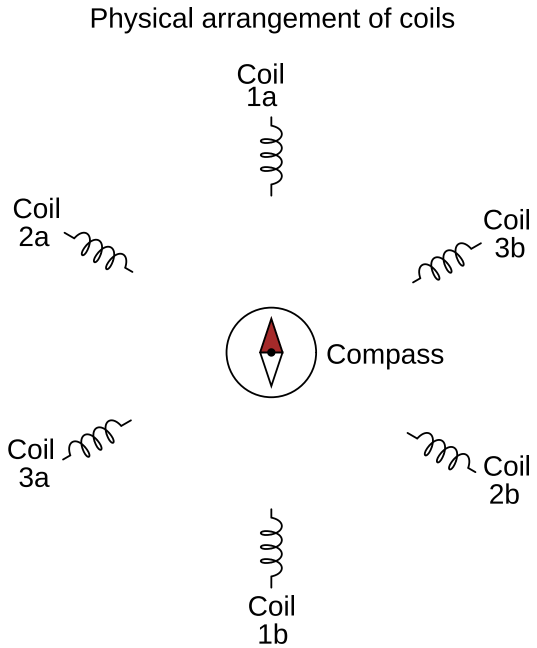


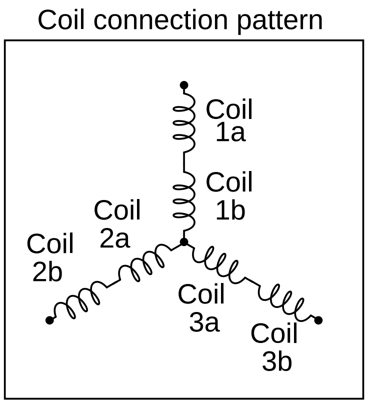
What would the effect be if this string of lights were arranged in a *circle* instead of a line? Also, explain what would have to change electrically to alter the "speed" of the blinking lights' "motion".

file 00734

Question 60

If a set of six electromagnet coils were spaced around the periphery of a circle and energized by 3-phase AC power, what would a magnetic compass do that was placed in the center?



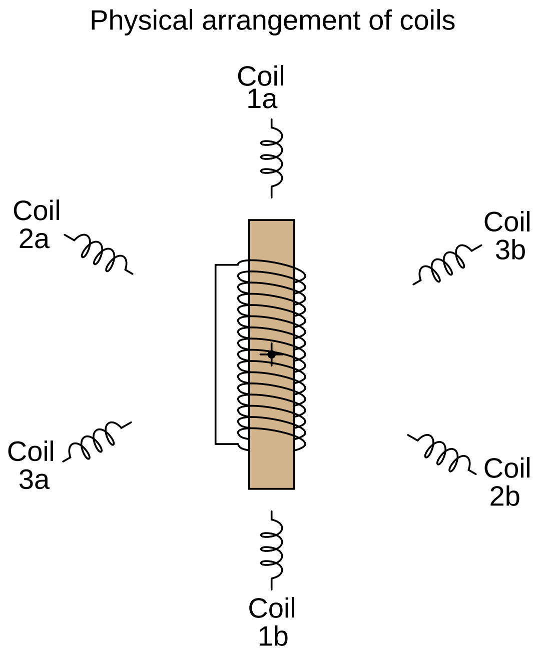


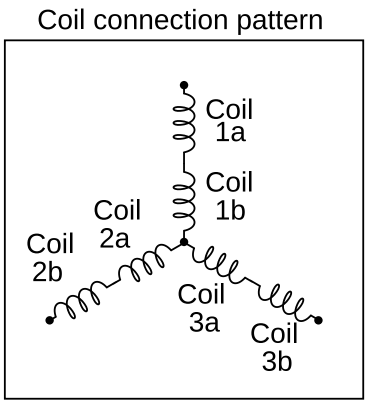
Hint: imagine the electromagnets were light bulbs instead, and the frequency of the AC power was slow enough to see each light bulb cycle in brightness, from fully dark to fully bright and back again. What would the pattern of lights appear to do?

file 00737

Question 61

Explain what will happen to the unmagnetized rotor when 3-phase AC power is applied to the stationary electromagnet coils. Note that the rotor is actually a short-circuited electromagnet:

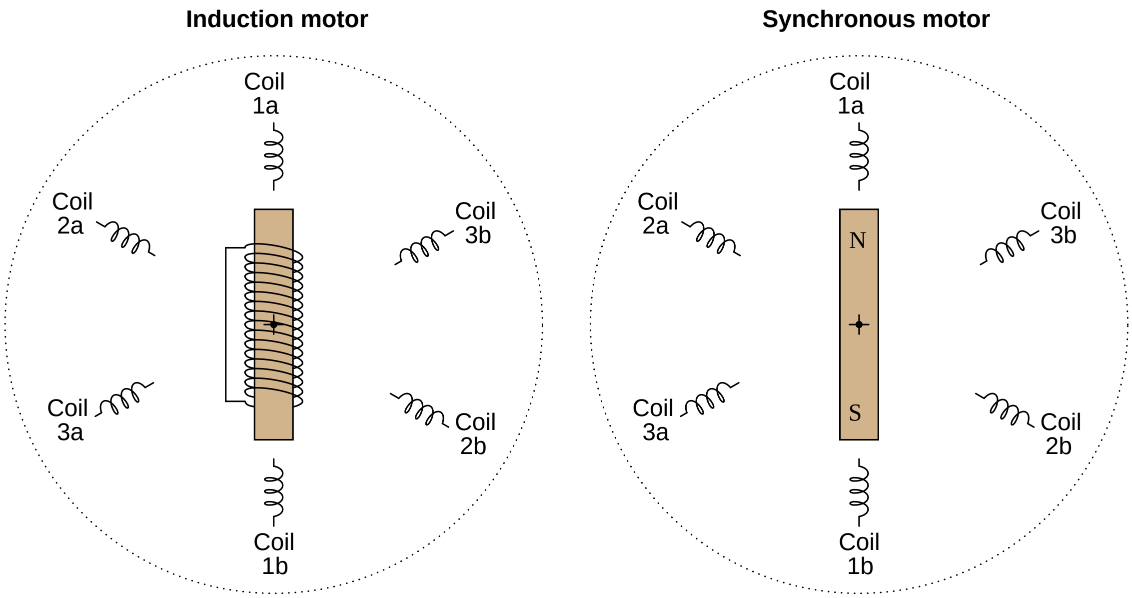




file 00739

Question 62

These two electric motor designs are quite similar in appearance, but differ in the specific principle that makes the rotor move:

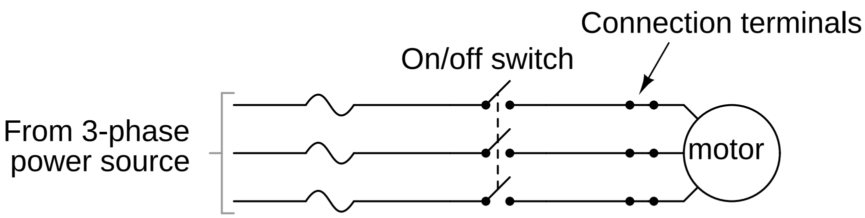


Synchronous AC motors use a permanent magnet rotor, while *induction* motors use an electromagnet rotor. Explain what practical difference this makes in each motor's operation, and also explain the meaning of the motors' names. Why is one called "synchronous" and the other called "induction"?

file 00740

Question 63

What would we have to do in order to reverse the rotation of this three-phase induction motor?

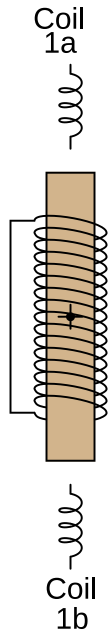


Explain your answer. Describe how the (simple) solution to this problem works.

file 00415

Question 64

Suppose an induction motor were built to run on single-phase AC power rather than polyphase AC power. Instead of multiple sets of windings, it only has one set of windings:

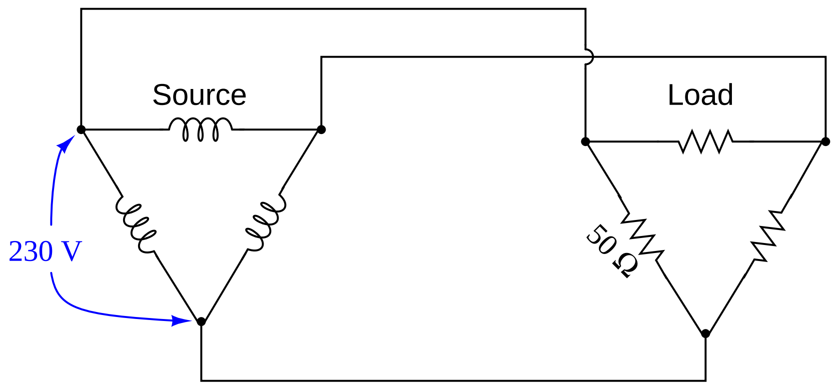


Which way would the rotor start to spin as power is applied?

file 00743

Question 65

Calculate all voltages, currents, and total power in this balanced Delta-Delta system:

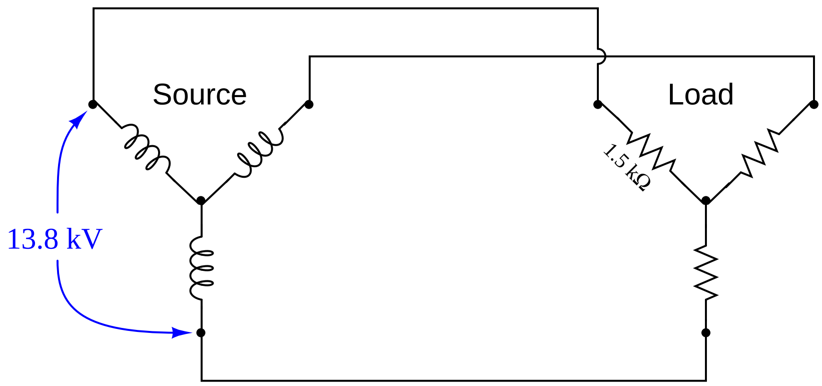


$E_{line} =$
$I_{line} =$
$E_{phase(source)} =$
$I_{phase(source)} =$
$E_{phase(load)} =$
$I_{phase(load)} =$
$P_{total} =$

file 02203

Question 66

Calculate all voltages, currents, and total power in this balanced Y-Y system:

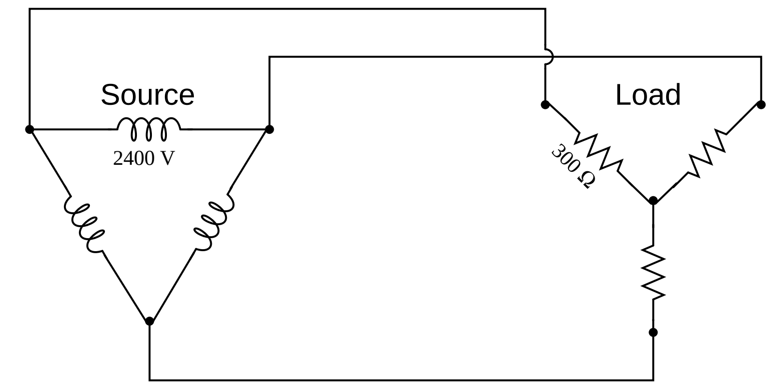


$E_{line} =$
$I_{line} =$
$E_{phase(source)} =$
$I_{phase(source)} =$
$E_{phase(load)} =$
$I_{phase(load)} =$
$P_{total} =$

file 02202

Question 67

Calculate all voltages, currents, and total power in this balanced Delta-Y system:

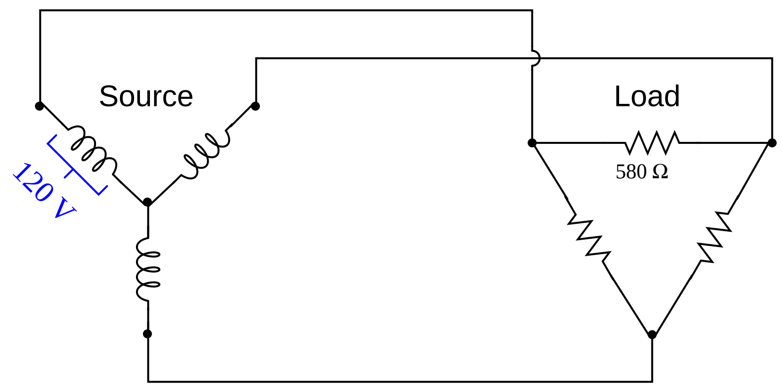


E_{line} =
I_{line} =
$E_{phase(source)}$ =
$I_{phase(source)}$ =
$E_{phase(load)}$ =
$I_{phase(load)}$ =
P_{total} =

file 00428

Question 68

Calculate all voltages, currents, and total power in this balanced Y-Delta system:

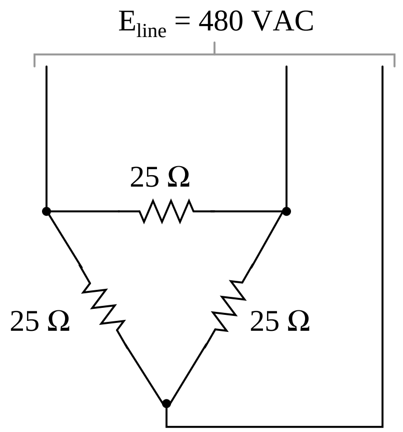


E_{line} =
I_{line} =
$E_{phase(source)}$ =
$I_{phase(source)}$ =
$E_{phase(load)}$ =
$I_{phase(load)}$ =
P_{total} =

file 02204

Question 69

The line voltage to this three-phase load is 480 volts. How much power (total) is dissipated by the load? How much current is there in each line supplying the load?

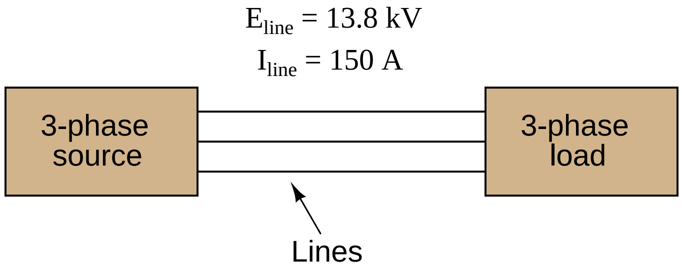


One more question: write an equation for calculating power in a balanced, three-phase circuit, given line voltage and line current only.

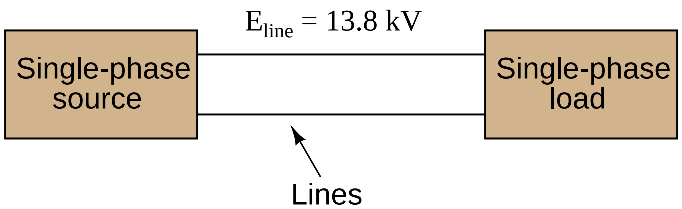
file 00421

Question 70

A balanced, three-phase power system has a line voltage of 13.8 kV volts and a line current of 150 amps. How much power is being delivered to the load (assuming a power factor of 1)?



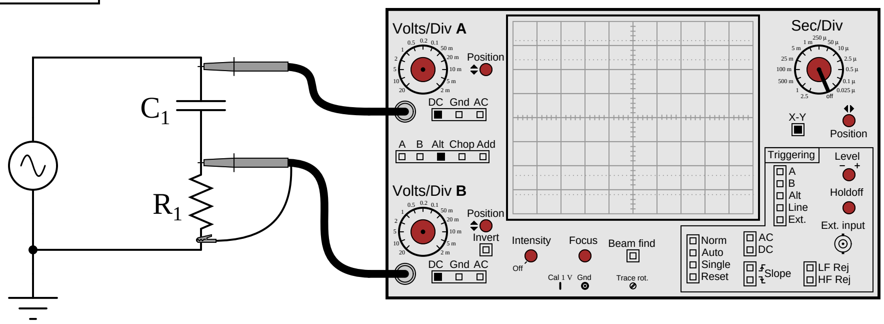
A 13.8 kV single-phase system could be designed to provide the same amount of power to a load, but it would require heavier-gauge (more expensive!) conductors. Determine the extra percentage of expense in wire cost (based on the weight of the wires) resulting from the use of single-phase instead of three-phase.



file 00414

Competency: **Lissajous figures for phase shift measurement** Version:

Schematic



Given conditions

f_{supply} = C_1 = R_1 =

Parameters

Predicted

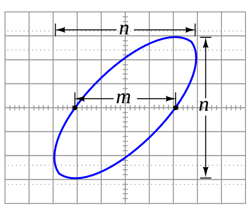
θ

Measured

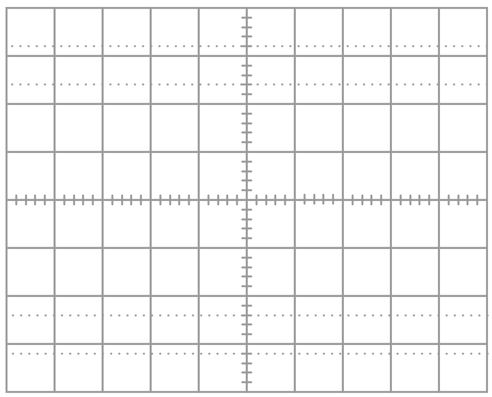
n (Divisions)

m (Divisions)

θ



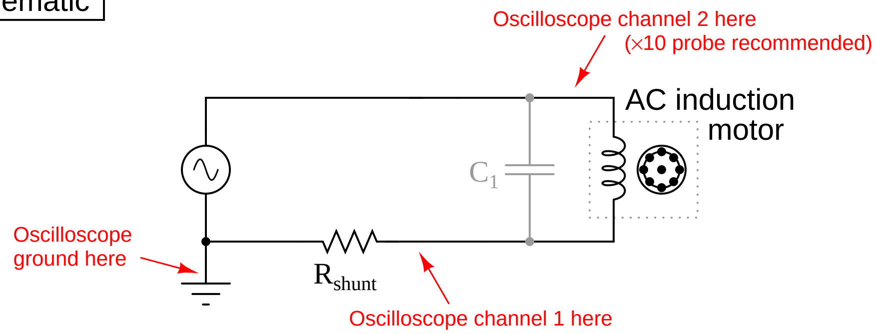
Lissajous figure (measured)



file 01676

Competency: **Power factor correction for AC motor** Version:

Schematic



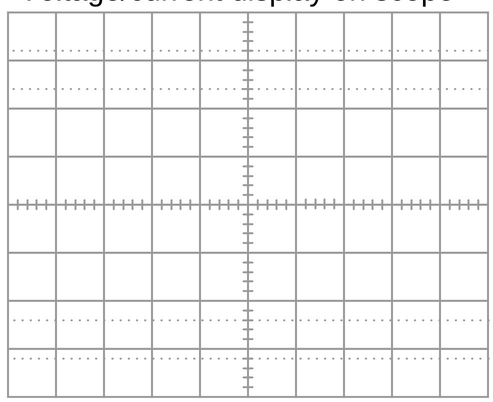
Given conditions

Volts/div =

Sec/div =

R_{shunt} =

Voltage/current display on scope



Parameters

	(Without C_1) Measured	(With C_1 connected) Measured
θ		
I_{total}		

Predicted

C_1 [ ] To correct P.F. to a value of unity

file 01685

Question 73

NAME: _______________ **Project Grading Criteria** PROJECT: _______________

You will receive the highest score for which *all* criteria are met.

<u>100 %</u> *(Must meet or exceed all criteria listed)*

A. Impeccable craftsmanship, comparable to that of a professional assembly
B. No spelling or grammatical errors anywhere in *any* document, upon first submission to instructor

<u>95 %</u> *(Must meet or exceed these criteria in addition to all criteria for 90% and below)*

A. Technical explanation sufficiently detailed to teach from, inclusive of every component (supersedes 75.B)
B. Itemized parts list complete with part numbers, manufacturers, and (equivalent) prices for *all* components, including recycled components and parts kit components (supersedes 90.A)

<u>90 %</u> *(Must meet or exceed these criteria in addition to all criteria for 85% and below)*

A. Itemized parts list complete with prices of components purchased for the project, plus total price
B. No spelling or grammatical errors anywhere in *any* document upon final submission

<u>85 %</u> *(Must meet or exceed these criteria in addition to all criteria for 80% and below)*

A. "User's guide" to project function (in addition to 75.B)
B. Troubleshooting log describing all obstacles overcome during development and construction

<u>80 %</u> *(Must meet or exceed these criteria in addition to all criteria for 75% and below)*

A. All controls (switches, knobs, etc.) clearly and neatly labeled
B. All documentation created on computer, not hand-written (including the schematic diagram)

<u>75 %</u> *(Must meet or exceed these criteria in addition to all criteria for 70% and below)*

A. Stranded wire used wherever wires are subject to vibration or bending
B. Basic technical explanation of all major circuit sections
C. Deadline met for working prototype of circuit (Date/Time = __________ / __________)

<u>70 %</u> *(Must meet or exceed these criteria in addition to all criteria for 65%)*

A. All wire connections sound (solder joints, wire-wrap, terminal strips, and lugs are all connected properly)
B. No use of glue where a fastener would be more appropriate
C. Deadline met for submission of fully-functional project (Date/Time = __________ / __________) – supersedes 75.C if final project submitted by that (earlier) deadline

<u>65 %</u> *(Must meet or exceed these criteria in addition to all criteria for 60%)*

A. Project fully functional
B. All components securely fastened so nothing is "loose" inside the enclosure
C. Schematic diagram of circuit

<u>60 %</u> *(Must meet or exceed these criteria in addition to being safe and legal)*

A. Project minimally functional, with all components located inside an enclosure (if applicable)
B. Passes final safety inspection (proper case grounding, line power fusing, power cords strain-relieved)

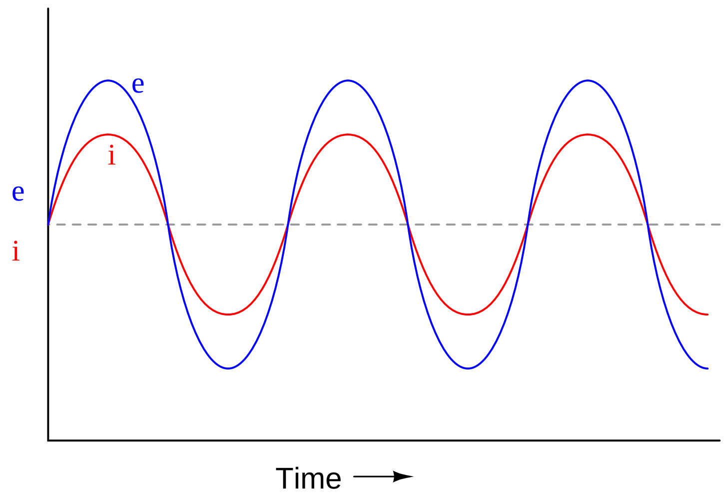
<u>0 %</u> *(If <u>any</u> of the following conditions are true)*

A. Fails final safety inspection (improper grounding, fusing, and/or power cord strain relieving)
B. Intended project function poses a safety hazard
C. Project function violates any law, ordinance, or school policy

<u>file 03173</u>

Question 74

If a sinusoidal voltage is applied to an impedance with a phase angle of 0^o, the resulting voltage and current waveforms will look like this:

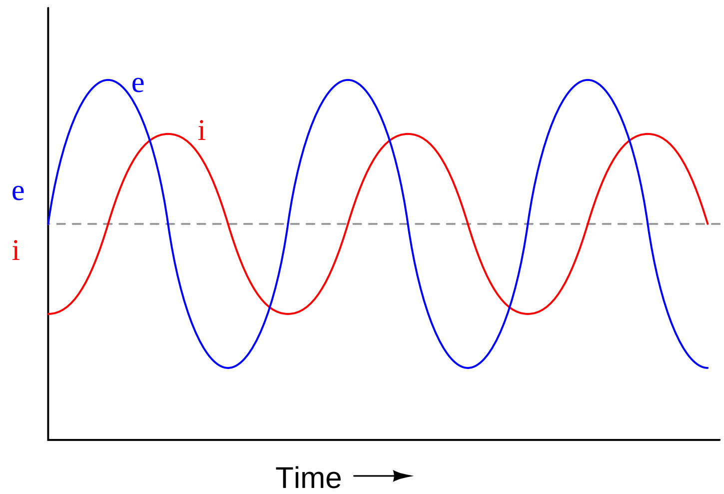


Given that power is the product of voltage and current ($p = ie$), plot the waveform for power in this circuit.

file 00631

Question 75

If a sinusoidal voltage is applied to an impedance with a phase angle of 90^o, the resulting voltage and current waveforms will look like this:

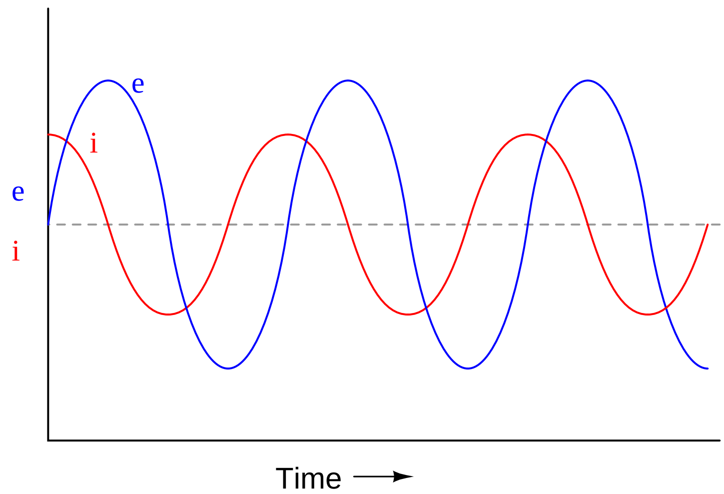


Given that power is the product of voltage and current ($p = ie$), plot the waveform for power in this circuit. Also, explain how the mnemonic phrase *"ELI the ICE man"* applies to these waveforms.

file 00632

Question 76

If a sinusoidal voltage is applied to an impedance with a phase angle of -90^o, the resulting voltage and current waveforms will look like this:

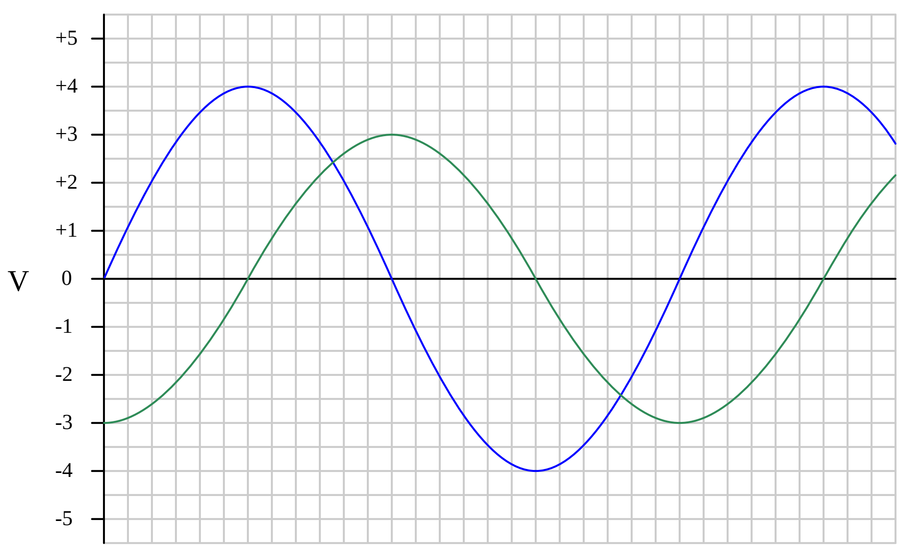


Given that power is the product of voltage and current ($p = ie$), plot the waveform for power in this circuit. Also, explain how the mnemonic phrase *"ELI the ICE man"* applies to these waveforms.

file 00633

Question 77

In this graph of two AC voltages, which one is *leading* and which one is *lagging*?



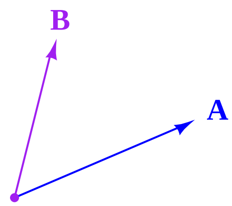
If the 4-volt (peak) sine wave is denoted in phasor notation as 4 V$\angle$ 0^o, how should the 3-volt (peak) waveform be denoted? Express your answer in both polar and rectangular forms.

If the 4-volt (peak) sine wave is denoted in phasor notation as 4 V$\angle$ 90^o, how should the 3-volt (peak) waveform be denoted? Express your answer in both polar and rectangular forms.

file 00499

Question 78

In this phasor diagram, determine which phasor is *leading* and which is *lagging* the other:

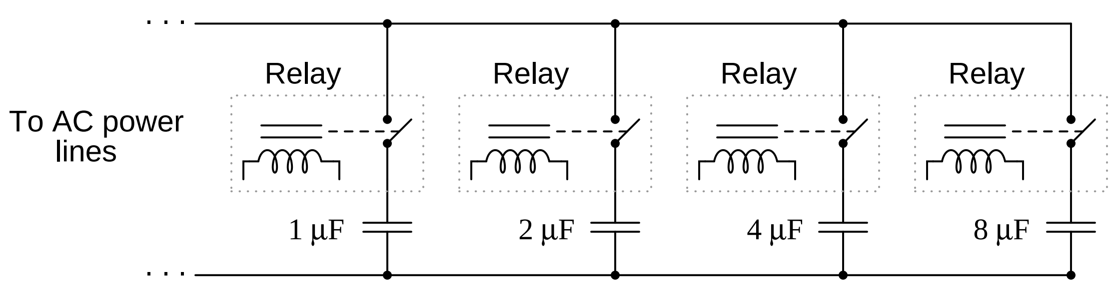


file 03286

Question 79

Large power distribution centers are often equipped with capacitors to correct for lagging (inductive) power factor of many industrial loads. There is never any one value for capacitance that will precisely correct for the power factor, though, because load conditions constantly change. At first it may seem that a variable capacitor would be the answer (adjustable to compensate for *any* value of lagging power factor), but variable capacitors with the ratings necessary for power line compensation would be prohibitively large and expensive.

One solution to this problem of variable capacitance uses a set of electromechanical relays with fixed-value capacitors:

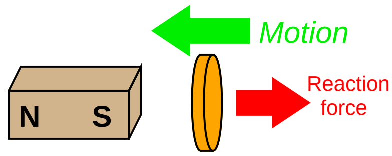


Explain how a circuit such as this provides a step-variable capacitance, and determine the range of capacitance it can provide.

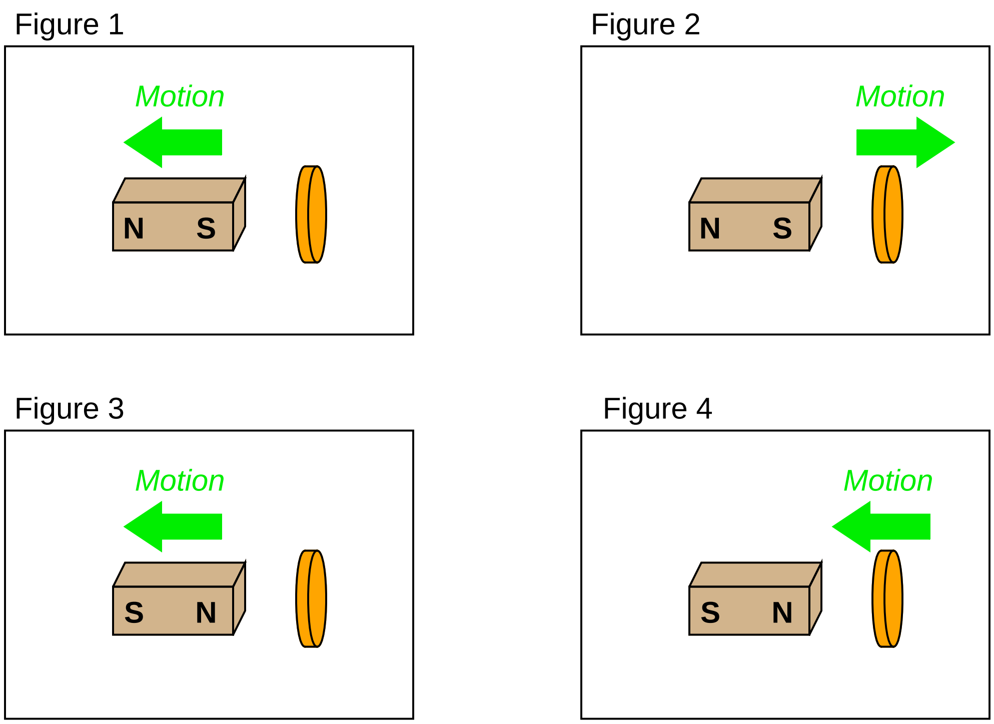
file 03625

Question 80

Lenz's Law describes the opposition to changes in magnetic flux resulting from electromagnetic induction between a magnetic field and an electrical conductor. One apparatus capable of demonstrating Lenz's Law is a copper or aluminum disk (electrically conductive, but non-magnetic) positioned close to the end of a powerful permanent magnet. There is no attraction or repulsion between the disk and magnet when there is no motion, but a force will develop between the two objects if either is suddenly moved. This force will be in such a direction that it tries to resist the motion (i.e. the force tries to maintain the gap constant between the two objects):



We know this force is magnetic in nature. That is, the induced current causes the disk itself to *become* a magnet in order to react against the permanent magnet's field and produce the opposing force. For each of the following scenarios, label the disk's induced magnetic poles (North and South) as it reacts to the motion imposed by an outside force:



file 01982

Question 81

Combining Lenz's Law with the right-hand rule (or left-hand rule, if you follow electron flow instead of conventional flow) provides a simple and effective means for determining the direction of induced current in an induction coil. In the following examples, trace the direction of current through the load resistor:

Figure 1

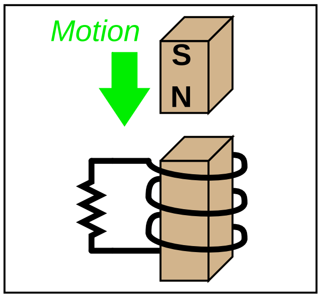


Figure 2

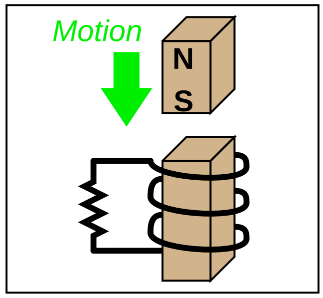


Figure 3

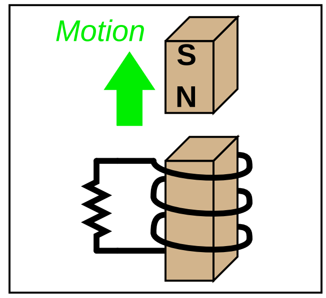


Figure 4

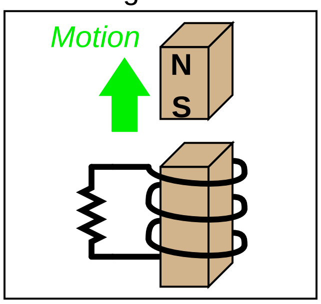


Figure 5

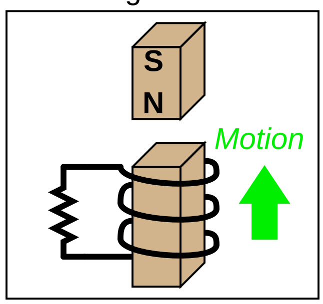
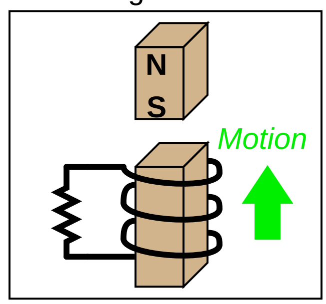


Figure 6



file 01787

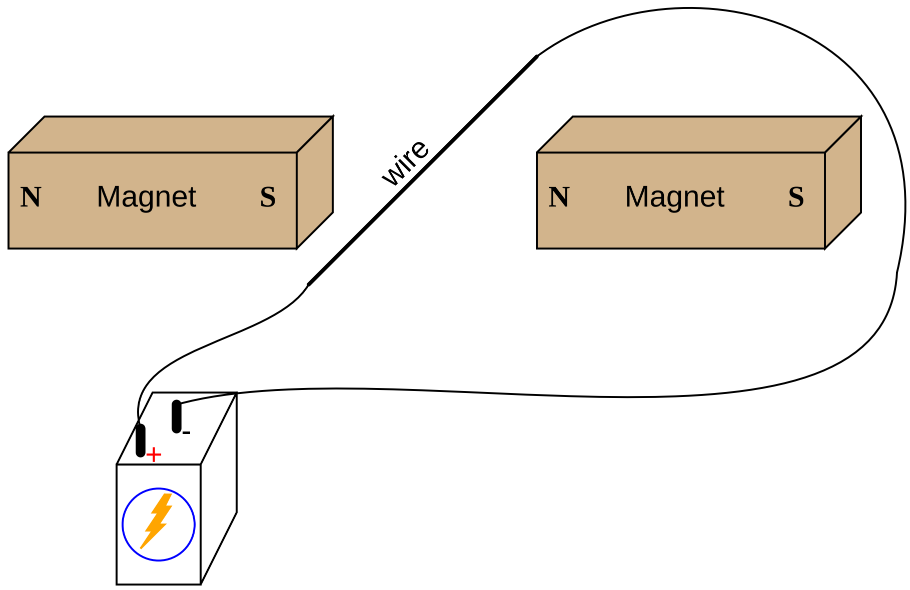
Question 82

Based on your knowledge of Lenz's Law, explain how one could construct an *electromagnetic brake*, whereby the energization of an electromagnet coil would produce mechanical "drag" on a rotating shaft without the need for contact between the shaft and a brake pad.

file 01786

Question 83

If an electric current is passed through this wire, which direction will the wire be pushed (by the interaction of the magnetic fields)?

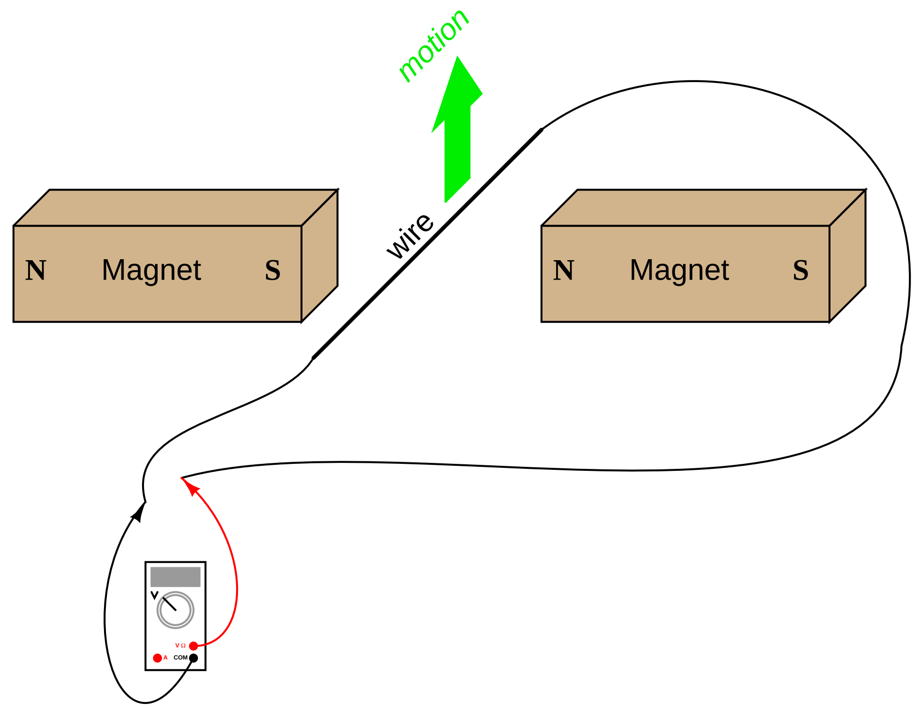


Is this an example of an electric *motor* or an electric *generator*?

file 00382

Question 84

If this wire (between the magnet poles) is moved in an upward direction, what polarity of voltage will the meter indicate?

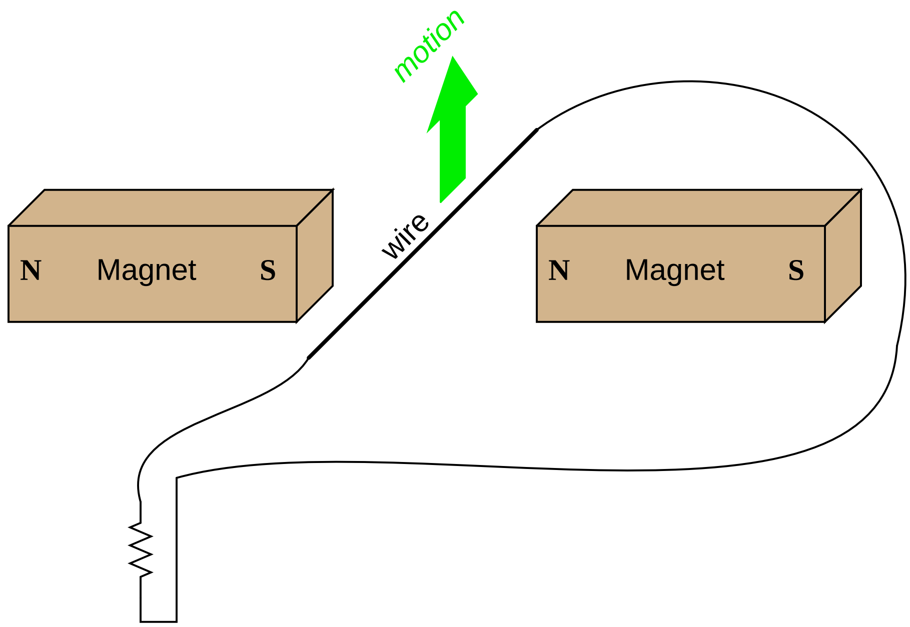


Describe the factors influencing the magnitude of the voltage induced by motion, and determine whether this is an example of an electric *motor* or an electric *generator*.

file 00806

Question 85

If this wire (between the magnet poles) is moved in an upward direction, and the wire ends are connected to a resistive load, which way will current go through the wire?

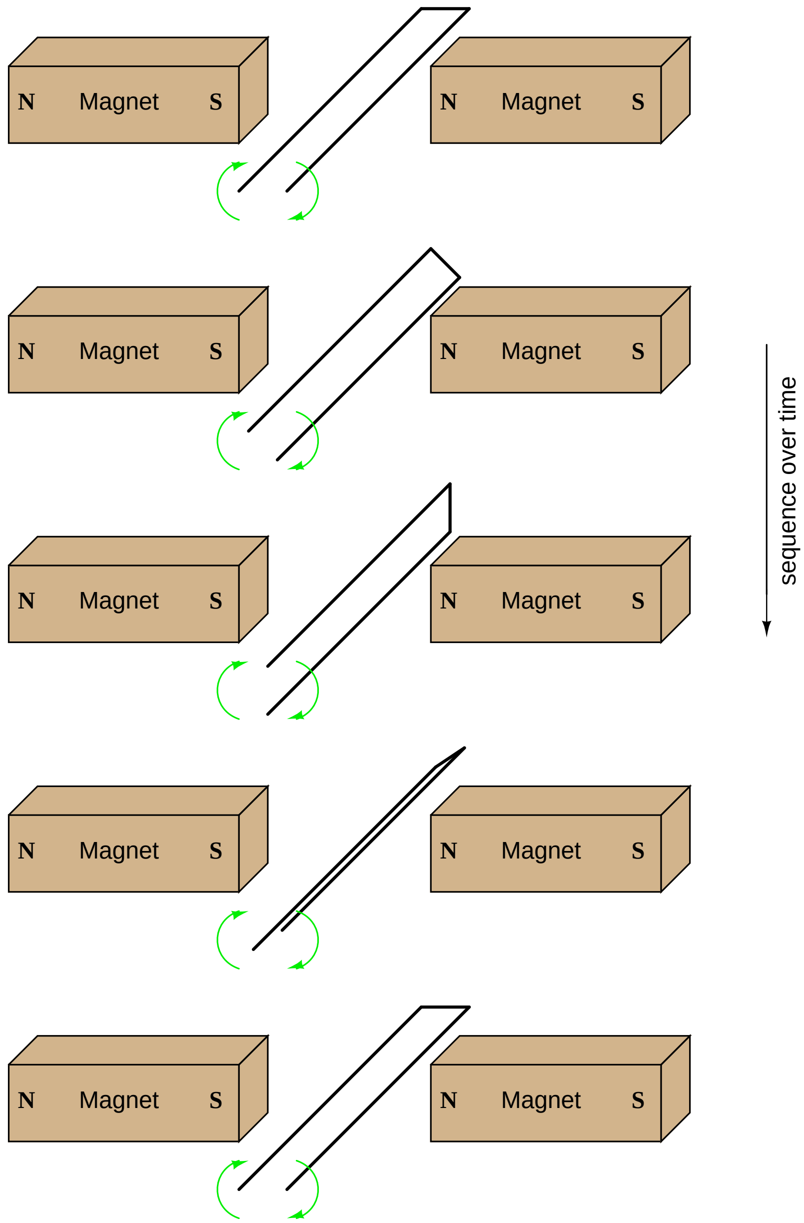


We know that current moving through a wire will create a magnetic field, and that this magnetic field will produce a reaction force against the static magnetic fields coming from the two permanent magnets. Which direction will this reaction force push the current-carrying wire? How does the direction of this force relate to the direction of the wire's motion? Does this phenomenon relate to any principle of electromagnetism you've learned so far?

file 00807

Question 86

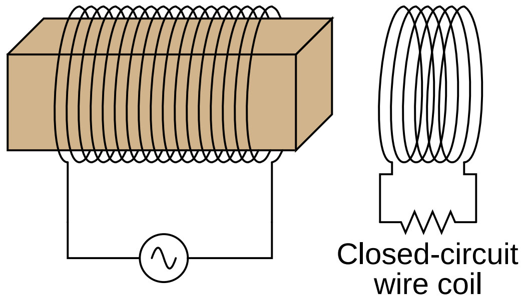
Determine the polarity of induced voltage between the ends of this wire loop, as it is rotated between the two magnets:



file 00808

Question 87

Describe what will happen to a closed-circuit wire coil if it is placed in close proximity to an electromagnet energized by alternating current:



Also, describe what will happen if the wire coil fails open.

file 00736

Question 88

Explain what *slip speed* is for an AC induction motor, and why there must be such as thing as "slip" in order for an induction motor to generate torque.

file 03216

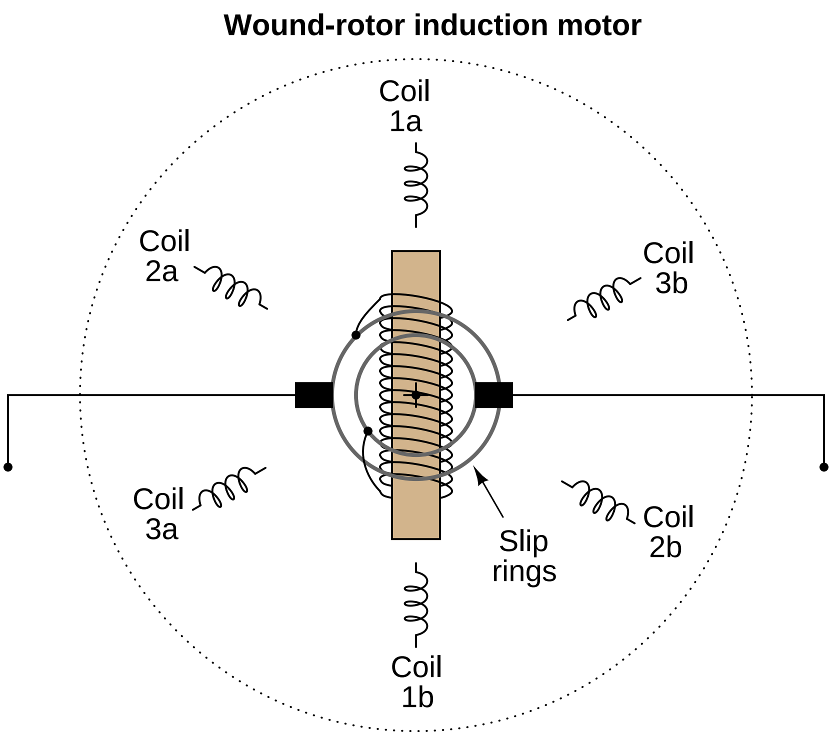
Question 89

Synchronous AC motors operate with zero *slip*, which is what primarily distinguishes them from induction motors. Explain what "slip" means for an induction motor, and why synchronous motors do not have it.

file 03217

Question 90

An interesting variation on the induction motor theme is the *wound-rotor* induction motor. In the simplest form of a wound-rotor motor, the rotor's electromagnet coil terminates on a pair of slip rings which permit contact with stationary carbon brushes, allowing an external circuit to be connected to the rotor coil:



Explain how this motor can be operated as either a synchronous motor or a "plain" induction motor.

file 00741

Question 91

A very common design of AC motor is the so-called *squirrel cage* motor. Describe how a "squirrel cage" motor is built, and classify it as either an "induction" motor or a "synchronous" motor.

file 00742

Question 92

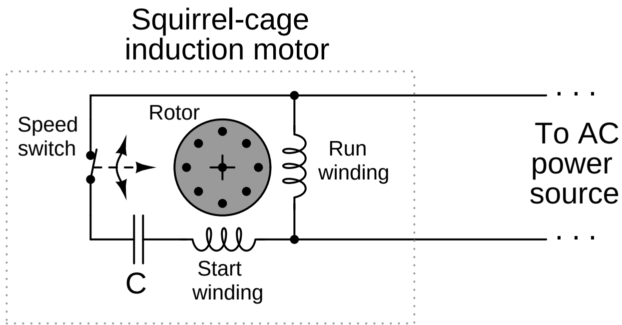
Describe the operating principles of these three methods for starting single-phase induction motors:

- Shaded pole
- Split-phase, capacitor
- Split-phase (resistor or inductor)

file 00744

Question 93

Many single-phase "squirrel-cage" induction motors use a special *start winding* which is energized only at low (or no) speed. When the rotor reaches full operating speed, the starting switch opens to de-energize the start winding:

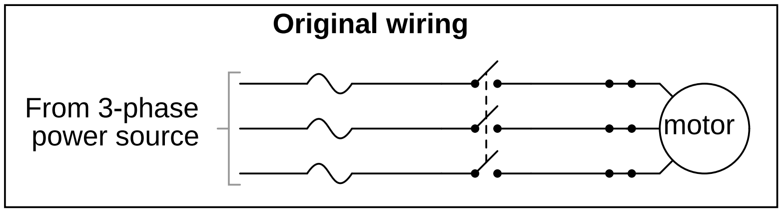


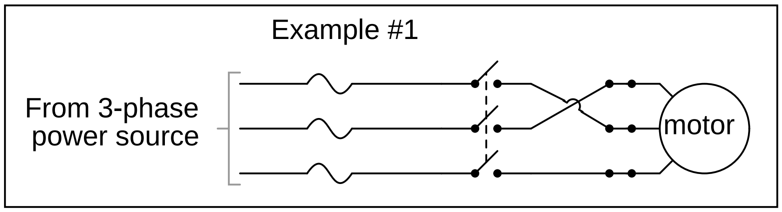
Explain why this special winding is necessary for the motor to start, and also why there is a capacitor connected in series with this start winding. What would happen if the start switch, capacitor, or start winding were to fail open?

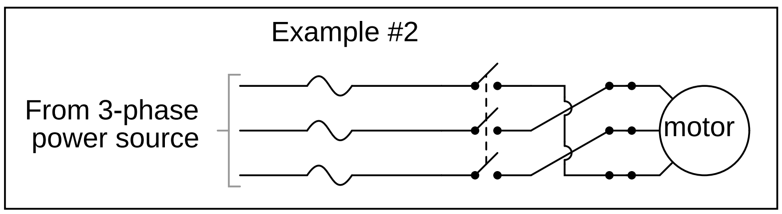
file 03622

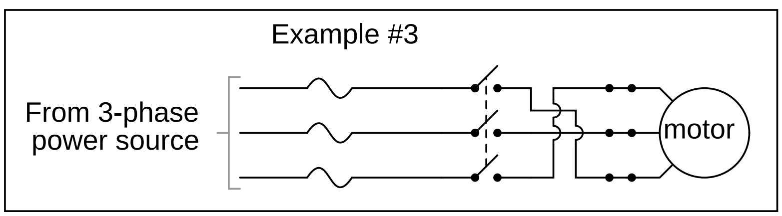
Question 94

The lines of a three-phase power system may be connected to the terminals of a three-phase motor in several different ways. Which of these altered motor connections will result in the motor reversing direction?





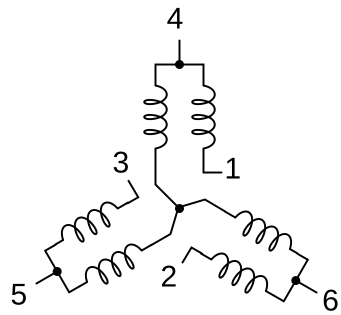




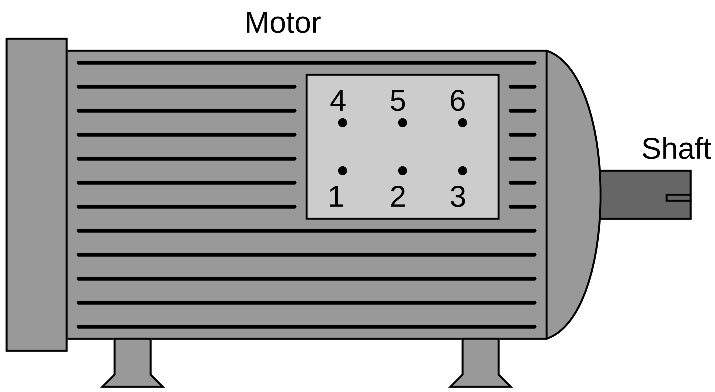
file 00419

Question 95

Some AC induction motors are equipped with multiple windings so they may operate at two distinct speeds (low speed usually being one-half of high speed). Shown here is the connection diagram for one type of two-speed motor:



There are six terminals on the motor itself where the connections are made:



The motor's datasheet will specify how the connections are to be made. This is typical:

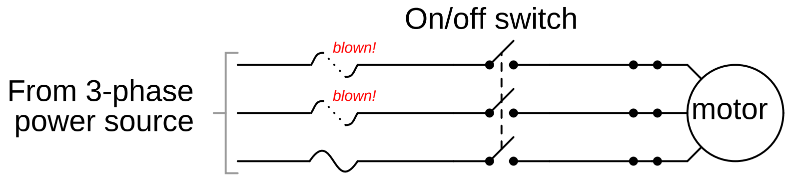
Speed	ϕ-A	ϕ-B	ϕ-C	Left open	Shorted together
Low	1	2	3	4,5,6	
High	4	5	6		1,2,3

Explain why the motor runs at half-speed in one connection scheme and full speed in the other. What is going on that makes this possible?

file 03218

Question 96

This electric motor was operating just fine, then one day it mysteriously shut down. The electrician discovered two blown fuses, which he then replaced:



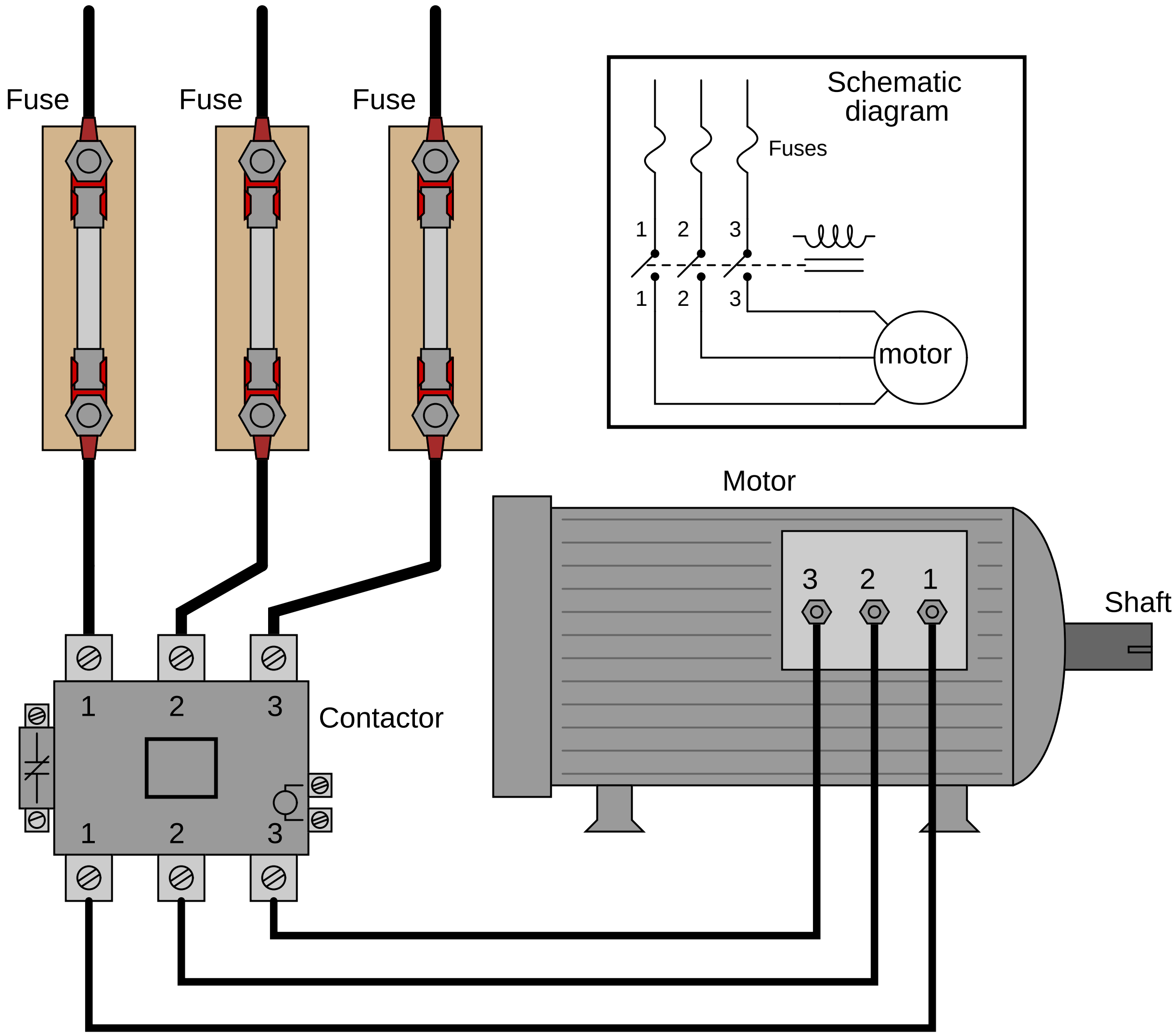
When the on/off switch was closed again, the motor made a loud "humming" noise, then became quiet after a few seconds. It never turned, though. Upon inspection, the electrician discovered the same two fuses had blown again.

If you were asked to help troubleshoot this electric motor circuit, what would you recommend as the next step?

file 00422

Question 97

Examine this three-phase motor control circuit, where fuses protect against overcurrent and a three-pole relay (called a *contactor*) turns power on and off to the motor:



After years of faithful service, one day this motor refuses to start. It makes a "humming" sound when the contactor is energized (relay contacts close), but it does not turn. A mechanic checks it out and determines that the shaft is not seized, but is free to turn. The problem must be electrical in nature!

You are called to investigate. Using a clamp-on ammeter, you measure the current through each of the lines (immediately after each fuse) as another start is once again attempted. You then record the three current measurements:

Line	Current
1	52.7 amps
2	51.9 amps
3	0 amps

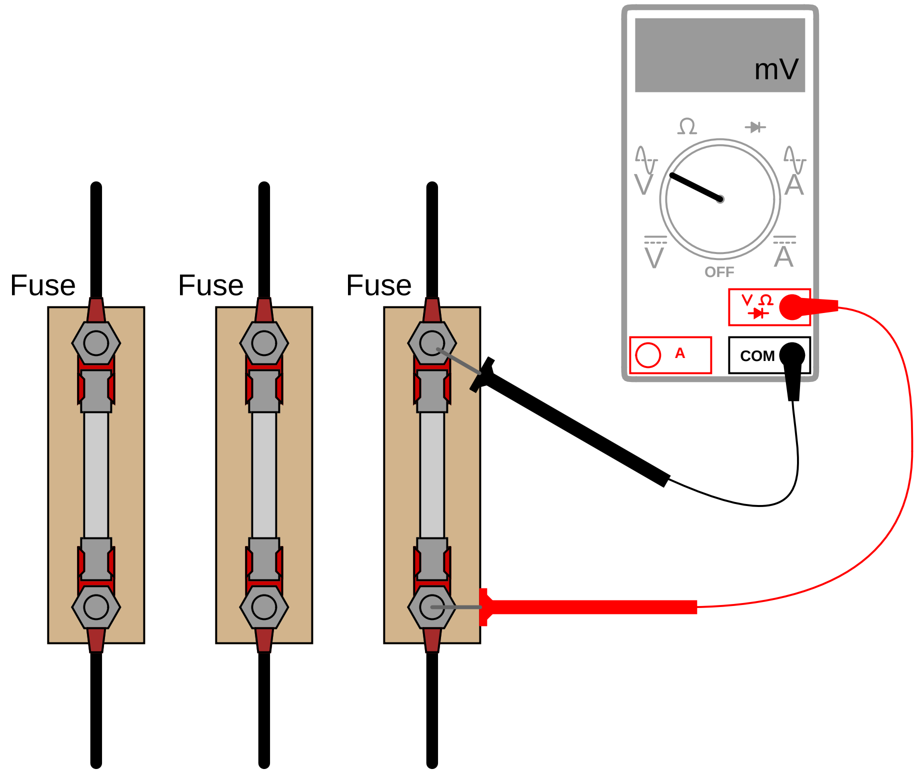
Determine at least two possible faults which could account for the motor's refusal to start and the three current measurements taken. Then, decide what your next measurement(s) will be to isolate the exact location and nature of the fault.

file 03623

Question 98

Working on a job site with an experienced technician, you are tasked with trying to determine whether the line currents going to a three-phase electric motor are balanced. If everything is okay with the motor and the power circuitry, of course, the three line currents should be precisely equal to each other.

The problem is, neither of you brought a clamp-on ammeter for measuring the line currents. Your multimeters are much too small to measure the large currents in this circuit, and connecting an ammeter in series with such a large motor could be dangerous anyway. So, the experienced technician decides to try something different – he uses his multimeter as an AC milli-voltmeter to measure the small voltage drop across each fuse, using the fuses as crude shunt resistors:



He obtains the following measurements:

Line	Fuse voltage drop
1	24.3 mV
2	37.9 mV
3	15.4 mV

Do these voltage drop measurements suggest imbalanced motor line currents? Why or why not?

file 03624

Question 99

How is polyphase (especially three-phase) electric power generated? Single-phase power is easy to understand, but how do we create three-phase AC voltage?

file 00416

Question 100

What is meant by the term *phase rotation sequence*, in a polyphase electrical system?

file 00417

Question 101

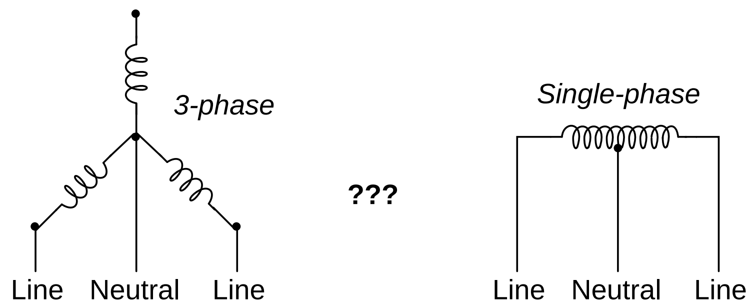
Suppose the electrical power supplied to a commercial building is labeled as "208/120 volt". What does this label mean, exactly? Relate this description to a schematic diagram.

file 00420

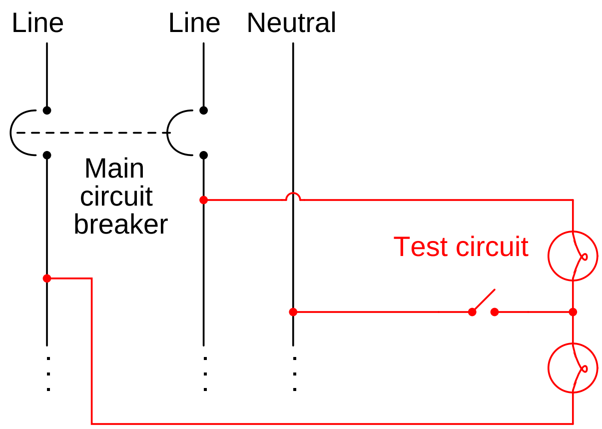
Question 102

Suppose you are working on the power wiring inside of a home, and are wondering whether or not the home is supplied with 3-phase or single-phase power. You do not have a voltmeter available to measure voltage, but you do have plenty of light bulbs, switches, wires, and other standard residential wiring components available for use.

The two possibilities for this home's power source are shown here, the coils representing secondary windings of the utility power transformer:



An experienced electrician suggests you build the following circuit to test whether or not the home's power is supplied by a 3-phase source or a single-phase source:



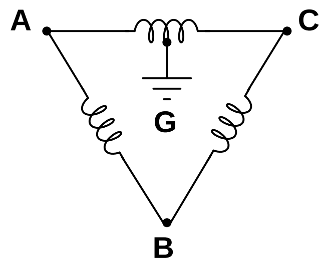
The electrician tells you to open and close the switch, and observe the brightness of the light bulbs. This will indicate whether or not the system is 3-phase.

Explain how this circuit works. What sort of light bulb behavior would indicate a 3-phase source? What sort of light bulb behavior would indicate a single-phase source?

file 00413

Question 103

This Delta-connected three-phase power source provides three different voltage levels: 120 V, 208 V, and 240 V. Determine which points of connection provide these voltages:



file 01058

Question 104

Explain the difference between a *balanced* polyphase system and an *unbalanced* polyphase system. What conditions typically cause a polyphase system to become unbalanced?

file 00418

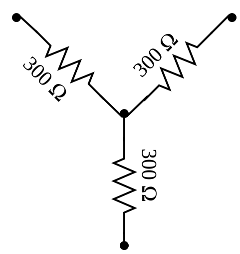
Question 105

In a balanced Y-connected power system, calculate the phase voltage (E_{phase}) if the line voltage (E_{line}) is 480 volts.

file 00412

Question 106

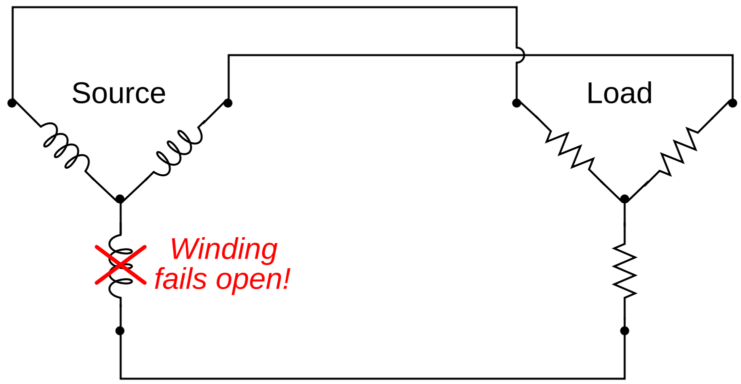
What resistor values would we have to choose in a Delta configuration to behave exactly the same as this Y-connected resistor network?

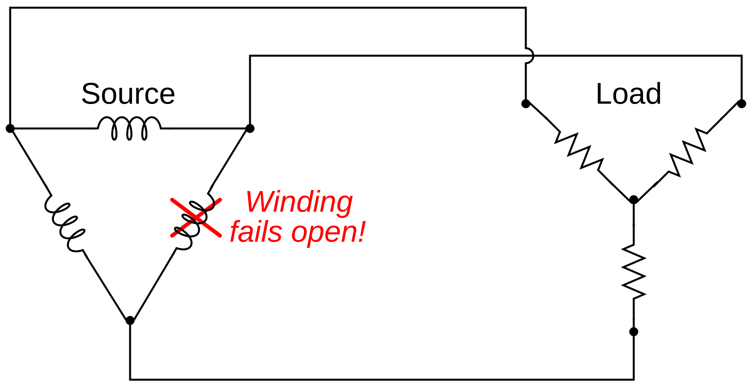


file 00429

Question 107

What will happen in each of these systems to the phase voltages of the load, if one of the source phases fails open?

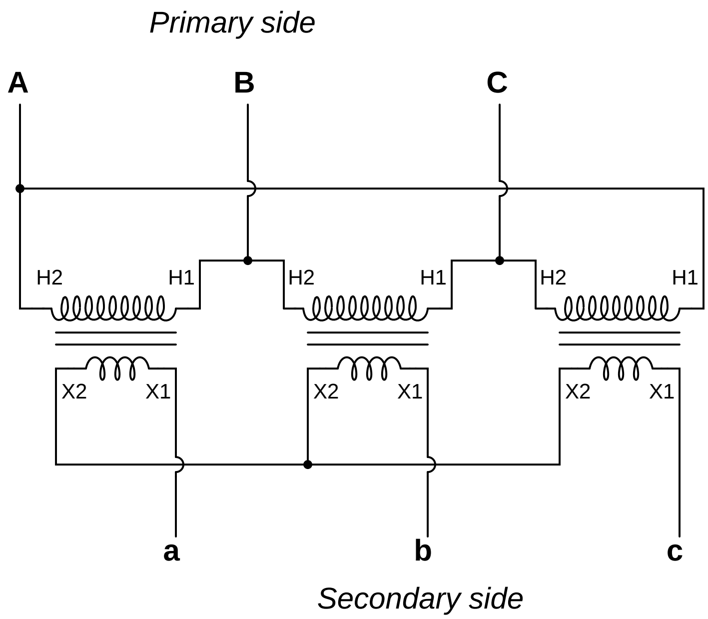




file 00423

Question 108

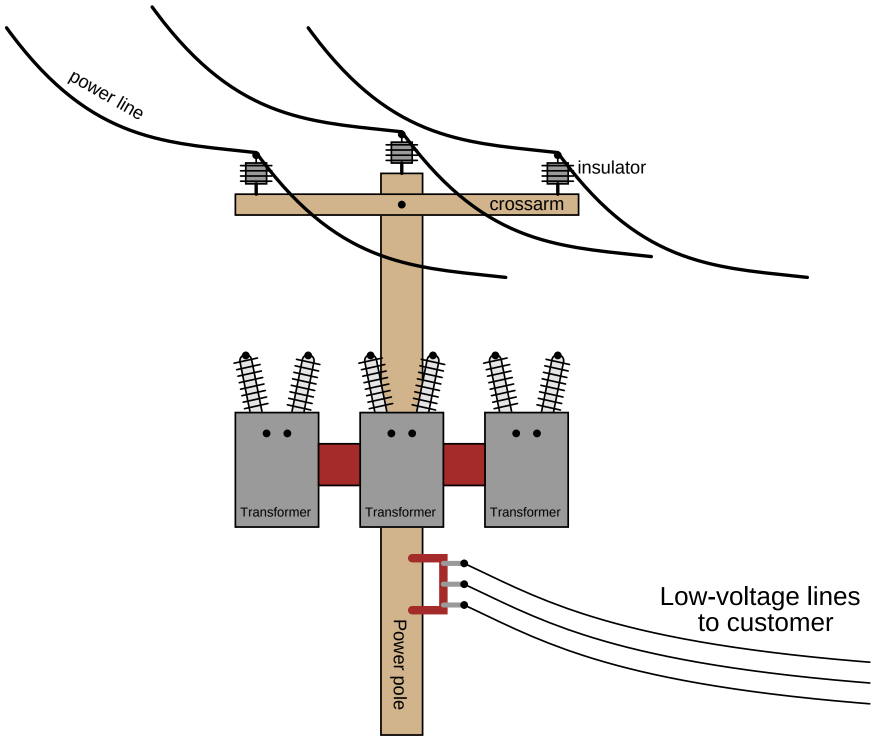
Identify the primary-secondary connection configuration of these three power transformers (i.e. Y-Y, Y-Delta, Delta-Y, etc.):



file 01889

Question 109

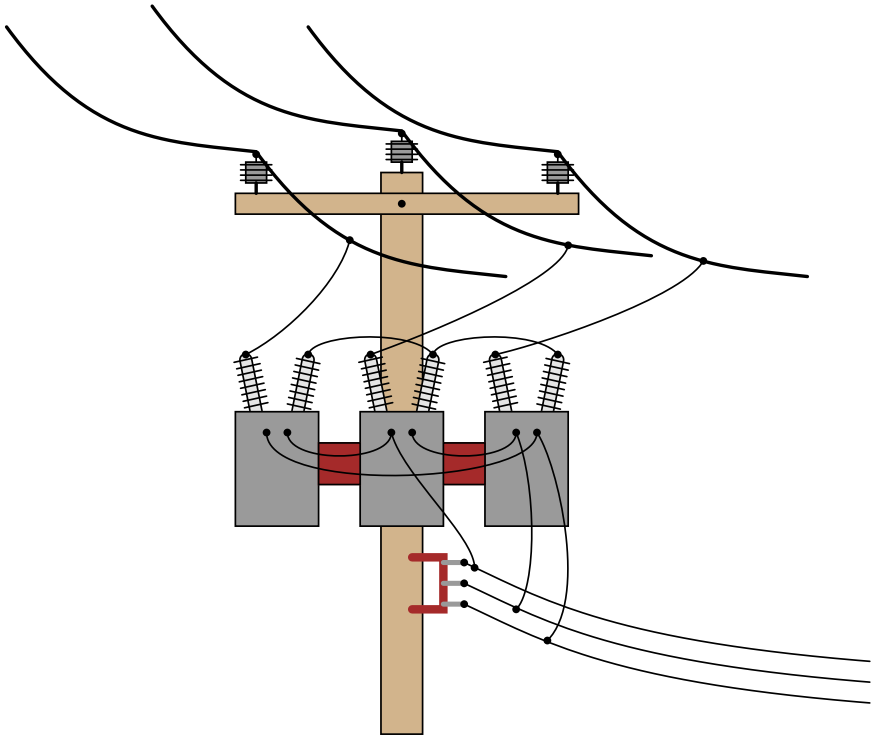
An electrical lineman is connecting three single-phase transformers in a Y(primary)-Y(secondary) configuration, for power service to a business. Draw the connecting wires necessary between the transformer windings, and between the transformer terminals and the lines:



Note: fuses have been omitted from this illustration, for simplicity.
file 00424

Question 110

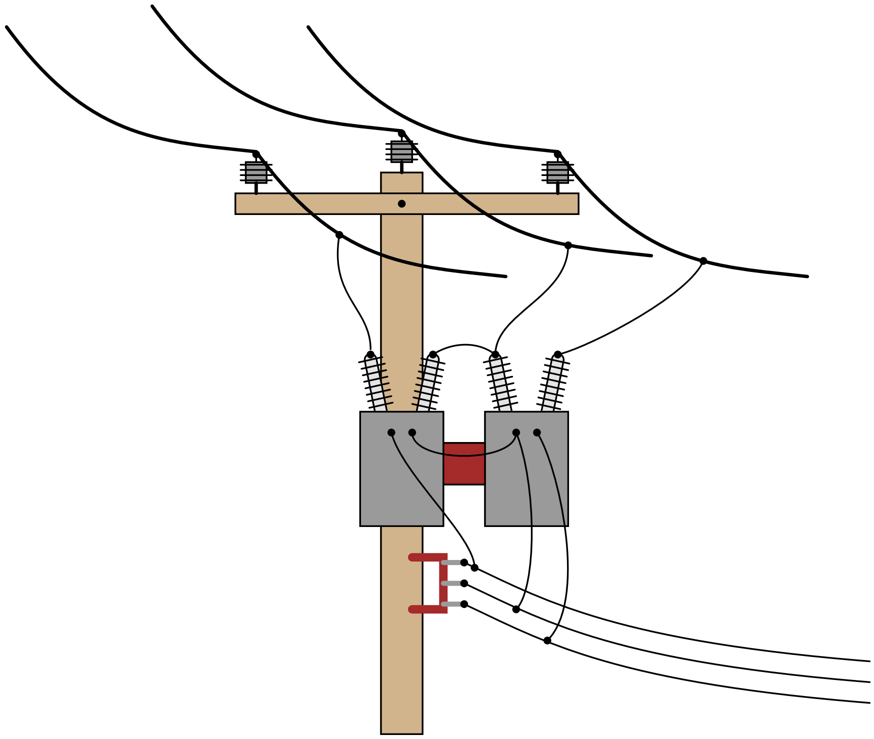
Identify the primary-secondary connection configuration of these pole-mounted power transformers (i.e. Y-Y, Y-Delta, Delta-Y, etc.):



file 00425

Question 111

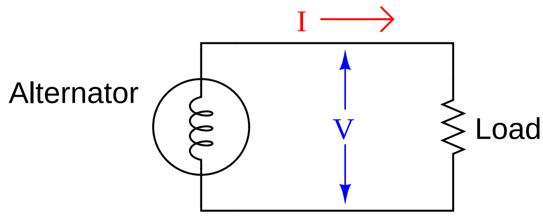
Identify the primary-secondary connection configuration of these pole-mounted power transformers (i.e. Y-Y, Y-Delta, Delta-Y, etc.):



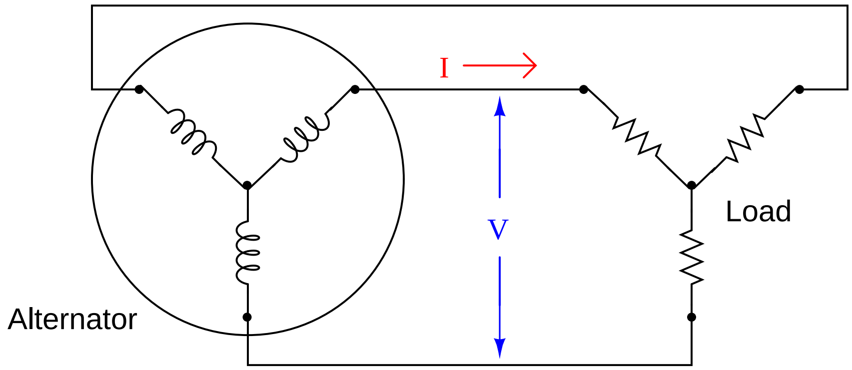
file 00427

Question 112

Calculating apparent power for a single-phase AC circuit is easy – simply multiply line voltage by line current ($S = VI$):



How do we calculate apparent power in a balanced three-phase circuit, given the same figures?



file 03592

Question 113

A very large 3-phase alternator at a hydroelectric dam has the following continuous full-power ratings:

- 600 MW power output
- 15 kV line voltage
- 23.686 kA line current

Calculate the continuous full-load apparent power for this alternator (in MVA), its continuous full-load reactive power (in MVAR), and its power factor (in percent).

file 03591

Question 114

Calculate the full-load line current for a three-phase motor, given a horsepower rating of 150 HP, an efficiency of 93%, and a line voltage of 480 volts. Assume a power factor of 0.90 for full-load conditions.

file 00426

Answer 1

$P = 264$ Watts

If the source is a chemical battery, energy comes from the chemical reactions occurring in the battery's electrolyte, becomes transfered to electrical form, and then converted to heat and light in the bulb, all at the rate of 264 Joules per second (J/s).

Answer 2

The energy consumed by the load must be supplied by whatever mechanical source turns the generator. In this case, the source is the human being pedaling the bicycle.

Follow-up question: what would it mean if a generator required no physical effort to turn while it was powering an electrical load?

Answer 3

Positive power represents energy flowing from the source to the (resistive) load, in this case meaning that energy never returns from the load back to the source.

Answer 4

A symmetrically oscillating power waveform represents energy going back and forth between source and load, never actually dissipating.

Answer 5

The inductor can only store and release energy, not dissipate it. Therefore, its actual power dissipation is zero!

Answer 6

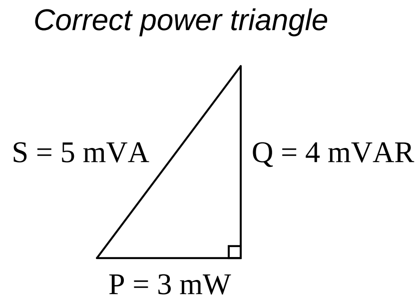
$I = 141.18$ A
$P = 90.8$ horsepower

Answer 7

$I = 141.18$ A
$P = 0$ horsepower, so long as the inductor is "pure" (100 percent inductance, with no resistance).

Answer 8

Only the resistor actually dissipates power. The capacitor only absorbs and releases power, so its "4 mW" figure does not actually represent power in the same sense as the resistor. To make this sensible, we must think of all the non-resistive "powers" as something other than actual work being done over time:



Follow-up question: when making the leap from DC circuit analysis to AC circuit analysis, we needed to expand on our understanding of "opposition" from just resistance (R) to include reactance (X) and (ultimately) impedance (Z). Comment on how this expansion of terms and quantities is similar when dealing with "power" in an AC circuit.

Answer 9

"Apparent" power is *apparently* the total circuit power when volts and amps are multiplied together. "Reactive" power is due to reactive components (L and C) only, and "True" power is the only type that actually accounts for energy leaving the circuit through a load component.

Answer 10

$I = 99.82$ A
$P = 45.4$ horsepower

Answer 11

Fluorescent lamp: $I = 0.674$ A ; Actual power = 60 W

Incandescent lamp: $I = 0.5$ A ; Actual power = 60 W

Induction motor: $I = 0.465$ A ; Actual power = 52.0 W

In every load except for the incandescent lamp, more current is drawn from the source than is "necessary" for the amount of power actually dissipated by the load.

Answer 12

Power factor is the ratio between true power (Watts) and apparent power (Volt-Amps), ranging between 0 and 1 inclusive.

Answer 13

$$S = IV \qquad S = I^2 Z \qquad S = \frac{V^2}{Z} \qquad \text{Apparent power in AC circuits}$$

$$P = IV \cos \Theta \qquad P = I^2 R \qquad P = \frac{V^2}{R} \qquad \text{True power in AC circuits}$$

$$Q = IV \sin \Theta \qquad Q = I^2 X \qquad Q = \frac{V^2}{X} \qquad \text{Reactive power in AC circuits}$$

Follow-up question #1: algebraically manipulate each of the following equations to solve for all the other variables in them:

$$Q = I^2 X \qquad S = \frac{V^2}{Z} \qquad P = I^2 R$$

Follow-up question #2: substitute π, f, and either L or C into the reactive power equations so that one may calculate Q without having to directly know the value of X.

Answer 14

P.F. = 0.872

Answer 15

A *leading* power factor is one created by a predominantly capacitive load, whereas a *lagging* power factor is one created by a predominantly inductive load.

Answer 16

Fluorescent lamp: $P = 60$ W ; $Q = 54.3$ VAR ; $S = 80.9$ VA ; $PF = 0.74$, leading

Incandescent lamp: $P = 60$ W ; $Q = 0$ VAR ; $S = 60$ VA ; $PF = 1.0$

Induction motor: $P = 52.0$ W ; $Q = 20.4$ VAR ; $S = 55.8$ VA ; $PF = 0.93$, lagging

---

Answer 17

$\Theta = \arccos(PF) = 14.1^o$

Answer 18

The beer itself is "true" power (P, measured in Watts). Good beer, good. Ideally, we'd like to have a full mug of beer (true power). Unfortunately, we also have foam in the mug, representing "reactive" power (Q, measured in Volt-Amps-Reactive), which does nothing but occupy space in the mug. Bad foam, bad. Together, their combined volume constitutes the "apparent" power in the system (S, measured in Volt-Amps).

Follow-up question: can you think of any potential safety hazards that low power factor may present in a high-power circuit? We're talking AC power circuits here, not beer!

Answer 19

Use an oscilloscope to measure the circuit's Θ (phase shift between voltage and current), and then calculate the power factor from that angle.

Follow-up question #1: explain how you could safely measure currents in the range of hundreds or thousands of amps, and also measure voltages in the range of hundreds or thousands of volts, using an *oscilloscope*. Bear in mind that you need to simultaneously plot both variables on the oscilloscope in order to measure phase shift!

Follow-up question #2: explain how you could measure either S, Q, or P using a multimeter.

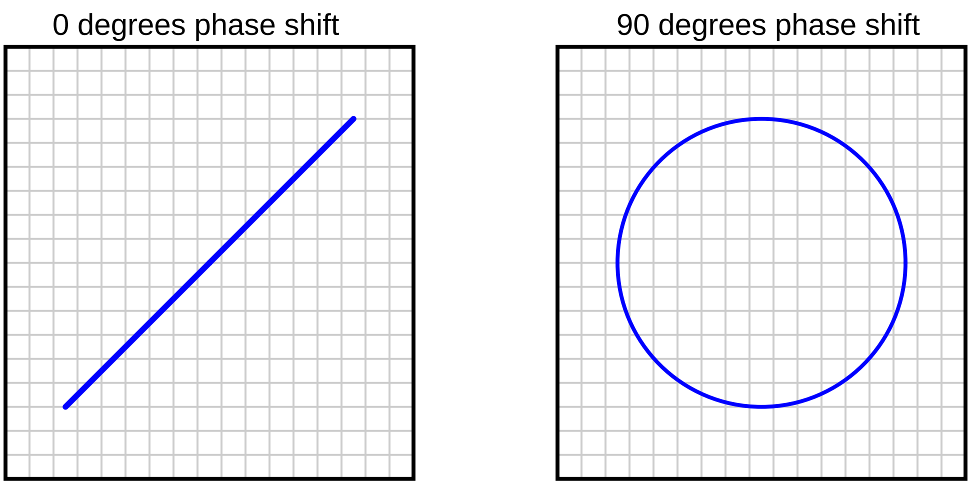
Answer 20

P.F. = 1 ; current = 72.98 amps

P.F. = 0.65 ; current = 112.3 amps

Follow-up question: what is the "extra" current in the 0.65 power factor scenario doing, if not contributing to the motor's mechanical power output?

Answer 21



Challenge question: what kind of Lissajous figures would be plotted by the oscilloscope if the signals were non-sinusoidal? Perhaps the simplest example of this would be two square waves instead of two sine waves.

Answer 22

$$\Theta = \sin^{-1}\left(\frac{m}{n}\right)$$

Challenge question: what kind of Lissajous figure would be drawn by two sinusoidal waveforms at slightly different frequencies?

Answer 23

$\Theta \approx 57^o$ P.F. ≈ 0.54

Follow-up question: is this the only way we could have used the oscilloscope to measure phase shift between voltage and current, or is there another mode of operation besides plotting Lissajous figures?

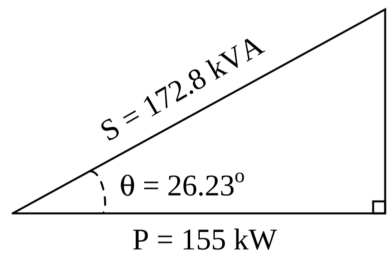
Answer 24

P.F. ≈ 0.84, lagging (most likely)

Follow-up question: is it possible to determine which waveform is leading or lagging the other from a Lissajous figure? Explain your answer.

Answer 25

P.F. = 0.897 $\Theta = 26.23^o$



Answer 26

Without capacitor

- $S = 1.432$ VA
- $P = 0$ W
- $Q = 1.432$ VAR

With capacitor

- $S = 0.369$ VA
- $P = 0$ W
- $Q = 0.369$ VAR

Answer 27

Without capacitor

- $I_{line} = 48$ A
- P.F. = 0.829

With capacitor

- $I_{line} = 39.87$ A
- P.F. = 0.998

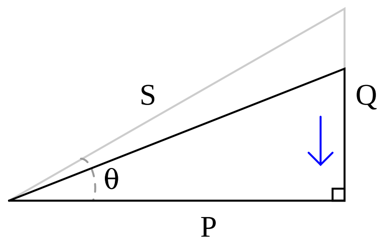
Follow-up question: does the addition of the capacitor affect the amount of current through the 5 Ω load? Why or why not?

Answer 28

Low power factors result in excessive line current.

Answer 29

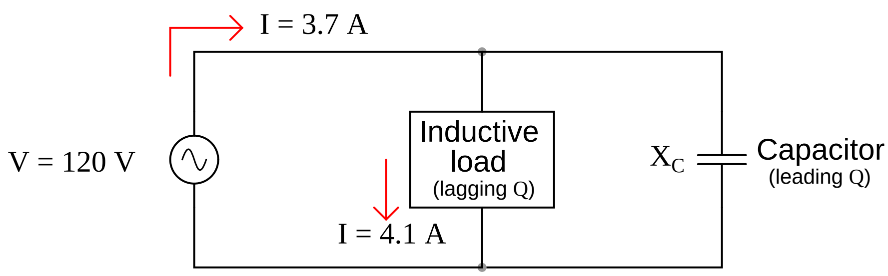
As power factor is brought closer to unity (1), the power triangle "flattens," with P remaining constant:



Answer 30

$$Q_C = \frac{E^2}{X_C} \qquad Q_C = I^2 X_C$$

Follow-up question: which of the two equations shown above would be easiest to use in calculating the reactive power of a capacitor given the following information?



Answer 31

- Apparent power (S) = 2.787 kVA
- True power (P) = 2.567 kW
- Reactive power (Q) = 1.089 kVAR
- Power factor = 0.921
- Correction capacitor value = 66.77 μF

Challenge question: write an equation solving for the power factor correction capacitor size (in Farads) given any or all of the variables provided in the question (S, P, Q, f, V, P.F.).

Answer 32

- Apparent power (S) = 72.45 kVA
- True power (P) = 52.89 kW
- Reactive power (Q) = 49.52 kVAR
- $\Theta = 43.11^o$
- Necessary parallel C size to correct power factor to unity = 2,483 μF

Answer 33

- Apparent power (S) = 17.23 MVA
- Reactive power (Q) = 8.107 MVAR
- Power factor = 0.882
- $\Theta = 28.1^o$
- Necessary parallel C size to correct power factor to unity = 1.951 μF

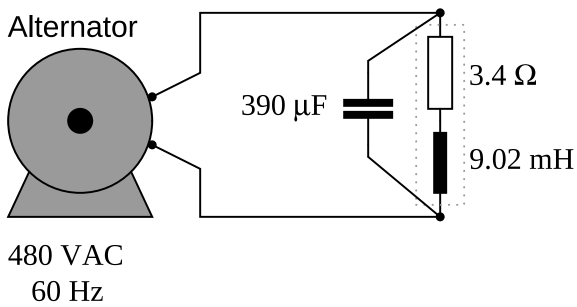
Answer 34

- Apparent power (S) = 352 VA
- True power (P) = 328.2 W
- Reactive power (Q) = 127.2 VAR
- $\Theta = 21.2^o$
- Power factor = 0.932
- Necessary parallel C size to correct power factor to unity = 27.9 μF

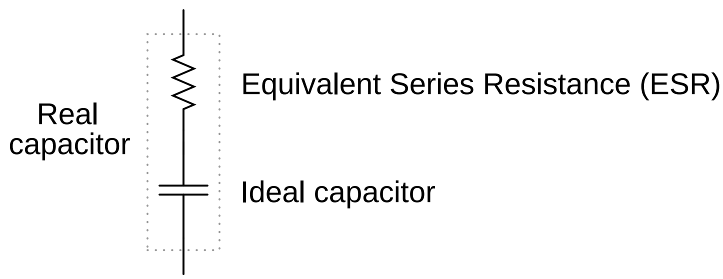
Follow-up question: identify which waveform represents voltage and which waveform represents current on the oscilloscope display.

Answer 35

Uncorrected power factor = 0.707, lagging



Follow-up question: when we use capacitors as power factor correction components in an AC power system, the equivalent series resistance (ESR) inside the capacitor becomes a significant factor:



Current through this equivalent series resistance produces heat, and when we're dealing with MVARs worth of reactive power in high-current circuits, this heat can be substantial unless ESR is held low by special capacitor designs. Describe some possible hazards of excessive ESR for a power factor correction capacitor in a high-current circuit.

Challenge question: the ideal location for power factor correction capacitors is at the load terminals, where the reduction in current will be "felt" by all components in the system except the load itself. However, in real life, power factor correction capacitors are often located at the power plant (the alternator). Why would anyone choose to locate capacitors there? What benefit would they provide at all, in that location?

Answer 36

I'll let you determine your own procedure, based on the steps you had to take to correct power factor in other questions!

Power factor correction calculation procedure

-
-
-
-
-
-

Answer 37

This is essentially a series-resonant circuit, with all the inherent dangers of series resonance (I'll let you review what those dangers are!).

Follow-up question: aside from safety, there is also the matter of reliability that concerns us. Examine the parallel-capacitor circuit and the series-capacitor circuit from the perspective of a failed capacitor. Explain how each type of capacitor failure (open versus short) will affect these two circuits.

Answer 38

If inductive loads have their low power factors corrected by the addition of parallel capacitors, the solution to correcting low power factor for a capacitive load should be easy to identify. I'll let you figure out the answer to this!

Challenge question: explain how you could exploit the inductive nature of electric motors and other more common load devices in correcting for an excessively low leading power factor.

Answer 39

It is true that inductors and capacitors alike neither dissipate nor generate electrical energy. They do, however, *store* and *release* energy. And they do so in complementary fashion, inductors storing energy at the same time that capacitors release, and visa-versa.

Part of the answer to this question lies in the fact that most large AC loads are inductive in nature. From a power plant's perspective, the reactive power of a customer (a "consumer" of power) is inductive in nature, and so that form of reactive power would naturally be considered "consumption."

Answer 40

A "synchronous condenser" is a special type of AC electric motor that happens to have a variable power factor. They are used as variable capacitors to correct for changing power factors.

Challenge question: capacitors are considered reactive devices because they have to ability to store and release energy. How would a synchronous condenser store and release energy, seeing as it does not make use of electric fields as capacitors do?

Answer 41

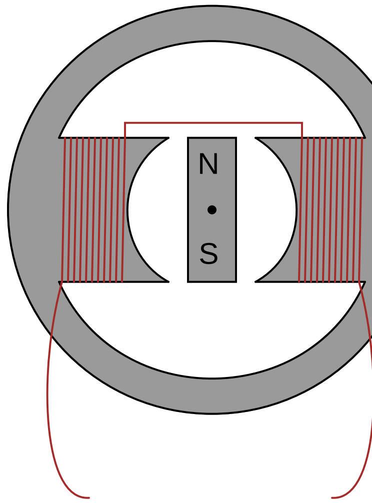
The answer to this question is easy enough to determine experimentally. I'll let you discover it for yourself rather than give you the answer here.

Hint: the voltage generated by a magnetic field with a single wire is quite weak, so I recommend using a very sensitive voltmeter and/or a powerful magnet. Also, if the meter is analog (has a moving pointer and a scale rather than a digital display), you must keep it far away from the magnet, so that the magnet's field does not directly influence the pointer position.

Follow-up question: identify some potential problems which could arise in this experiment to prevent induction from occurring.

Answer 42

The alternator voltage peaks when the magnetic flux is at the zero-crossover point:



(The actual magnet polarities are not essential to the answer. Without knowing which way the coils were wound and which way the rotor is spinning, it is impossible to specify an exact magnetic polarity, so if your answer had "N" facing down and "S" facing up, it's still acceptable.)

Answer 43

Increase the $\frac{d\phi}{dt}$ rate of change, or increase the number of turns in the stator winding, to increase the magnitude of the AC voltage generated by this machine.

Follow-up question: AC generators, or *alternators* as they are sometimes called, are typically long-lived machines when operated under proper conditions. But like all machines, they will eventually fail. Based on the illustration given in the question, identify some probable modes of failure for an alternator, and what conditions might hasten such failures.

Answer 44

It is more practical by far to build an alternator with a stationary wire coil and a rotating magnet than to build one with a stationary magnet and a rotating wire coil, because a machine with a rotating coil would require some form of *brushes* and *slip rings* to conduct power from the rotating shaft to the load.

Follow-up question: what is so bad about brushes and slip rings that we want to avoid them in alternator design if possible?

Answer 45

$f = 75$ Hz

Answer 46

$S = 600$ RPM, for $f = 60$ Hz.

$$S = \frac{120f}{N}$$

Follow-up question: algebraically manipulate this equation to solve for the number of poles (N) needed in a generator given speed (S) and frequency (f).

Answer 47

8 poles, which is the same as 4 pole *pairs*.

Follow-up question: algebraically manipulate the speed/poles/frequency equation to solve for the frequency generated (f) given the number of poles (N) and the generator speed (S).

Answer 48

The rotor cannot be a permanent magnet, but must be an electromagnet, where we can change its magnetic field strength at will.

Follow-up question: how is it possible to conduct electric power to windings on a spinning rotor? Should we energize the rotor winding with AC or DC? Explain your answer.

Answer 49

The lamps will blink from left to right (**C-B-A-C-B-A**).

Follow-up question: suppose lamp **B** stopped blinking, while lamps **A** and **C** continued. Identify at least two possible causes for this failure.

Answer 50

99 volts

Hint: if you don't understand how this voltage value was calculated, plot the voltage output of the two windings as if they were shown on an oscilloscope. The *phase relationship* between the two voltages is key to the solution.

Follow-up question: draw a phasor diagram showing how the difference in potential (voltage) between the wire ends is equal to 99 volts, when each winding coil's voltage is 70 volts.

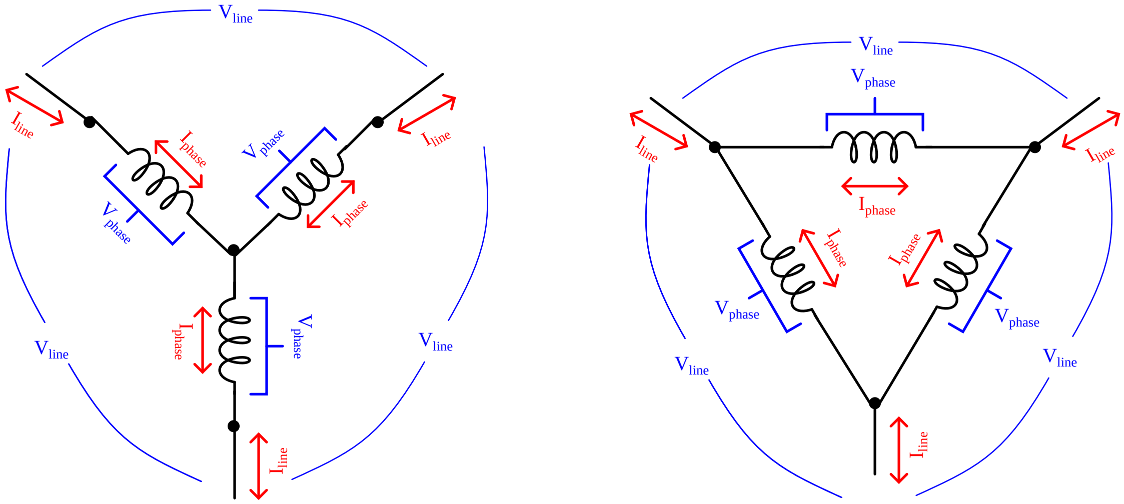
Answer 51

121.2 volts

Follow-up question: draw a phasor diagram showing how the difference in potential (voltage) between the wire ends is equal to 121.2 volts, when each winding coil's voltage is 70 volts.

Answer 52

In polyphase systems, there are multiple voltages phase-shifted apart from each other so as to be intentionally "out of step."



Y configuration

- $I_{phase} = I_{line}$
- $V_{phase} < V_{line}$

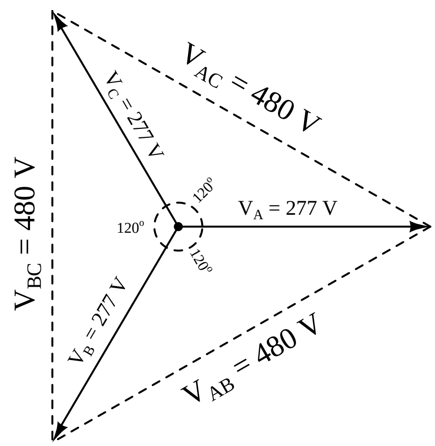
Delta configuration

- $V_{phase} = V_{line}$
- $I_{phase} < I_{line}$

Follow-up question: how do Kirchhoff's Voltage and Current Laws explain the relationships between unequal quantities in "Y" and "Delta" configurations?

Answer 54

Phase voltage = 277 volts AC (given)
Line voltage = $V_{AB} = V_{BC} = V_{AC} = 480$ volts AC



Follow-up question #1: what is the ratio between the line and phase voltage magnitudes in a Y-connected three-phase system?

Follow-up question #2: what would happen to the output of this alternator if the rotor winding were to fail open? Bear in mind that the rotor winding is typically energized with DC through a pair of brushes and slip rings from an external source, the current through this winding being used to control voltage output of the alternator's three-phase "stator" windings.

Answer 55

Phase current = 17 amps AC (given)
Line current = $I_A = I_B = I_C = 29.4$ amps AC

Follow-up question #1: what is the ratio between the line and phase current magnitudes in a Delta-connected three-phase system?

Follow-up question #2: what would happen to the output of this alternator if the rotor winding were to fail open? Bear in mind that the rotor winding is typically energized with DC through a pair of brushes and slip rings from an external source, the current through this winding being used to control voltage output of the alternator's three-phase "stator" windings.

Answer 56

The phenomenon is known as *Lenz' Law*. If the copper ring is moved *away* from the end of the permanent magnet, the direction of force will reverse and become attractive rather than repulsive.

Follow-up question: trace the direction of rotation for the induced electric current in the ring necessary to produce both the repulsive and the attractive force.

Challenge question: what would happen if the magnet's orientation were reversed (south pole on left and north pole on right)?

Answer 57

The phenomenon is known as *Lenz' Law*, and it exists only when there is a continuous path for current (i.e. a complete circuit) in the wire coil.

Answer 58

This is an example of *Lenz' Law*. A rotating magnet would cause a torque to be generated in the disk.

Answer 59

If arranged in a circle, the lights would appear to rotate. The speed of this "rotation" depends on the *frequency* of the on/off blinking.

Follow-up question: what electrical change(s) would you have to make to reverse the direction of the lights' apparent motion?

Challenge question: what would happen to the apparent motion of the lights if one of the phases (either 1, 2, or 3) were to fail, so that none of the bulbs with that number would ever light up?

Answer 60

The compass needle would rotate.

Challenge question: what would happen to the apparent motion of the magnetic field if one of the phases (either 1, 2, or 3) were to fail, so that none of the coils with that number would ever energize?

Answer 61

The rotor will rotate due to the action of Lenz's Law.

Follow-up question: what would happen if the rotor's coil were to become open-circuited?

Answer 62

Synchronous motors rotate in "sync" to the power line frequency. Induction motors rotate a bit slower, their rotors always "slipping" slightly slower than the speed of the rotating magnetic field.

Challenge question: what would happen if an induction motor were mechanically brought up to speed with its rotating magnetic field? Imagine using an engine or some other prime-mover mechanism to force the induction motor's rotor to rotate at synchronous speed, rather than "slipping" behind synchronous speed as it usually does. What effect(s) would this have?

Answer 63

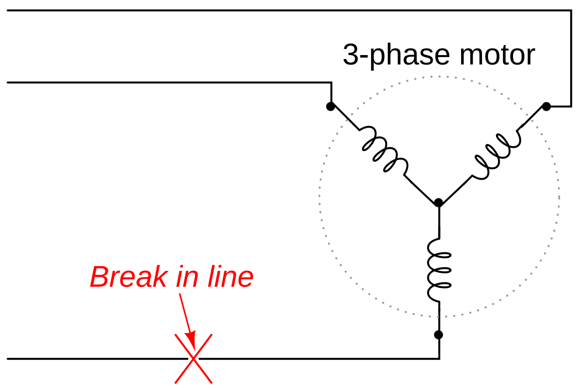
Reverse any two lines. This will reverse the phase sequence (from ABC to CBA).

Answer 64

The rotor would not spin at all – it would merely vibrate. However, if you mechanically forced the rotor to spin in one direction, it would keep going that direction, speeding up until it reached full speed.

Follow-up question: what does this tell us about the behavior of single-phase induction motors that is fundamentally different from polyphase induction motors?

Challenge question: what does this tell us about the effects of an open line conductor on a three-phase induction motor?



Answer 65

$E_{line} = 230$ V
$I_{line} = 7.967$ A
$E_{phase(source)} = 230$ V
$I_{phase(source)} = 4.6$ A
$E_{phase(load)} = 230$ V
$I_{phase(load)} = 4.6$ A
$P_{total} = 3.174$ kW

Answer 66

$E_{line} = 13.8$ kV
$I_{line} = 5.312$ A
$E_{phase(source)} = 7.967$ kV
$I_{phase(source)} = 5.312$ A
$E_{phase(load)} = 7.967$ kV
$I_{phase(load)} = 5.312$ A
$P_{total} = 126.96$ kW

Answer 67

$E_{line} = 2400$ V
$I_{line} = 4.619$ A
$E_{phase(source)} = 2400$ V
$I_{phase(source)} = 2.667$ A
$E_{phase(load)} = 1385.6$ V
$I_{phase(load)} = 4.619$ A
$P_{total} = 19.2$ kW

Answer 68

$E_{line} = 207.8$ V
$I_{line} = 0.621$ A
$E_{phase(source)} = 120$ V
$I_{phase(source)} = 0.621$ A
$E_{phase(load)} = 207.8$ V
$I_{phase(load)} = 0.358$ A
$P_{total} = 223.4$ W

Answer 69

$P_{total} = 27.648$ kW
$I_{line} = 33.255$ A

I'll let you derive your own equation for power calculation. Be ready to show your work!

Answer 70

$P_{load} = 3.59$ MW

A single-phase system operating at 13.8 kV would require at least 1/0 ("one-ought") gauge copper conductors to transmit 3.59 MW of power. A three-phase system operating at the same voltage would require at least #2 gauge copper conductors.

Answer 71

Use circuit simulation software to verify your predicted and measured parameter values.

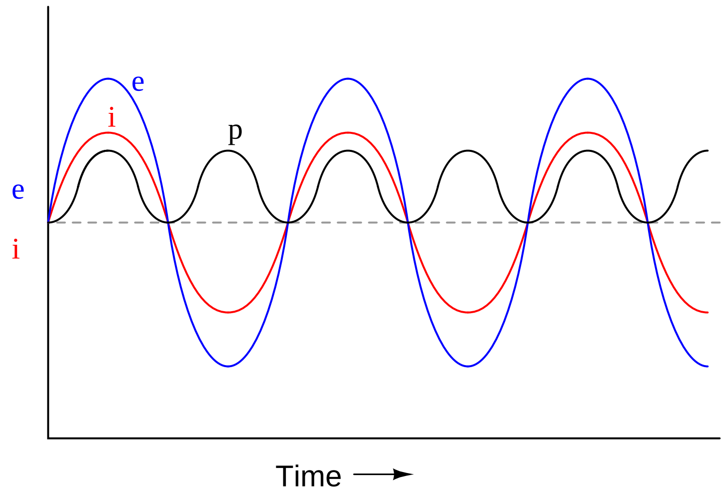
Answer 72

The meter measurements you take will constitute the "final word" for validating your predictions.

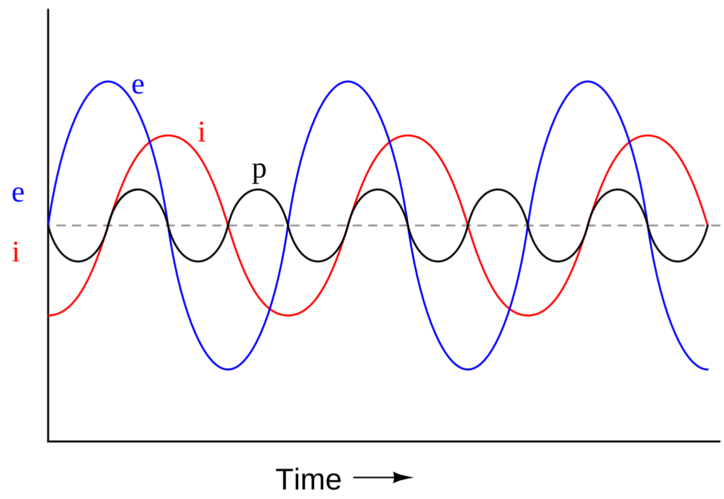
Answer 73

Be sure you meet with your instructor if you have any questions about what is expected for your project!

Answer 74

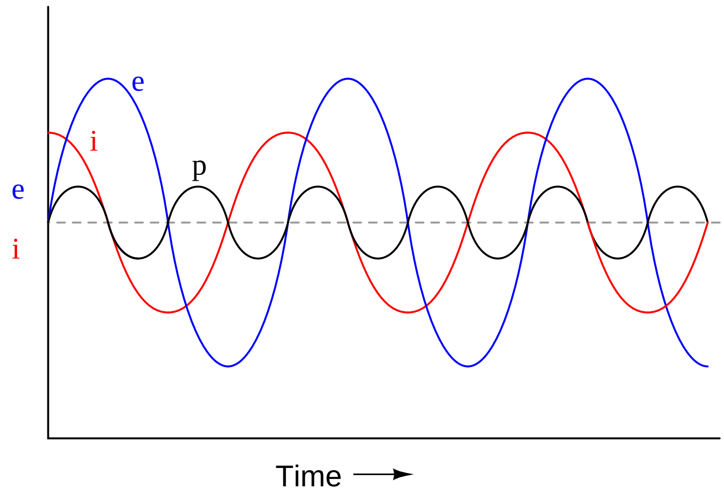


Answer 75



The mnemonic phrase, "ELI the ICE man" indicates that this phase shift is due to an inductance rather than a capacitance.

Answer 76



The mnemonic phrase, "ELI the ICE man" indicates that this phase shift is due to a capacitance rather than an inductance.

Answer 77

The 4-volt (peak) waveform *leads* the 3-volt (peak) waveform. Conversely, the 3-volt waveform *lags* behind the 4-volt waveform.

If the 4-volt waveform is denoted as 4 V $\angle$ 0^o, then the 3-volt waveform should be denoted as 3 V $\angle$ -90^o, or $0 - j3$ V.

If the 4-volt waveform is denoted as 4 V $\angle$ 90^o ($0 + j4$ V in rectangular form), then the 3-volt waveform should be denoted as 3 V $\angle$ 0^o, or $3 + j0$ V.

Answer 78

In this diagram, phasor **B** is leading phasor **A**.

Follow-up question: using a protractor, estimate the amount of phase shift between these two phasors.

Answer 79

Capacitors may be selected in combination to provide anywhere from 0 μF to 15 μF, in 1 μF steps.

Answer 80

The disk's own magnetic field will develop in such a way that it "fights" to keep a constant distance from the magnet:

Figure 1

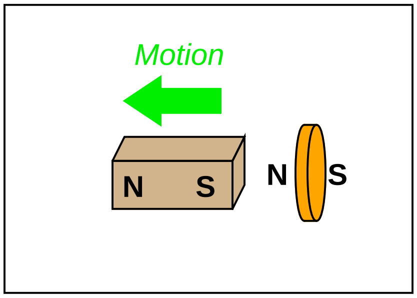


Figure 2

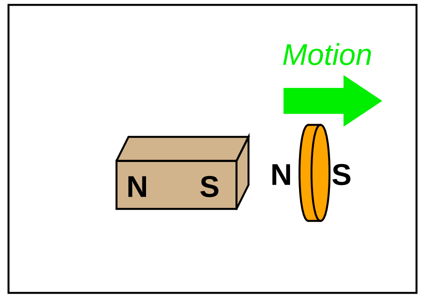


Figure 3

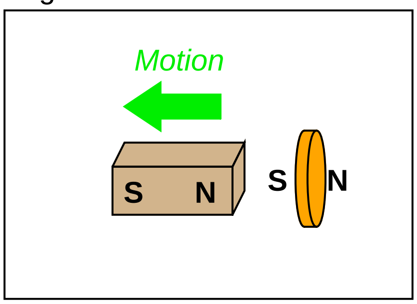
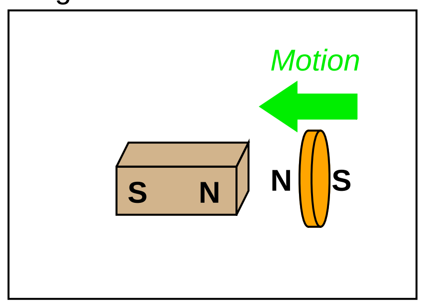


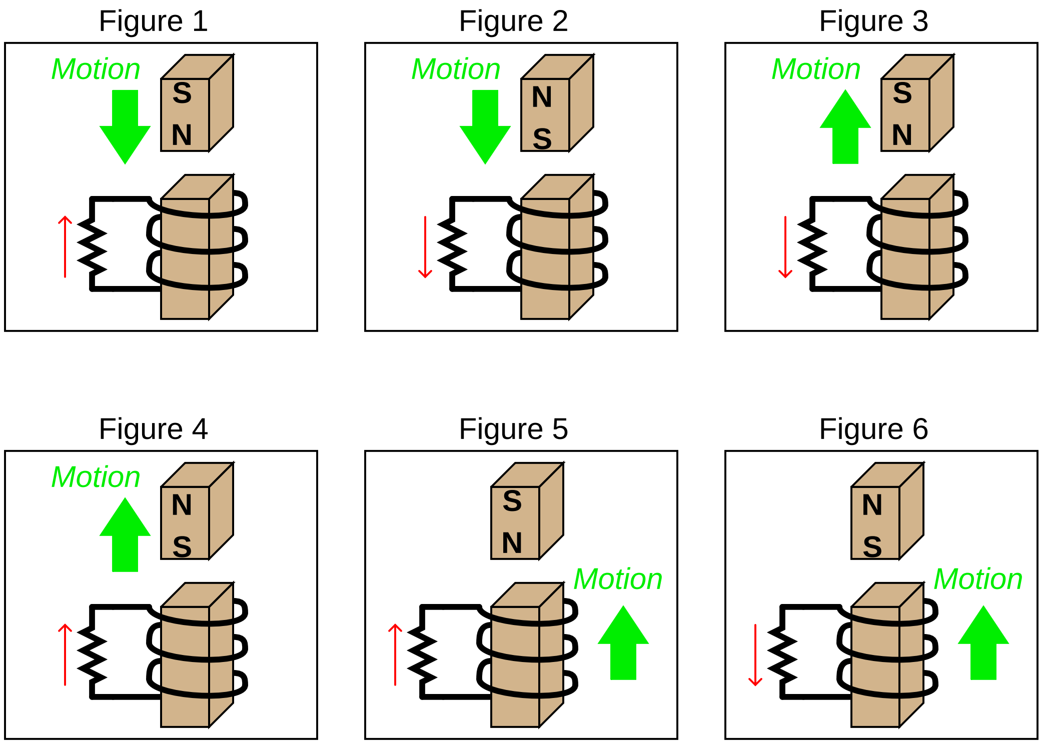
Figure 4



Follow-up question: trace the direction of rotation for the induced electric current in the disk necessary to produce both the repulsive and the attractive force.

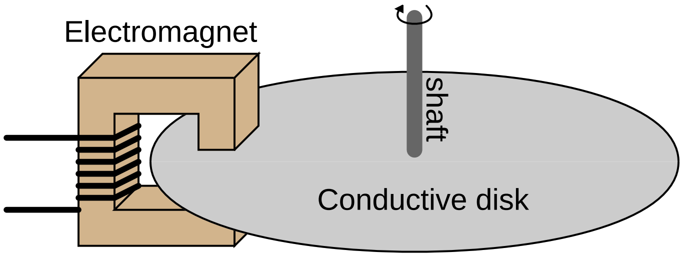
Answer 81

Note: in case it isn't clear from the illustrations, Figures 1 through 4 show the magnet moving in relation to a stationary coil. Figures 5 and 6 show a coil moving in relation to a stationary magnet.



Note: all current directions shown using conventional flow notation (following the right-hand rule)

Answer 82



Follow-up question: describe some of the advantages and disadvantages that a magnetic brake would have, compared to mechanical brakes (where physical contact produces friction on the shaft).

Challenge question: normal (mechanical) brakes become hot during operation, due to the friction they employ to produce drag. Will an electromechanical brake produce heat as well, given that there is no physical contact to create friction?

Answer 83

The wire will be pushed *up* in this *motor* example.

Answer 84

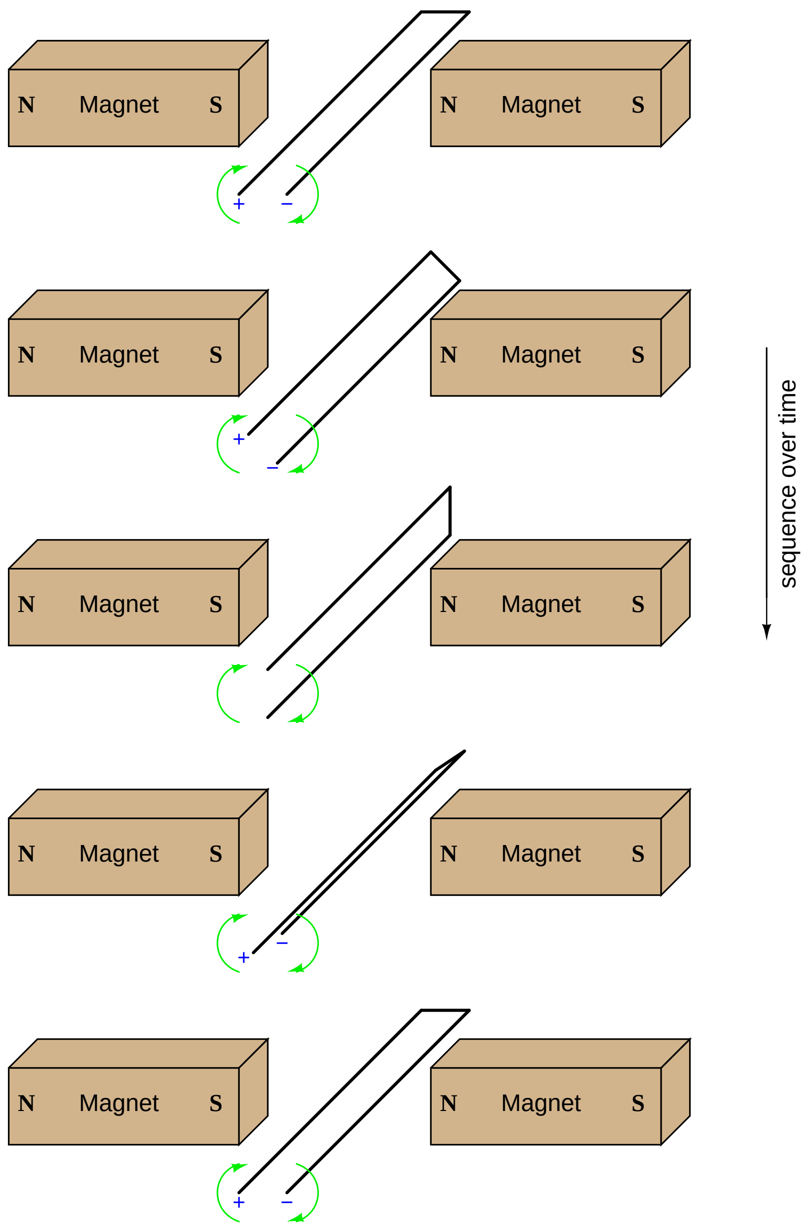
The voltmeter will indicate a negative voltage in this *generator* example.

Answer 85

The reaction force will be directly opposed to the direction of motion, as described by Lenz's Law.

Follow-up question: What does this phenomenon indicate to us about the ease of moving a generator mechanism under load, versus unloaded? What effect does placing an electrical load on the output terminals of a generator have on the mechanical effort needed to turn the generator?

Answer 86



Challenge question: if a resistor were connected between the ends of this wire loop, would it "see" direct current (DC), or alternating current (AC)?

Answer 87

The wire coil will vibrate as it is alternately attracted to, and repelled by, the electromagnet. If the coil fails open, the vibration will cease.

Challenge question: how could we *vary* the coil's vibrational force without varying the amplitude of the AC power source?

Answer 88

The difference between the speed of the rotating magnetic field (fixed by line power frequency) and the speed of the rotor is called "slip speed". Some amount of slip is necessary to generate torque because without it there would be no change in magnetic flux ($\frac{d\phi}{dt}$) seen by the rotor, and thus no induced currents in the rotor.

Answer 89

Synchronous motors do not slip because their rotors are magnetized so as to always follow the rotating magnetic field precisely. Induction motor rotors are become magnetized by induction, necessitating a difference in speed ("slip") between the rotating magnetic field and the rotor.

Answer 90

A wound-rotor motor with a single rotor coil may be operated as a synchronous motor by energizing the rotor coil with direct current (DC). Induction operation is realized by short-circuiting the slip rings together, through the brush connections.

Challenge question: what will happen to this motor if a *resistance* is connected between the brushes, instead of a DC source or a short-circuit?

Answer 91

There is a lot of information on "squirrel cage" electric motors. I will leave it to you to do the research.

Answer 92

In each of these techniques, a "trick" is used to create a truly rotating magnetic field from what would normally be a reciprocating (single-phase) magnetic field. The "shaded pole" technique is magnetic, while the other two techniques use phase-shifting. I will leave research of the details up to you.

Answer 93

Single-phase AC has no definite direction of "rotation" like polyphase AC does. Consequently, a second, phase-shifted magnetic field must be generated in order to give the rotor a starting torque.

Challenge question: explain what you would have to do to reverse the direction of this "capacitor-start" motor.

Answer 94

Examples #1 and #3 will reverse the motor's rotation (as compared to the original wiring). Example #2 will not.

Answer 95

The difference between the two connection schemes is the polarity of three of the coils in relation to the other three. This is called the *consequent pole* design of two-speed motor, where you essentially double the number of poles in the motor by reconnection.

Answer 96

Obviously, something is wrong with the circuit, if it keeps blowing the same two fuses. So, the answer is *not*, "Install larger fuses!"

It would make sense to proceed by answering this question: what type of fault typically blows fuses? What types of tests could you perform on a circuit like this in order to locate those types of faults? Bear in mind that the behavior of electric motors is quite unlike many other types of loads. This is an electromechanical device, so the problem may not necessarily be limited to electrical faults!

Answer 97

Here are some possibilities:

- Fuse #3 blown open
- Third relay contact damaged (failed open) inside the contactor
- One winding failed open inside the motor (assuming a "Y" winding configuration)

There are several valid "next steps" you could take from this point. Discuss alternatives with your classmates.

Answer 98

The results are inconclusive, because resistance for the whole fuse and holder assembly is not a reliably stable quantity. Corrosion between one of the fuse ends and the fuse holder clip, for example, would increase resistance between the points where millivoltage is shown measured.

Follow-up question: just because the results of these millivoltage measurements are inconclusive in this scenario does not necessarily mean the principle of using fuses as current-indicating shunt resistors is useless. Describe one application where using a fuse as a current-indicating shunt would yield trustworthy information about the current.

Challenge question: determine where you could measure millivoltage, that might be more reliable in terms of quantitatively indicating line current.

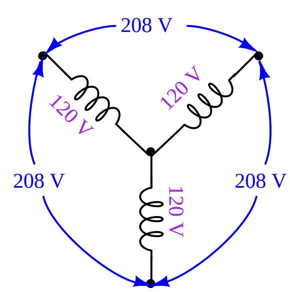
Answer 99

Polyphase AC voltages are usually created by special alternators, with different "phase" windings spaced around the circumference of the stator.

Answer 100

"Phase rotation sequence" refers to the successive order in which the various phase voltages reach their positive peaks.

Answer 101



Answer 102

On a single-phase system, there should be no change in light bulb brightness as the switch is opened and closed. On a three-phase system, there will be a change in brightness between the two different switch states (I'll let you figure out which switch state makes the light bulbs glow brighter!).

Answer 103

$V_{AB} = V_{BC} = V_{AC} = 240$ volts

$V_{AG} = V_{CG} = 120$ volts

$V_{BG} = 208$ volts

Answer 104

A "balanced" polyphase system is one where all line voltages are equal to each other, and all line currents are also equal to each other. "Unbalanced" conditions usually stem from unsymmetrical loads, although severe imbalances may be caused by faults in the system.

Answer 105

$E_{phase} = 277$ V

Answer 106

Each resistor in a Delta-connected network must have a value of 900 Ω, to be equivalent to a Y-connected network of 300 Ω resistors.

Answer 107

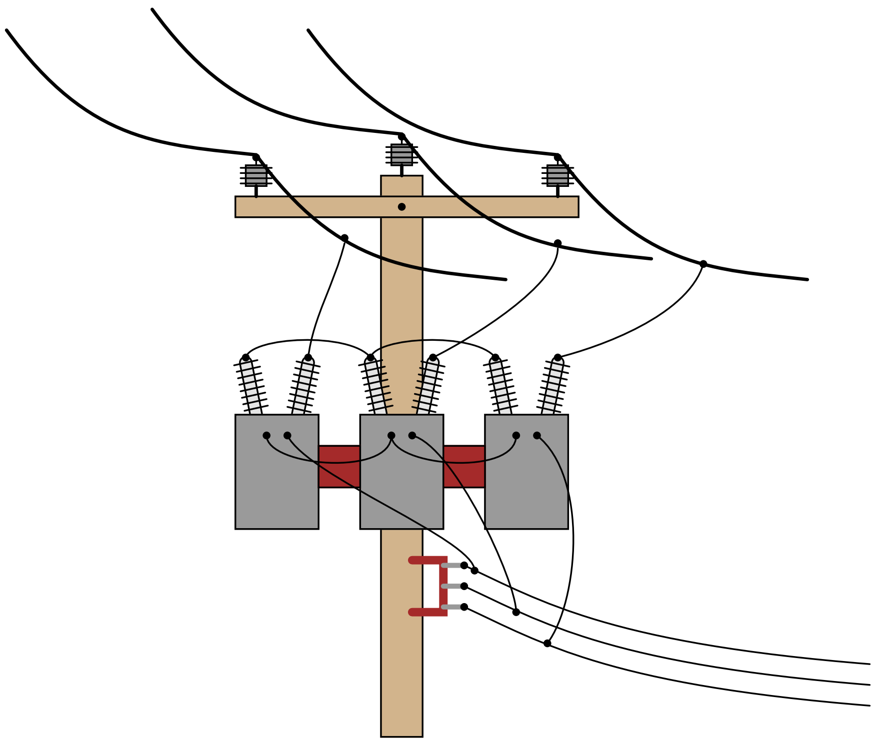
In the Y-Y system, with no neutral wire, one of the load phases will completely lose power, while the voltages of the other two load phases will be reduced to 86.7 % of normal.

In the Delta-Y system, none of the phase voltages will be affected by the failure of the source phase winding.

Answer 108

Delta-Y

Answer 109



Of course, this is not the only way these three transformers could be connected in a Y-Y configuration.

Answer 110

These transformers are connected in a Y-Delta configuration.

Answer 111

These transformers are connected in an *open-Delta* configuration.

Answer 112

$S = \sqrt{3}(VI)$

Follow-up question: suppose the three-phase system were a Delta configuration instead of a Wye configuration. Does this influence the apparent power calculation? Why or why not?

Answer 113

$S = 615.38$ MVA $\quad$ $Q = 136.72$ MVAR $\quad$ P.F. = 97.5%

Answer 114

$I_{line} = 160.81$ amps

Notes 1

Discuss with your students the one-way flow of energy in a circuit such as this. Although electric current takes a circular path, the actual transfer of energy is one-way: from source to load. This is very important to understand, as things become more complex when reactive (inductive and capacitive) components are considered.

Notes 2

Discuss how the Law of Energy Conservation relates to this scenario.

Notes 3

Ask your students what it means in physical terms for energy to flow to a resistive load, and what it would mean for energy to flow from a resistive load back to the source.

Notes 4

Discuss with your students the energy-storing and energy-releasing ability of capacitors and inductors, and how they differ from resistors. This is key to understanding the zero net power dissipation of reactive components in AC circuits.

Notes 5

This question seeks to challenge students' perceptions of what constitutes electrical power. From the physical effects described, it is evident that there is more to calculating power than simply multiplying a voltage drop by a current!

Notes 6

Solving this problem requires unit conversions: from "watts" to "horsepower." Let your students research how to perform this conversion, then discuss their various techniques during discussion time.

Notes 7

The answer to this question will surprise many of your students, because they are accustomed to calculating power simply by multiplying voltage by current ($P = IE$).

Ask your students how they calculated line current in this circuit, and then challenge them with the question of how 0 watts of power can be dissipated in this circuit with all this current and all this voltage (480 volts).

Notes 8

The point of this question is to ease the pain of learning about power factor by relating it to a parallel concept: opposition to electric current (R expanding into X and Z). This makes the follow-up question very significant.

Notes 9

These definitions may be found in any number of textbooks, but that does not mean they are easy to understand. Be sure to discuss these very important concepts with your students, given their tendency to generate confusion!

Notes 10

Ask students what each of the load components (inductor and resistor) do with the electrical energy delivered to them by the alternator. The two components behave very differently with regard to power, and only one if them is dissipative.

Notes 11

Your students should realize that the only dissipative element in each load is the resistor. Inductors and capacitors, being reactive components, do not actually dissipate power. I have found that students often fail to grasp the concept of device modeling, instead thinking that the resistances shown in the schematic are actual resistors (color bands and all!). Discuss with them if necessary the concept of using standard electrical elements such as resistors, capacitors, and inductors to simulate characteristics of real devices such as lamps and motors. It is not as though one could take an LCR meter and statically measure each of these characteristics! In each case, the resistance represents whatever mechanism is responsible for converting electrical energy into a form that does not return to the circuit, but instead leaves the circuit to do work.

Ask your students how the "excess" current drawn by each load potentially influences the size of wire needed to carry power to that load. Suppose the impedance of each load were 100 times less, resulting in 100 times as much current for each load. Would the "extra" current be significant then?

Being that most heavy AC loads happen to be strongly inductive in nature (large electric motors, electromagnets, and the "leakage" inductance intrinsic to large transformers), what does this mean for AC power systems in general?

Notes 12

This is not the only way to define power factor ($\frac{P}{S}$), but it is perhaps the most straightforward.

Notes 13

Nothing much to comment on here, as these equations may be found in any number of texts. One thing you might consider doing to encourage participation from your students is to ask three of them to write these equations on the board in front of class, one student per power type (S, P, and Q). This would be an ideal question for your more timid students, because there is little explanation involved and therefore little chance of embarrassment.

Notes 14

In order to solve for power factor, your students must find at least one formula to use for calculating it. There is definitely more than one method of solution here, so be sure to ask multiple students to share their strategies for the benefit of all.

Notes 15

Ask your students to explain the phase relationships between voltage and current for each of these two conditions: a circuit with a "leading" power factor, and a circuit with a "lagging" power factor. The terms may make a lot more sense once these relationships are seen.

Notes 16

Your students should realize that the only dissipative element in each load is the resistor. Inductors and capacitors, being reactive components, do not actually dissipate power.

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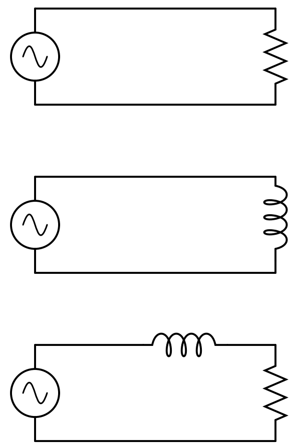
Notes 17

Ask your students whether this circuit is predominantly capacitive or predominantly inductive, and also how they know it is such.

It is very important for students to be able to solve for angles in simple trigonometric equations, using "arcfunctions," so be sure you discuss the method of solution for this question with your students.

Notes 18

Ask your students to apply this analogy to the following AC circuits: how much beer versus foam exists in each one?



Notes 19

This is a very practical question! There is a lot to discuss here, including what specific devices to use for measuring voltage and current, what safety precautions to take, how to interpret the oscilloscope's display, and so on. Of course, one of the most important aspects of this question to discuss is the concept of empirically determining power factor by measuring a circuit's V/I phase shift.

Notes 20

Points of discussion for this question should be rather obvious: why is a current of 112.3 amps worse than a current of 72.98 amps when the exact same amount of mechanical work is being done? What circuit components would have to be oversized to accommodate this extra current?

Notes 21

Many students seem to have trouble grasping how Lissajous figures are formed. One of the demonstrations I use to overcome this conceptual barrier is an analog oscilloscope and two signal generators set to very low frequencies, so students can see the "dot" being swept across the screen by both waveforms in slow-motion. Then, I speed up the signals and let them see how the Lissajous pattern becomes more "solid" with persistence of vision and the inherent phosphor delay of the screen.

Notes 22

This is a great exercise in teaching students how to derive an equation from physical measurements when the fundamental nature of that equation (trigonometric) is already known. They should already know what the Lissajous figures for both 0^o and 90^o look like, and should have no trouble figuring out what a and b values these two scenarios would yield if measured similarly on the oscilloscope display. The rest is just fitting the pieces together so that the trigonometric function yields the correct angle(s).

Notes 23

Ask your students to explain the function of the resistor R_{shunt} shown in the schematic diagram. Discuss whether or not this resistor should have a very low or a very high resistance value. Also discuss the placement of the oscilloscope's ground clip, which is very important in a potentially lethal AC power circuit.

Notes 24

This question provides a good opportunity to review the functions of PTs and CTs. Remember that PTs are transformers with precise step-down ratios used to measure a *proportion* of the line or phase voltage, which in many cases is safer than measuring the line or phase voltage directly. CTs are specially-formed transformers which fit around the current-carrying conductor for the purpose of stepping down current (stepping up voltage) so that a low-range ammeter may measure a fraction of the line current.

Students familiar with large electric motors will realize that a 4160 volt motor is going to be three-phase and not single-phase, and that measuring power factor by means of phase shift between voltage and current may be a bit more complicated than what is shown here. This scenario would work for a Y-connected four-wire, three-phase system, but not all three-phase systems are the same!

Notes 25

This question provides more practice for students with trigonometry, as well as reinforcing the relationships between S, P, Θ, and power factor.

Notes 26

Although the power factor of this circuit is still 0, the total current drawn from the source has been substantially reduced. This is the essence of power factor correction, and the point of this question.

Notes 27

The answers to this question may seem really strange to students accustomed to DC circuit calculations, where parallel branch currents always add up to a *greater* total. With complex numbers, however, the sum is not necessarily greater than the individual values!

Notes 28

Ask your students to elaborate on the given answer, explaining *why* power factor results in excessive line current. Ask them what is meant by the word "excessive."

Notes 29

Ask your students to explain what the "triangle" looks like at a power factor of unity.

Notes 30

This step seems to be one of the most difficult for students to grasp as they begin to learn to correct for power factor in AC circuits, so I wrote a question specifically focusing on it. Once students calculate the amount of reactive power consumed by the load (Q_{load}), they may realize the capacitor needs to produce the same (Q_C), but they often become mired in confusion trying to take the next step(s) in determining capacitor size.

Notes 31

There are multiple methods of solution for this problem, so be sure to have your students present their thoughts and strategies during discussion! The formula they write in answer to the challenge question will be nothing more than a formalized version of the solution strategy.

Notes 32

There are multiple methods of solution for this problem, so be sure to have your students present their thoughts and strategies during discussion!

Notes 33

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Notes 34

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Notes 35

Though there are other methods for correcting power factor in AC circuits, the addition of capacitors is perhaps the simplest. Ideally, correction capacitors should be added as close to the load terminals as possible, but in real life they are sometimes located at the power plant (near the alternators). Compare the reduction in conductor currents with the correction capacitor located in different parts of the circuit, and you will see one place in the system where current is reduced no matter where the capacitor is located!

Still, this does not answer the question of why correction capacitors are not always located at the load terminals. Discuss this with your students and see if you can figure out why (hint: what happens when the load's effective resistance changes, as would happen to an electric motor under varying mechanical loads?).

Notes 36

Students generally do not like to explain procedures. They would much rather follow a procedure given by an Authority, because it requires less thinking. It is your responsibility as their instructor to enforce the requirement for thinking in the classroom. It serves your students little to provide them with step-by-step instructions on how to calculate certain things, because ultimately their success will depend on their ability to think deeply and critically, and to problem-solve all on their own.

Answering this question in a group discussion setting need not be intimidating. You may choose to have groups of students answer this question instead of just one or two, or you may even assign this question specifically to a group of students so that there is the impetus of shared responsibility and the safety of friendly assistance in finding an answer.

Notes 37

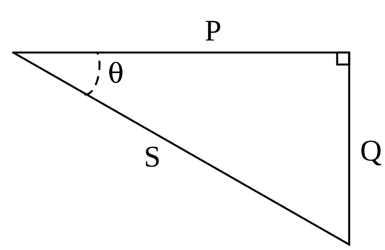
Not only would a series-resonant power circuit be dangerous, but it would also require capacitors rated for handling large continuous currents. The equivalent series resistance (ESR) of the capacitor would have to be very low in order to not experience problems handling full load current for extended periods of time.

It should be mentioned that series capacitors sometimes are used in power systems, most notably at the connection points of some high-voltage distribution lines, at the substation(s).

Notes 38

If some students fail to understand the answer to this question, try drawing an "upside-down" power triangle to illustrate:

Power triangle for capacitive circuit



Notes 39

Ask your students this question: if customers on an electrical system "consume" reactive power, then who has the job of supplying it? Carrying this question a bit further, are the alternators used to generate power rated in watts or in volt-amps? Is it possible for an alternator to supply an infinite amount of purely reactive power, or is there some kind of limit inherent to the device? To phrase the question another way, does the necessity of "supplying" reactive power to customers limit the amount of true power than a power plant may output?

Notes 40

There is a fair amount of information available on the internet and also in power engineering texts on the subject of synchronous condensers, although this mature technology is being superseded by solid-state *static VAR compensator* circuits which have no moving parts.

You might wish to mention that most AC generators (alternators) have the ability to run as synchronous motors, and therefore as synchronous condensers. It is commonplace for spare generators at power plants to be "idled" as electric motors and used to generate leading VARs to reduce heating in the windings of the other generators. This is especially true at hydroelectric dams, where frequent shut-downs and start-ups of generator units is discouraged due to the massive size of the units and the physical wear incurred during that cycling.

Notes 41

This is another one of those concepts that is better learned through experimentation than by direct pronouncement, especially since the experiment itself is so easy to set up.

Notes 42

This question challenges students to relate the magnetic flux waveform (ϕ) to an instantaneous rotor position. The answer may come as a surprise to some, who expected maximum induced voltage to occur when the rotor is in-line with the stator poles. This answer, however, makes the mistake of confusing flux (ϕ) with rate-of-flux-change over time ($\frac{d\phi}{dt}$). A rotor lined up with the stator poles would result in maximum flux (ϕ) through those poles, but not maximum rate-of-flux-change over time ($\frac{d\phi}{dt}$).

Notes 43

Ask your students to write the equation for Faraday's Law on the whiteboard, and then analyze it in a qualitative sense (with variables increasing or decreasing in value) to validate the answers.

The first answer to this question (increase $\frac{d\phi}{dt}$) has been left purposefully vague, in order to make students think. What, specifically, must be changed in order to increase this rate-of-change over time? Which real-world variables are changeable after the generator has been manufactured, and which are not?

Notes 44

Answering the follow-up question may require a bit of research on the part of your students. Ask them to describe what "brushes" are and what "slip rings" are, and then the mechanical wearing aspects of these parts should become plain.

Notes 45

Students should realize that there is one cycle of AC voltage produced for every revolution of the rotor shaft. From that point, the problem is simply a matter of unit conversions.

Notes 46

This may be especially confusing to some students, until they realize that alternator poles are always multiples of 2 (the simplest alternator having 2 poles).

Notes 47

Some references provide equations in terms of *pole pairs* instead of individual alternator poles.

Notes 48

Ask your students how this voltage regulation strategy compares with that of DC generators. Ask them to describe the difference between "commutator bars" and "slip rings."

Notes 49

This question is really a prelude to discussing *phase rotation* in polyphase systems.

Notes 50

This question is a good exercise of students' knowledge of phase shift, in a very practical context.

Notes 51

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Notes 52

Although the rationale for polyphase electrical power may not be apparent from either the question or the given answer, your students need to be aware of its existence.

Notes 53

Your students will need to know what "phase" and "line" represents in both types of polyphase configurations, especially when using formulae that reference quantities by these labels.

Notes 54

Students will quickly discover that $\sqrt{3}$ is the "magic number" for practically all balanced three-phase circuit calculations!

It should be noted that although the *magnitudes* of V_{AB}, V_{BC}, and V_{AC} are equal, their phasor angles are most definitely not. Therefore,

$$V_{AB} = V_{BC} = V_{AC} \qquad \text{Scalar values equal}$$

$$\mathbf{V_{AB}} \neq \mathbf{V_{BC}} \neq \mathbf{V_{AC}} \qquad \text{Phasors unequal}$$

Notes 55

Students will quickly discover that $\sqrt{3}$ is the "magic number" for practically all balanced three-phase circuit calculations!

It should be noted that although the *magnitudes* of I_A, I_B, and I_C are equal, their phasor angles are most definitely not. Therefore,

$$I_A = I_B = I_C \qquad \text{Scalar values equal}$$

$$\mathbf{I_A} \neq \mathbf{I_B} \neq \mathbf{I_C} \qquad \text{Phasors unequal}$$

Notes 56

This phenomenon is difficult to demonstrate without a very powerful magnet. However, if you have such apparatus available in your lab area, it would make a great piece for demonstration!

One practical way I've demonstrated Lenz's Law is to obtain a rare-earth magnet (*very* powerful!), set it pole-up on a table, then drop an aluminum coin (such as a Japanese Yen) so it lands on top of the magnet. If the magnet is strong enough and the coin is light enough, the coin will gently come to rest on the magnet rather than hit hard and bounce off.

A more dramatic illustration of Lenz's Law is to take the same coin and spin it (on edge) on a table surface. Then, bring the magnet close to the edge of the spinning coin, and watch the coin promptly come to a halt, without contact between the coin and magnet.

Another illustration is to set the aluminum coin on a smooth table surface, then quickly move the magnet over the coin, parallel to the table surface. If the magnet is close enough, the coin will be "dragged" a short distance as the magnet passes over.

In all these demonstrations, it is significant to show to your students that the coin itself is not magnetic. It will not stick to the magnet as an iron or steel coin would, thus any force generated between the coin and magnet is strictly due to *induced currents* and not ferromagnetism.

Notes 57

The phenomenon of Lenz's Law is usually showcased using a metal solid such as a disk or ring, rather than a wire coil, but the phenomenon is the same.

Notes 58

Mechanical speedometer assemblies used on many automobiles use this very principle: a magnet assembly is rotated by a cable connected to the vehicle's driveshaft. This magnet rotates in close proximity to a metal disk, which gets "dragged" in the same direction that the magnet spins. The disk's torque acts against the resistance of a spring, deflecting a pointer along a scale, indicating the speed of the vehicle. The faster the magnet spins, the more torque is felt by the disk.

Notes 59

Ask your students to describe what would happen to the blinking lights if the *voltage* were increased or decreased. Would this alter the perceived speed of motion?

Although this question may seem insultingly simple to many, its purpose is to introduce other sequenced-based phenomenon such as polyphase electric motor theory, where the answers to analogous questions are not so obvious.

Notes 60

The concept of the rotating magnetic field is central to AC motor theory, so it is imperative that students grasp this concept before moving on to more advanced concepts. If you happen to have a string of blinking "Christmas lights" to use as a prop in illustrating a rotating magnetic field, this would be a good thing to show your students during discussion time.

Notes 61

Here, we see a practical 3-phase *induction* motor. Be sure to thoroughly discuss what is necessary to increase or decrease rotor speed, and compare this with what is necessary to increase or decrease speed in a DC motor.

Notes 62

It is very important that students realize Lenz's Law is an *induced* effect, which only manifests when a *changing* magnetic field cuts through perpendicular conductors. Ask your students to explain how the word "induction" applies to Lenz's Law, and to the induction motor design. Ask them what conditions are necessary for electromagnetic induction to occur, and how those conditions are met in the normal operation of an induction motor.

The challenge question is really a test of whether or not students have grasped the concept. If they truly understand how electromagnetic induction takes place in an induction motor, they will realize that there will be no induction when the rotor rotates in "sync" with the rotating magnetic field, and they will be able to relate this loss of induction to rotor torque.

Notes 63

One of the reasons three-phase motors are preferred in industry is the simplicity of rotation reversal. However, this is also a problem because when you connect a three-phase motor to its power source during maintenance or installation procedures, you often do not know which way it will rotate until you turn the power on!

Discuss with your students how an electrician might go about his or her job when installing a three-phase motor. What would be the proper lock-out/tag-out sequence, and steps to take when connecting a motor to its power source? What would have to be done if it is found the motor rotates in the wrong direction?

Notes 64

This is a "trick" question, in that the student is asked to determine which direction the rotor will start to spin, when in fact it has no "preferred" direction of rotation. An excellent means of demonstrating this effect is to take a regular single-phase motor and disconnect its start switch so that it is electrically identical to the motor shown in the question, then connect it to an AC power source. It will not spin until you give the shaft a twist with your hand. But be careful: once it starts to turn, it ramps up to full speed quickly!

The real purpose of this question is to get students to recognize the main "handicap" of a single-phase AC motor, and to understand what is required to overcome that limitation. The challenge question essentially asks students what happens to a three-phase motor that is suddenly forced to operate as a single-phase motor due to a line failure. Incidentally, this is called *single-phasing* of the motor, and it is not good!

Notes 65

Be sure to ask your students to describe *how* they arrived at the answers to this question. There is more than one place to start in determining the solution here, and more than one way to calculate some of the figures. No matter how your students may have approached this question, though, they should all obtain the same answers.

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Notes 69

Now, students will surely be able to find a power equation from textbooks, but the purpose of this question is to have them derive it themselves. In a single-phase, resistive AC circuit, power is given by the equation $P = IE$, just as in DC circuits. However, if you multiply the line voltage by line current, you do not get the correct answer of 27.648 kW. So, obviously, the equation of $P = IE$ will require some modification for calculating total three-phase power. However, this modification is not complicated to perform.

Notes 70

This question is good for provoking discussion on the practical, cost-saving benefits of three-phase power systems over single-phase. Your students will have to do some "review" research on wire gauges and weights, but the exercise is well worth it.

Notes 71

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard resistor and capacitor values.

I recommend using components that produce a phase shift of approximately 45 degrees within the low audio frequency range (less than 1 kHz). This allows most multimeters to be used for voltage measurement in conjunction with the oscilloscope.

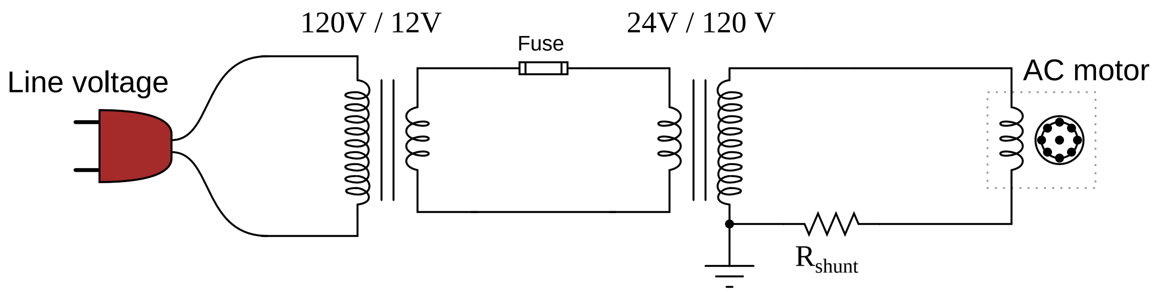
Something to suggest that students do is use their oscilloscopes' *ground* position on the coupling switch, to help center the dot on the screen before they set up their Lissajous figures for phase shift measurement.

One way for students to do this assessment is to have them predict what the Lissajous figure will look like, based on circuit component values. They sketch the predicted Lissajous figure on the grid provided (working the math "backward" to arrive at n and m values before actually hooking up an oscilloscope), then the instructor assesses them based on the conformity of the real oscilloscope display to their prediction.

Notes 72

When presenting this as a performance assessment for a group of students, you will need to show the voltage/current waveforms as part of the "given" conditions. A good way to do this is to use a PC-based oscilloscope to measure the waveforms, and then display the image using a video projector.

I have found that small synchronous AC motors such as those used in clock mechanisms and in some appliances (microwave oven carousels, for example) will run satisfactorily at 24 volts AC. Small shaded-pole motors such as those used in household bathroom fans and household appliances (microwave oven cooling fans, for example) may be operated in a relatively safe manner from low-voltage AC power by stepping the voltage up through a power transformer connected directly to the motor. Use a "step down" power transformer operating in reverse (as a step-up unit), with the higher voltage wires connected and taped to the motor so that the only "loose" wire connections are on the low-voltage side. Here is a power supply circuit I recommend for the task:



This circuit ensures the motor only receives about 60 volts, reducing shock hazard somewhat and allowing the use of capacitors rated for 100 volts (a common mylar capacitor rating). The smaller the motor, the less capacitance will be required to correct for power factor. Remind your students that the capacitors used in this exercise must be *non-polarized*, since they must operate on AC and not DC!

A shunt resistor value of 1 ohm is recommended, but not absolutely required. You just need a low-value resistor that will provide a ready point of measurement for current (with the oscilloscope) without imposing too much series resistance in the motor circuit.

Notes 73

The purpose of this assessment rubric is to act as a sort of "contract" between you (the instructor) and your student. This way, the expectations are all clearly known in advance, which goes a long way toward disarming problems later when it is time to grade.

Notes 74

Ask your students to observe the waveform shown in the answer closely, and determine what *sign* the power values always are. Note how the voltage and current waveforms alternate between positive and negative, but power does not. Of what significance is this to us? What does this indicate about the nature of a load with an impedance phase angle of 0^o?

Notes 75

Ask your students to observe the waveform shown in the answer closely, and determine what *sign* the power values are. Note how the power waveform alternates between positive and negative values, just as the voltage and current waveforms do. Ask your students to explain what *negative* power could possibly mean.

Of what significance is this to us? What does this indicate about the nature of a load with an impedance phase angle of 90^o?

The phrase, "ELI the ICE man" has been used be generations of technicians to remember the phase relationships between voltage and current for inductors and capacitors, respectively. One area of trouble I've noted with students, though, is being able to interpret which waveform is leading and which one is lagging, from a time-domain plot such as this.

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Of what significance is this to us? What does this indicate about the nature of a load with an impedance phase angle of -90^o?

The phrase, "ELI the ICE man" has been used be generations of technicians to remember the phase relationships between voltage and current for inductors and capacitors, respectively. One area of trouble I've noted with students, though, is being able to interpret which waveform is leading and which one is lagging, from a time-domain plot such as this.

Notes 77

In my years of teaching, I have been surprised at how many students struggle with identifying the "leading" and "lagging" waveforms on a time-domain graph. Be sure to discuss this topic well with your students, identifying methods for correctly distinguishing "leading" waves from "lagging" waves.

This question also provides students with good practice expressing leading and lagging waves in phasor notation. One of the characteristics of phasors made evident in the answer is the relative nature of angles. Be sure to point this out to your students.

Notes 78

It may be helpful to your students to remind them of the standard orientation for phase angles in phasor diagrams (0 degrees to the right, 90 degrees up, etc.).

Notes 79

Although semiconductor-based static VAR compensator circuits are now the method of choice for modern power systems, this technique is still valid and is easy enough for beginning students to comprehend. A circuit such as this is a great application of the binary number system, too!

Notes 80

This phenomenon is difficult to demonstrate without a very powerful magnet. However, if you have such apparatus available in your lab area, it would make a great piece for demonstration!

One practical way I've demonstrated Lenz's Law is to obtain a rare-earth magnet (*very* powerful!), set it pole-up on a table, then drop an aluminum coin (such as a Japanese Yen) so it lands on top of the magnet. If the magnet is strong enough and the coin is light enough, the coin will gently come to rest on the magnet rather than hit hard and bounce off.

A more dramatic illustration of Lenz's Law is to take the same coin and spin it (on edge) on a table surface. Then, bring the magnet close to the edge of the spinning coin, and watch the coin promptly come to a halt, without contact between the coin and magnet.

Another illustration is to set the aluminum coin on a smooth table surface, then quickly move the magnet over the coin, parallel to the table surface. If the magnet is close enough, the coin will be "dragged" a short distance as the magnet passes over.

In all these demonstrations, it is significant to show to your students that the coin itself is not magnetic. It will not stick to the magnet as an iron or steel coin would, thus any force generated between the coin and magnet is strictly due to *induced currents* and not ferromagnetism.

Notes 81

An easy way I find to remember Lenz's Law is to interpret is as *opposition to change*. The coil will try to become a magnet that fights the motion. A good way to get students thinking along these lines is to ask them, "What magnetic polarity would the coil have to assume (in each case) to resist the magnet's relative motion?" In other words, if the magnet moves closer to the coil, the coil will "magnetize" so as to push against the magnet. If the magnet moves away from the coil, the coil will "magnetize" so as to attract the magnet.

Notes 82

Electromagnetic brakes are very useful devices in industry. One interesting application I've seen for this technology is the mechanical load for an automotive dynamometer, where a car is driven onto a set of steel rollers, with one roller coupled to a large metal disk (with electromagnets on either side). By varying the amount of current sent to the electromagnets, the degree of mechanical drag may be varied.

Incidentally, this disk becomes very hot when in use, because the automobile's power output cannot simply vanish – it must be converted into a different form of energy in the braking mechanism, and heat it is.

Notes 83

A visual aid to understanding the interaction of the two magnetic fields is a diagram showing the lines of flux emanating from the permanent magnets, against the circular lines of flux around the wire. Ask those students who came across similar illustrations in their research to draw a picture of this on the board in front of the class, for those who have not seen it.

Notes 84

Ask your students to explain their answers regarding factors that influence voltage magnitude. Where did they obtain their information? Are there any mathematical formulae relating these factors to induced voltage?

Notes 85

If you happen to have a large, permanent magnet DC motor available in your classroom, you may easily demonstrate this principle for your students. Just have them spin the shaft of the motor (generator) with their hands, with the power terminals open versus shorted together. Your students will notice a huge difference in the ease of turning between these two states.

After your students have had the opportunity to discuss this phenomenon and/or experience it themselves, ask them why electromechanical meter movement manufacturers usually ship meters with a shorting wire connecting the two meter terminals together. In what way does a PMMC meter movement resemble an electric generator? How does shorting the terminals together help to protect against damage from physical vibration during shipping?

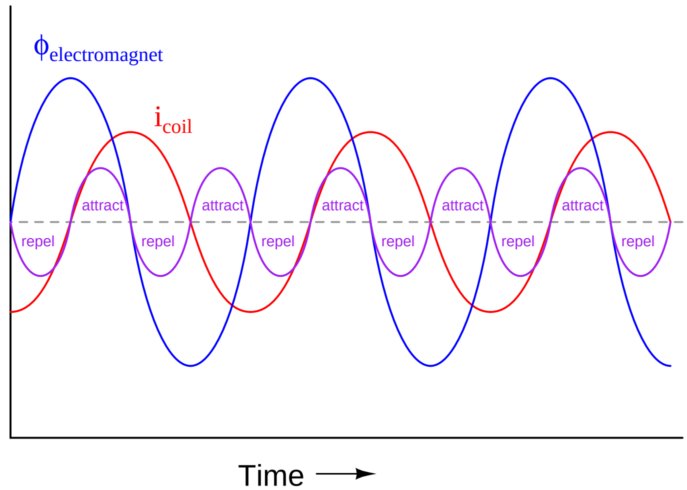
Ask your students to describe what factors influence the magnitude of this reaction force.

Notes 86

Note that the two wire ends switch polarity as the loop rotates. Ask your students to explain why the polarities are as they are.

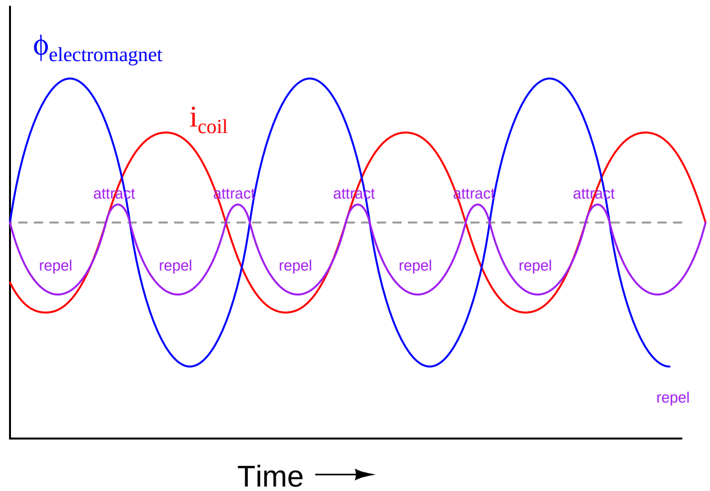
Be sure to note in your discussion with students that the coil does not have to be made of a magnetic material, such as iron. Copper or aluminum will work quite nicely because Lenz's Law is an *electro*magnetic effect, not a magnetic effect.

The *real* answer to this question is substantially more complex than the one given. In the example given, I assume that the resistance placed in the coil circuit swamps the coil's self-inductance. In a case such as this, the coil current will be (approximately) in-phase with the induced voltage. Since the induced voltage will lag 90 degrees behind the incident (electromagnet) field, this means the coil current will also lag 90 degrees behind the incident field, and the force generated between that coil and the AC electromagnet will alternate between attraction and repulsion:



Note the equal-amplitude attraction and repulsion peaks shown on the graph.

However, in situations where the coil's self-inductance is significant, the coil current will lag behind the induced voltage, causing the coil current waveform to fall further out of phase with the electromagnet current waveform:



Given a phase shift between the two currents greater than 90 degrees (approaching 180 degrees), there is greater repulsion force for greater duration than there is attractive force. If the coil were a superconducting ring (no resistance whatsoever), the force would *only* be repulsive!

So, the answer to this "simple" Lenz's Law question really depends on the coil circuit: whether it is considered primarily resistive or primarily inductive. Only if the coil's self-inductance is negligible will the reactive force equally alternate between attraction and repulsion. The more inductive (the less resistive) the coil circuit becomes, the more net repulsion there will be.

Notes 88

It is easy enough for students to research "slip speed" in any motor reference book and present a definition. It is quite another for them to explain *why* slip is necessary. Be sure to allow ample time in class to discuss this concept, because it is at the heart of induction motor operation.

Notes 89

The concept of "slip" is confusing to many students, so be prepared to help them understand by way of multiple explanations, Socratic questioning, and perhaps live demonstrations.

Notes 90

In reality, almost all large synchronous motors are built this way, with an electromagnetic rotor rather than a permanent-magnet rotor. This allows the motor to start much easier. Ask your students why they think this would be an important feature in a large synchronous motor, to be able to start it as an induction motor. What would happen if AC power were suddenly applied to a large synchronous motor with its rotor already magnetized?

If a resistance is connected between the brushes, it allows for an even easier start-up. By "easier," I mean a start-up that draws less inrush current, resulting in a gentler ramp up to full speed.

Notes 91

Although it is easy enough for students to find information on squirrel cage motors classifying them as either induction or synchronous, you should challenge your students to *explain* why it is one type or the other. The goal here, as always, is *comprehension* over *memorization*.

Notes 92

There are many details which can be discussed with students regarding these methods of single-phase motor starting. Thankfully, there are many good-quality sources of information on single-phase motor theory and construction, so finding information on this topic will not be difficult for your students.

Notes 93

Capacitor-start squirrel-cage induction motors are very popular in applications where there is a need for high starting torque. Many induction motor shop tools (drill presses, lathes, radial-arm saws, air compressors) use capacitor-start motors.

Notes 94

It is helpful to review the concept of phase rotation sequences as a string of letters: A-B-C, or C-B-A. Although these two letter sequences are the most common for denoting the two different rotation directions, they are not the only sequences possible using three letters. For example, A-C-B, B-A-C, C-A-B, and B-C-A are also possibilities. Discuss with your students which of these letter sequences represents the same *direction* of rotation as A-B-C, and which represent the same direction of rotation as C-B-A. Then, ask your students how they might apply these letter sequences to the different wiring diagrams shown in the question.

Notes 95

Consequent pole motors are not the only design with multiple speeds. Sometimes motors are wound with completely separate, multiple windings, which give them any combinations of speeds desired.

Notes 96

This question should provoke some interesting discussion! An interesting "twist" to this problem is to suggest (after some discussion) that the motor itself checks out fine when tested with an ohmmeter (no ground faults, no open or shorted windings), and that its shaft may be turned freely by hand. What could possibly be the source of trouble now?

Notes 97

This is a practical scenario which you and your students should have some fun exploring. If they have never heard of a "contactor" before, this question is a good opportunity to introduce the component. Bring one with you to discussion if you have the opportunity!

Notes 98

While measuring millivoltage across a *fuse* may seem like a strange diagnostic technique, it is one I have gainfully applied for years. The "catch" is you have to know what it is good for and what it is not. It is *not* a precise, quantitative technique by any means!

Notes 99

An illustration of polyphase alternator construction would be excellent to aid understanding of this concept. Your students should have no trouble finding illustrations of three-phase alternator design from textbooks and from the internet.

Notes 100

Ask your students how the phase rotation sequence of a three-phase system is typically denoted. What symbols are used to describe the direction in which the phase voltages "rotate"?

Notes 101

Many students are confused by this when seeing it for the first time. How is it possible to measure voltage between two points in a circuit and obtain 208 volts, when the two series-connected voltage sources between those two points are 120 volts each? Why isn't it 240/120 volts instead?

The answer to this question, of course, is *phase shift*: the answer to most "strange" phenomenon in AC circuits!

Notes 102

The subject of this question is closely related to the subject of "single-phasing" a polyphase load as the result of a line conductor opening. In this case it is the neutral conductor we are intentionally opening, but the results are similar.

Notes 103

Despite the fact that this connection scheme is quite common in industry, I have found little reference to it in textbooks. The equilateral layout of the windings in this diagram facilitates graphical (phasor) analysis of the voltages, providing students with the opportunity to exercise their knowledge of trigonometry.

Notes 104

Ask your students which type of three-phase system (balanced or unbalanced) is easier to analyze, and why that is so.

Notes 105

More important than obtaining the correct answer is for students to explain what they did to get that answer. What general calculation may be applied to balanced, Y-connected systems relating phase and line voltages?

Notes 106

There exist long, complicated equations for converting between Y and Delta resistor networks, but there is a much simpler solution to this problem than that! Challenge your students to solve this problem without resorting to the use of one of those long conversion formulae.

Notes 107

Ask your students what these results indicate about the reliability of Y versus Delta source configurations. Also, be sure to ask what *does* change in the Delta-Y system as a result of the failure. Certainly, *something* must be different from before, with one winding completely failed open!

Notes 108

Three-phase power transformers are somewhat rare compared to combinations of multiple single-phase transformers. Questions such as this are really nothing more than pattern-recognition exercises, but like all skills this does not come naturally to all people, and practice improves it!

Notes 109

Being that pole-mounted power distribution transformers are exposed for anyone to look at, they provide an excellent opportunity for students to practice identifying three-phase connections. If there are any such transformer configurations located near your campus, it would be an interesting field exercise to bring students there (or send them there on "field research"!) to identify the connections. Photographs of transformer connections may also be used in the classroom to provide practical examples of this concept.

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Notes 111

Understanding the open-Delta configuration is made easier if students first understand the robustness of the regular Delta configuration: how it continues to provide true three-phase power with no degradation in line voltage in the event of a winding failure. Discuss the advantages and disadvantages of such a configuration with your students.

Notes 112

The formula for calculating power in a balanced three-phase system may be found in any textbook. Let your students do the necessary research!

Notes 113

These figures came from a real hydroelectric generator that I saw once on a tour. Needless to say, this alternator was *very* large!

- **Maximum continuous ratings**
- 615.38 MVA apparent power output
- 600 MW true power output
- 15 kV line voltage
- 23.686 kA line current
- 97.5% power factor
- 365 volts exciter voltage
- 3,425 amps exciter current

- **Maximum continuous overload ratings**
- 707.69 MVA apparent power output
- 690 MW true power output
- 15 kV line voltage
- 27.239 kA line current
- 97.5% power factor
- 410 volts exciter voltage
- 3,640 amps exciter current

Notes 114

Several conversions are necessary to calculate the answer for this question. As usual, the purpose of this question is not so much to obtain an answer, as it is to develop students' problem-solving skills. How did students approach this problem? Did any of them think of ways to simplify the problem so that it could be solved in incremental steps instead of all at once? If so, what was their method(s) of solution?