Recommended schedule

<u>Day 1</u>

Topics: *Capacitive reactance and impedance, trigonometry for AC circuits*
Questions: *1 through 20*
Lab Exercise: *Capacitive reactance and Ohm's Law for AC (question 71)*

<u>Day 2</u>

Topics: *Series and parallel RC circuits*
Questions: *21 through 40*
Lab Exercise: *Series RC circuit (question 72)*

<u>Day 3</u>

Topics: *Superposition principle, AC+DC oscilloscope coupling*
Questions: *41 through 55*
Lab Exercise: *Parallel RC circuit (question 73)*
MIT 6.002 video clip: Disk 1, Lecture 3; Superposition theorem 29:18 to 34:14

<u>Day 4</u>

Topics: *Passive RC and LR filter circuits*
Questions: *56 through 70*
Lab Exercise: *Time-domain phase shift measurement (question 74)*
MIT 8.02 video clip: Disk 3, Lecture 20; Lowpass filter using inductor 37:46 to 39:18

<u>Day 5</u>

Exam 2: *includes Series <u>or</u> Parallel RC circuit performance assessment*
Lab Exercise: *Troubleshooting practice (variable phase shift bridge circuit – question 75)*

<u>Practice and challenge problems</u>

Questions: *78 through the end of the worksheet*

<u>Impending deadlines</u>

Troubleshooting assessment (AC bridge circuit) due at end of ELTR110, Section 3
Question 76: Troubleshooting log
Question 77: Sample troubleshooting assessment 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.02 Demonstrate an understanding of the properties of an AC signal.
C.08 Understand principles and operations of AC capacitive circuits.
C.09 Fabricate and demonstrate AC capacitive circuits.
C.10 Troubleshoot and repair AC capacitive circuits.
C.27 Understand principles and operations of AC frequency selective filter 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.20 Graph functions.
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.

Common areas of confusion for students

Difficult concept: *Phasors, used to represent AC amplitude and phase relations.*

A powerful tool used for understanding the operation of AC circuits is the *phasor diagram*, consisting of arrows pointing in different directions: the length of each arrow representing the amplitude of some AC quantity (voltage, current, or impedance), and the angle of each arrow representing the shift in phase relative to the other arrows. By representing each AC quantity thusly, we may more easily calculate their relationships to one another, with the phasors showing us how to apply trigonometry (Pythagorean Theorem, sine, cosine, and tangent functions) to the various calculations. An analytical parallel to the graphic tool of phasor diagrams is *complex numbers*, where we represent each phasor (arrow) by a pair of numbers: either a magnitude and angle (polar notation), or by "real" and "imaginary" magnitudes (rectangular notation). Where phasor diagrams are helpful is in applications where their respective AC quantities *add*: the resultant of two or more phasors stacked tip-to-tail being the mathematical sum of the phasors. Complex numbers, on the other hand, may be added, subtracted, multiplied, and divided; the last two operations being difficult to graphically represent with arrows.

Difficult concept: *Conductance, susceptance, and admittance.*

Conductance, symbolized by the letter G, is the mathematical reciprocal of resistance ($\frac{1}{R}$). Students typically encounter this quantity in their DC studies and quickly ignore it. In AC calculations, however, conductance and its AC counterparts (*susceptance*, the reciprocal of reactance $B = \frac{1}{X}$ and *admittance*, the reciprocal of impedance $Y = \frac{1}{Z}$) are very necessary in order to draw phasor diagrams for parallel networks.

Difficult concept: *Capacitance adding in parallel; capacitive reactance and impedance adding in series.*

When students first encounter capacitance, they are struck by how this quantity adds when capacitors are connected in *parallel*, not in series as it is for resistors and inductors. They are surprised again, though, when they discover that the opposition to current offered by capacitors (either as scalar reactance or phasor impedance) adds in series just as resistance adds in series and inductive reactance/impedance adds in series. Remember: *ohms* always add in series, no matter what their source(s); only *farads* add in parallel (omitting *siemens* or *mhos*, the units for conductance and admittance and susceptance, which of course also add in parallel).

Difficult concept: *Identifying filter circuit types.*

Many students have a predisposition to memorization (as opposed to comprehension of concepts), and so when approaching filter circuits they try to identify the various types by memorizing the positions of reactive components. As I like to tell my students, *memory will fail you*, and so a better approach is to develop analytical techniques by which you may determine circuit function based on "first principles" of circuits. The approach I recommend begins by identifying component impedance (open or short) for very low and very high frequencies, respectively, then qualitatively analyzing voltage drops under those extreme conditions. If a filter circuit outputs a strong voltage at low frequencies and a weak voltage at high frequencies then it must be a low-pass filter. If it outputs a weak voltage at both low and high frequencies then it must be a band-pass filter, etc.

Difficult concept: *The practical purpose(s) for filter circuits.*

Bode plots show how filter circuits respond to inputs of changing frequency, but this is not how filters are typically used in real applications. Rarely does one find a filter circuit subjected to one particular frequency at a time – usually a simultaneous mix of frequencies are seen at the input, and it is the filter's job to select a particular range of frequencies to pass through from that simultaneous mix. Understanding the superposition theorem precedes an understanding of how filter circuits are practically used.

Question 1

As a general rule, capacitors oppose change in (**choose:** <u>voltage</u> or <u>current</u>), and they do so by . . . (complete the sentence).

Based on this rule, determine how a capacitor would react to a constant AC voltage that increases in frequency. Would an capacitor pass more or less current, given a greater frequency? Explain your answer.
<u>file 00579</u>

Answer 1

As a general rule, capacitors oppose change in <u>voltage</u>, and they do so by producing a current.

A capacitor will pass a greater amount of AC current, given the same AC voltage, at a greater frequency.

Notes 1

This question is an exercise in qualitative thinking: relating rates of change to other variables, without the use of numerical quantities. The general rule stated here is very, very important for students to master, and be able to apply to a variety of circumstances. If they learn nothing about capacitors except for this rule, they will be able to grasp the function of a great many capacitor circuits.

Question 2

$\int f(x)\,dx$ *Calculus alert!*

We know that the formula relating instantaneous voltage and current in a capacitor is this:

$$i = C\frac{de}{dt}$$

Knowing this, determine at what points on this sine wave plot for capacitor voltage is the capacitor current equal to zero, and where the current is at its positive and negative peaks. Then, connect these points to draw the waveform for capacitor current:
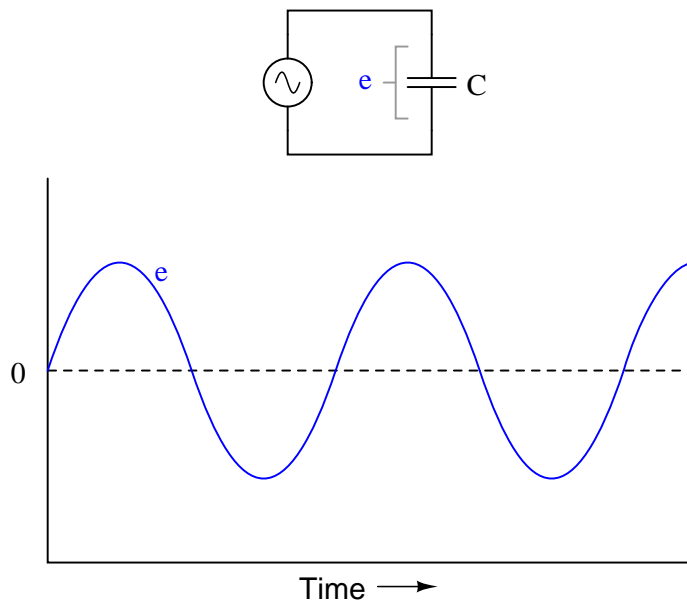
How much phase shift (in degrees) is there between the voltage and current waveforms? Which waveform is leading and which waveform is lagging?

<u>file 00577</u>

5

Answer 2
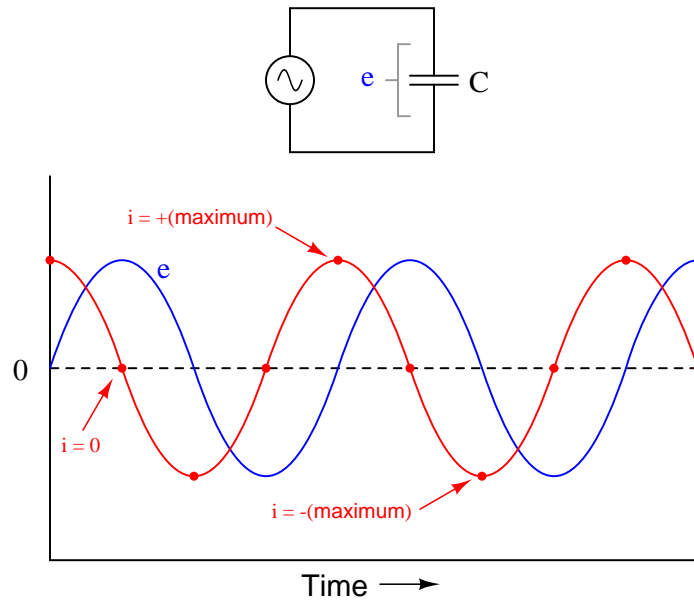
For a capacitor, voltage is lagging and current is leading, by a phase shift of 90°.

Notes 2

This question is an excellent application of the calculus concept of the *derivative*: relating one function (instantaneous current, i) with the instantaneous rate-of-change of another function (voltage, $\frac{de}{dt}$).

Question 3

You should know that a capacitor is formed by two conductive plates separated by an electrically insulating material. As such, there is no "ohmic" path for electrons to flow between the plates. This may be vindicated by an ohmmeter measurement, which tells us a capacitor has (nearly) infinite resistance once it is charged to the ohmmeter's full output voltage.

Explain then, how a capacitor is able to continuously pass *alternating* current, even though it cannot continuously pass DC.

file 01553

Answer 3

I'll let you figure this out on your own!

Notes 3

This feature of capacitors is extremely useful in electronic circuitry. Your students will find many applications of it later on in their studies!

Question 4

Does a capacitor's opposition to alternating current increase or decrease as the frequency of that current increases? Also, explain why we refer to this opposition of AC current in a capacitor as *reactance* instead of *resistance*.

file 00581

Answer 4

The opposition to AC current ("reactance") of a capacitor decreases as frequency increases. We refer to this opposition as "reactance" rather than "resistance" because it is non-dissipative in nature. In other words, reactance causes no power to leave the circuit.

Notes 4

Ask your students to define the relationship between capacitor reactance and frequency as either "directly proportional" or "inversely proportional". These are two phrases used often in science and engineering to describe whether one quantity increases or decreases as another quantity increases. Your students definitely need to be familiar with both these phrases, and be able to interpret and use them in their technical discussions.

Also, discuss the meaning of the word "non-dissipative" in this context. How could we prove that the opposition to current expressed by a capacitor is non-dissipative? What would be the ultimate test of this?

Question 5

Will the current through the resistor increase or decrease as the capacitor plates are moved closer together?
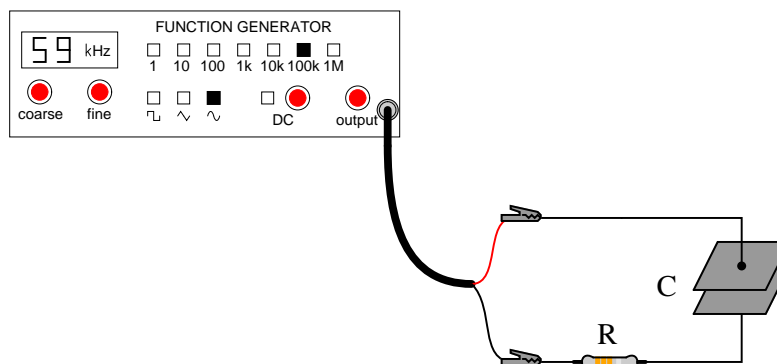
Explain why this happens, with reference to capacitive reactance (X_C).
file 01843

Answer 5

The current will *increase*.

Follow-up question: combine the physical capacitance equation and the capacitive reactance equation together to form a new equation that solves for reactance (X_C) given all the physical specifications of the capacitor (plate area, spacing, and permittivity) and the applied frequency:

$$C = \frac{\epsilon A}{d} \qquad X_C = \frac{1}{2\pi f C}$$

Notes 5

Students might be able to guess the correct answer even if they know nothing about capacitive reactance, just by assuming that closer plates means a more complete circuit. The real answer is more complex than this, though, and that is what you must draw out of the discussion with them.

Question 6

A capacitor rated at 2.2 microfarads is subjected to a sinusoidal AC voltage of 24 volts RMS, at a frequency of 60 hertz. Write the formula for calculating capacitive reactance (X_C), and solve for current through the capacitor.

file 00583

Answer 6

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

The current through this capacitor is 19.91 mA RMS.

Notes 6

I have consistently found that qualitative (greater than, less than, or equal) analysis is much more difficult for students to perform than quantitative (punch the numbers on a calculator) analysis. Yet, I have consistently found on the job that people lacking qualitative skills make more "silly" quantitative errors because they cannot validate their calculations by estimation.

In light of this, I always challenge my students to qualitatively analyze formulae when they are first introduced to them. Ask your students to identify what will happen to one term of an equation if another term were to either increase, or decrease (you choose the direction of change). Use up and down arrow symbols if necessary to communicate these changes graphically. Your students will greatly benefit in their conceptual understanding of applied mathematics from this kind of practice!

Question 7

At what frequency does a 33 μF capacitor have 20 Ω of reactance? Write the formula for solving this, in addition to calculating the frequency.

file 00587

Answer 7

$f = 241.1$ Hz

Notes 7

Be sure to ask your students to demonstrate the algebraic manipulation of the original formula, in providing the answer to this question. Algebraic manipulation of equations is a very important skill to have, and it comes only by study and practice.

Question 8

Explain how you could calculate the capacitance value of a capacitor (in units of Farads), by measuring AC voltage, AC current, and frequency in a circuit of this configuration:
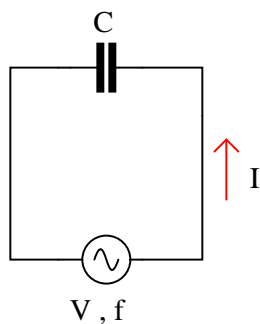
Write a single formula solving for capacitance given these three values (V, I, and f).
file 02113

Answer 8

$$C = \frac{I}{2\pi f V}$$

Notes 8

Ask your students to show how they arrived at the formula for calculating C. The algebra is not difficult, but some substitution is required.

12

Question 9

In this AC circuit, the resistor offers 3 kΩ of resistance, and the capacitor offers 4 kΩ of reactance. Together, their series opposition to alternating current results in a current of 1 mA from the 5 volt source:

$$I = 1 \text{ mA}$$
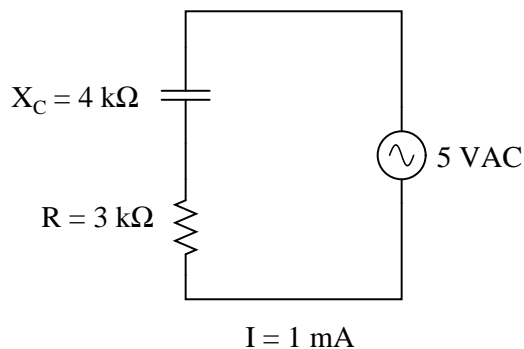
How many ohms of opposition does the series combination of resistor and capacitor offer? What name do we give to this quantity, and how do we symbolize it, being that it is composed of both resistance (R) and reactance (X)?

file 00585

Answer 9

$Z_{total} = 5$ kΩ.

Notes 9

Students may experience difficulty arriving at the same quantity for impedance shown in the answer. If this is the case, help them problem-solve by suggesting they **simplify the problem**: short past one of the load components and calculate the new circuit current. Soon they will understand the relationship between total circuit opposition and total circuit current, and be able to apply this concept to the original problem.

Ask your students why the quantities of 3 kΩ and 4 kΩ do not add up to 7 kΩ like they would if they were both resistors. Does this scenario remind them of another mathematical problem where $3 + 4 = 5$? Where have we seen this before, especially in the context of electric circuits?

Once your students make the cognitive connection to trigonometry, ask them the significance of these numbers' addition. Is it enough that we say a component has an opposition to AC of 4 kΩ, or is there more to this quantity than a single, scalar value? What type of number would be suitable for representing such a quantity, and how might it be written?

In DC circuits, we have Ohm's Law to relate voltage, current, and resistance together:

$$E = IR$$

In AC circuits, we similarly need a formula to relate voltage, current, and *impedance* together. Write three equations, one solving for each of these three variables: a set of Ohm's Law formulae for AC circuits. Be prepared to show how you may use algebra to manipulate one of these equations into the other two forms.

file 00590

Answer 10

$$E = IZ$$

$$I = \frac{E}{Z}$$

$$Z = \frac{E}{I}$$

If using phasor quantities (complex numbers) for voltage, current, and impedance, the proper way to write these equations is as follows:

$$\mathbf{E} = \mathbf{IZ}$$

$$\mathbf{I} = \frac{\mathbf{E}}{\mathbf{Z}}$$

$$\mathbf{Z} = \frac{\mathbf{E}}{\mathbf{I}}$$

Bold-faced type is a common way of denoting vector quantities in mathematics.

Notes 10

Although the use of phasor quantities for voltage, current, and impedance in the AC form of Ohm's Law yields certain distinct advantages over scalar calculations, this does not mean one cannot use scalar quantities. Often it is appropriate to express an AC voltage, current, or impedance as a simple scalar number.

Question 11

It is often necessary to represent AC circuit quantities as complex numbers rather than as scalar numbers, because both magnitude *and* phase angle are necessary to consider in certain calculations.

When representing AC voltages and currents in polar form, the angle given refers to the phase shift between the given voltage or current, and a "reference" voltage or current at the same frequency somewhere else in the circuit. So, a voltage of $3.5 \text{ V} \angle -45^o$ means a voltage of 3.5 volts magnitude, phase-shifted 45 degrees behind (lagging) the reference voltage (or current), which is defined to be at an angle of 0 degrees.

But what about *impedance* (Z)? Does impedance have a phase angle, too, or is it a simple scalar number like resistance or reactance?

Calculate the amount of current that would go "through" a 0.1 μF capacitor with 48 volts RMS applied to it at a frequency of 100 Hz. Then, based on Ohm's Law for AC circuits and what you know of the phase relationship between voltage and current for a capacitor, calculate the impedance of this capacitor *in polar form*. Does a definite angle emerge from this calculation for the capacitor's impedance? Explain why or why not.

file 00589

Answer 11

$\mathbf{Z_C} = 15.92 \text{ k}\Omega \angle$ -90°

Notes 11

This is a challenging question, because it asks the student to defend the application of phase angles to a type of quantity that does not really possess a wave-shape like AC voltages and currents do. Conceptually, this is difficult to grasp. However, the answer is quite clear through the Ohm's Law calculation ($Z = \frac{E}{I}$).

Although it is natural to assign a phase angle of 0° to the 48 volt supply, making it the reference waveform, this is not actually necessary. Work through this calculation with your students, assuming different angles for the voltage in each instance. You should find that the impedance computes to be the same exact quantity every time.

Question 12

If a sinusoidal voltage is applied to an impedance with a phase angle of 0°, the resulting voltage and current waveforms will look like this:
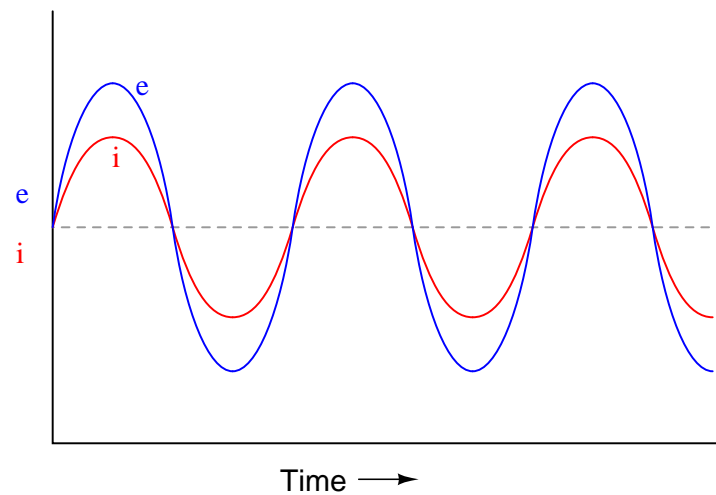
Given that power is the product of voltage and current $(p = ie)$, plot the waveform for power in this circuit.

file 00631

Answer 12
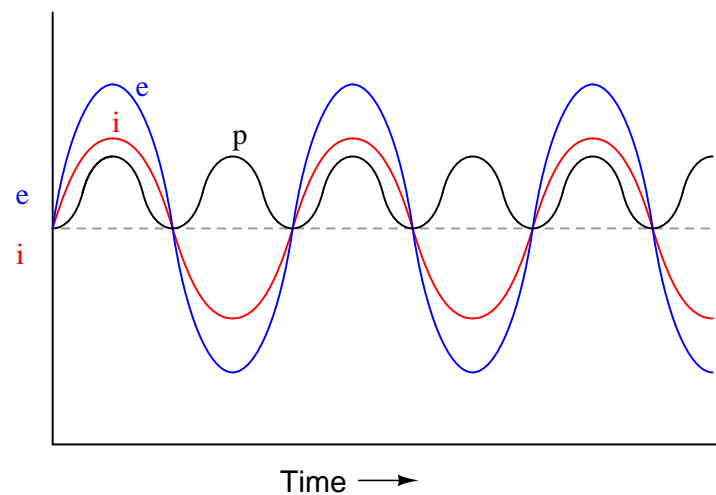
Notes 12

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°?

16

Question 13

If a sinusoidal voltage is applied to an impedance with a phase angle of -90°, the resulting voltage and current waveforms will look like this:
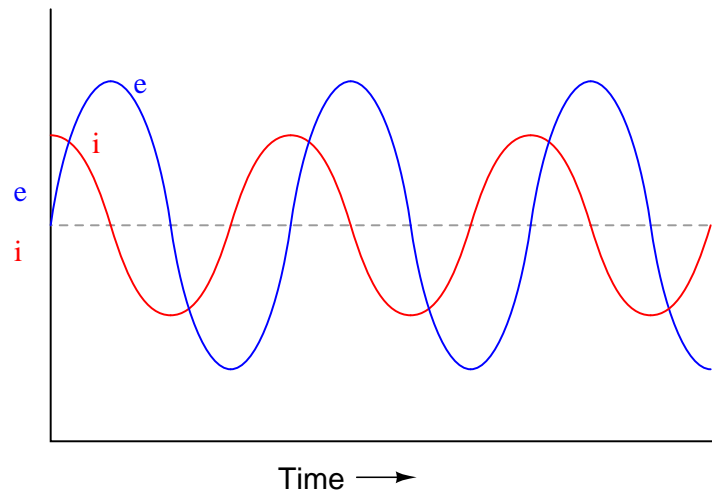
Time $\longrightarrow$

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

Answer 13

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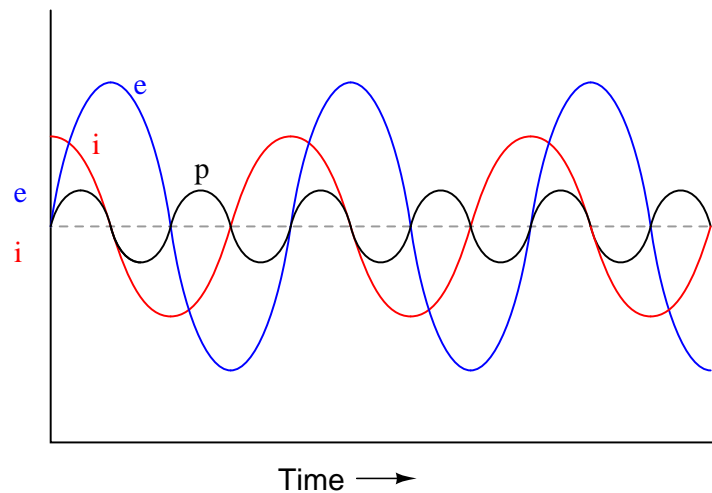
The mnemonic phrase, "ELI the ICE man" indicates that this phase shift is due to a capacitance rather than an inductance.

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°?

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.

Question 14

Express the impedance ($\mathbf{Z}$) in both polar and rectangular forms for each of the following components:

- A resistor with 500 Ω of resistance
- An inductor with 1.2 kΩ of reactance
- A capacitor with 950 Ω of reactance
- A resistor with 22 kΩ of resistance
- A capacitor with 50 kΩ of reactance
- An inductor with 133 Ω of reactance

file 00591

Answer 14

- A resistor with 500 Ω of resistance: 500 Ω ∠ 0° or 500 + j0 Ω
- An inductor with 1.2 kΩ of reactance: 1.2 kΩ ∠ 90° or 0 + j1.2k Ω
- A capacitor with 950 Ω of reactance: 950 Ω ∠ -90° or 0 - j950 Ω
- A resistor with 22 kΩ of resistance: 22 kΩ ∠ 0° or 22k + j0 Ω
- A capacitor with 50 kΩ of reactance: 50 kΩ ∠ -90° or 0 - j50k Ω
- An inductor with 133 Ω of reactance: 133 Ω ∠ 90° or 0 + j133 Ω

Follow-up question: what would the phasors look like for resistive, inductive, and capacitive impedances?

Notes 14

In your discussion with students, emphasize the consistent nature of phase angles for impedances of "pure" components.

A technician measures voltage across the terminals of a burned-out solenoid valve, in order to check for the presence of dangerous voltage before touching the wire connections. The circuit breaker for this solenoid has been turned off and secured with a lock, but the technician's digital voltmeter still registers about three and a half volts AC across the solenoid terminals!
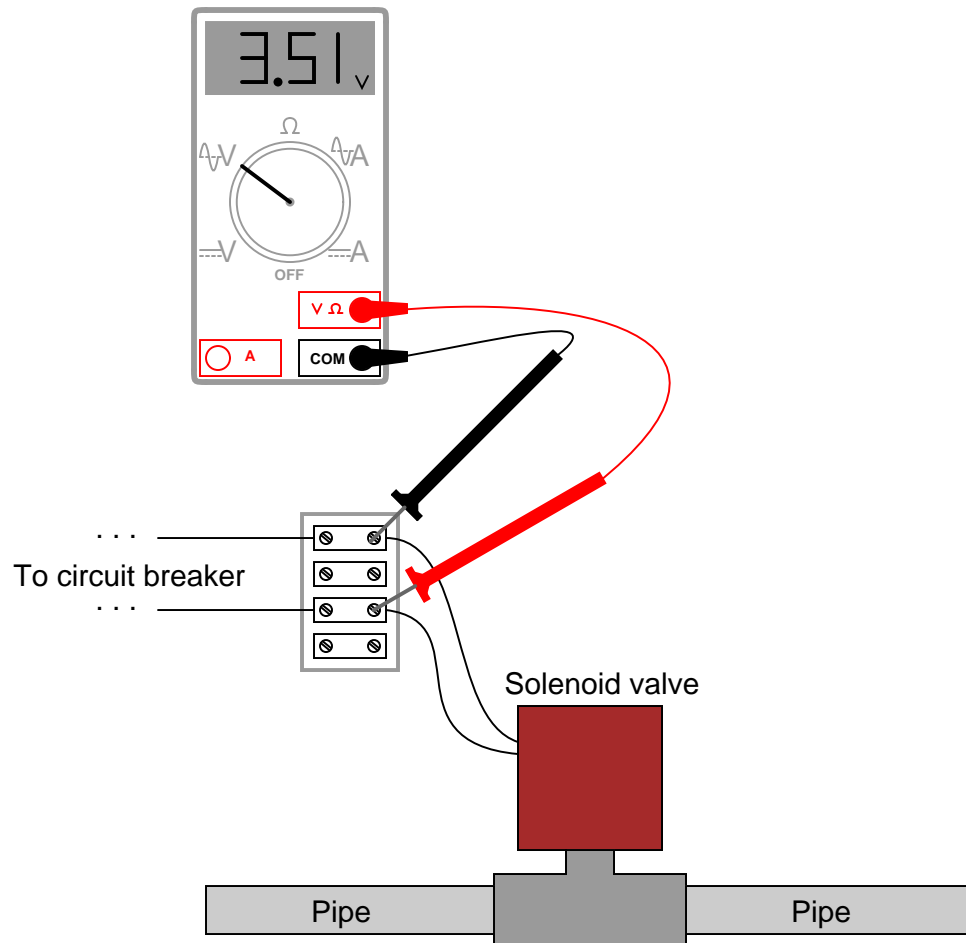
Now, three and a half volts AC is not enough voltage to cause any harm, but its presence confuses and worries the technician. Shouldn't there be 0 volts, with the breaker turned off?

Explain why the technician is able to measure voltage in a circuit that has been "locked out." Hint: digital voltmeters have extremely high *input impedance*, typically in excess of 10 MΩ.

file 00388

Answer 15

The stray capacitance existing between the open contacts of the breaker provides a high-impedance path for AC voltage to reach the voltmeter test leads.

Follow-up question: while the measured voltage in this case was well below the general industry threshold for shock hazard (30 volts), a slightly different scenario could have resulted in a much greater "phantom" voltage measurement. Could a capacitively-coupled voltage of this sort possibly pose a safety hazard? Why or why not?

Challenge question: is it possible for the technician to discern whether or not the 3.51 volts measured by the voltmeter is "real"? In other words, what if this small voltage is not the result of stray capacitance across the breaker contacts, but rather some other source of AC capable of delivering substantial current? How can the technician determine whether or not the 3.51 volts is capable of sourcing significant amounts of current?

Notes 15

I cannot tell you how many times I encountered this phenomenon: "phantom" AC voltages registered by high-impedance DMM's in circuits that are supposed to be "dead." Industrial electricians often use a different instrument to check for the presence of dangerous voltage, a crude device commonly known as a "Wiggy."

Question 16

Use the "impedance triangle" to calculate the necessary reactance of this series combination of resistance (R) and capacitive reactance (X) to produce the desired total impedance of 300 Ω:

R = 210 Ω

X = ???

Z = 300 Ω

R = 210 Ω

X = ???
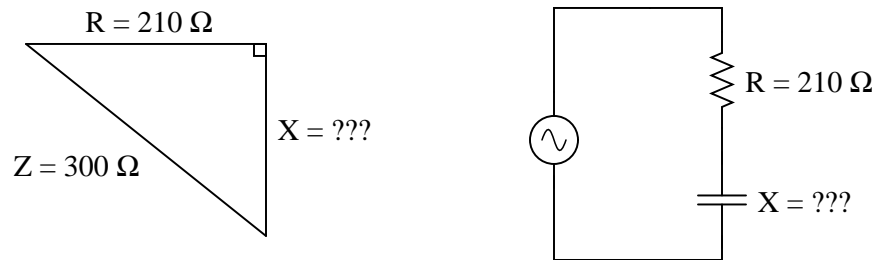
Explain what equation(s) you use to calculate X, and the algebra necessary to achieve this result from a more common formula.

<u>file 02092</u>

Answer 16

$X = 214.2$ Ω, as calculated by an algebraically manipulated version of the Pythagorean Theorem.

Notes 16

Be sure to have students show you the form of the Pythagorean Theorem, rather than showing them yourself, since it is so easy for students to research on their own.

Question 17

A series AC circuit exhibits a total impedance of 10 kΩ, with a phase shift of 65 degrees between voltage and current. Drawn in an impedance triangle, it looks like this:
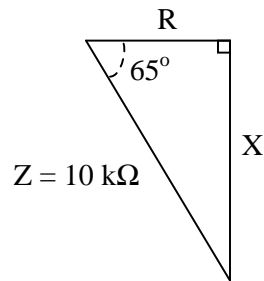
We know that the *sine* function relates the sides X and Z of this impedance triangle with the 65 degree angle, because the sine of an angle is the ratio of *opposite* to *hypotenuse*, with X being opposite the 65 degree angle. Therefore, we know we can set up the following equation relating these quantities together:

$$\sin 65^o = \frac{X}{Z}$$

Solve this equation for the value of X, in ohms.
file 02088

Answer 17

$X = 9.063$ kΩ

Notes 17

Ask your students to show you their algebraic manipulation(s) in setting up the equation for evaluation.

Question 18

A series AC circuit exhibits a total impedance of 2.5 kΩ, with a phase shift of 30 degrees between voltage and current. Drawn in an impedance triangle, it looks like this:
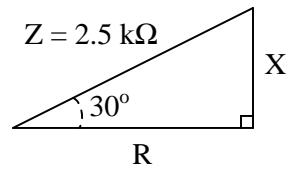
Use the appropriate trigonometric functions to calculate the equivalent values of R and X in this series circuit.

file 02087

Answer 18

$R = 2.165$ kΩ
$X = 1.25$ kΩ

Notes 18

There are a few different ways one could solve for R and X in this trigonometry problem. This would be a good opportunity to have your students present problem-solving strategies on the board in front of class so everyone gets an opportunity to see multiple techniques.

Question 19

A parallel AC circuit draws 100 mA of current through a purely resistive branch and 85 mA of current through a purely capacitive branch:
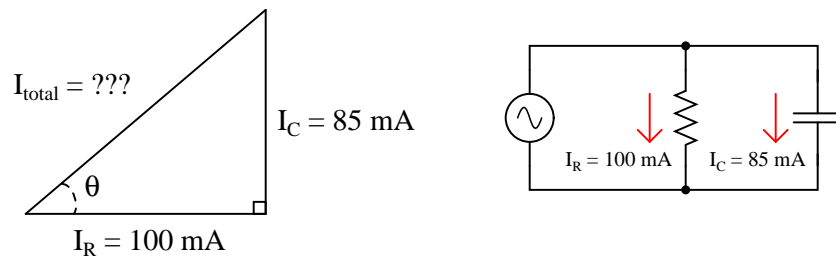
Calculate the total current and the angle Θ of the total current, explaining your trigonometric method(s) of solution.

file 02091

Answer 19

$I_{total} = 131.2$ mA

$\Theta = 40.36^o$

Follow-up question: in calculating Θ, it is recommended to use the arctangent function instead of either the arcsine or arc-cosine functions. The reason for doing this is accuracy: less possibility of compounded error, due to either rounding and/or calculator-related (keystroke) errors. Explain why the use of the arctangent function to calculate Θ incurs less chance of error than either of the other two arcfunctions.

Notes 19

The follow-up question illustrates an important principle in many different disciplines: avoidance of unnecessary risk by choosing calculation techniques using given quantities instead of derived quantities. This is a good topic to discuss with your students, so make sure you do so.

Question 20

A parallel RC circuit has 10 μS of susceptance (B). How much conductance (G) is necessary to give the circuit a (total) phase angle of 22 degrees?

Answer 20

$G = 24.75$ μS
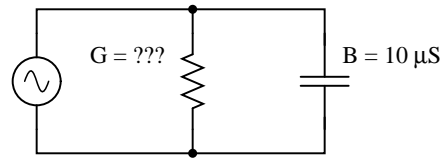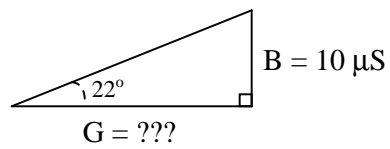
Follow-up question: how much resistance is this, in ohms?

Notes 20

Ask your students to explain their method(s) of solution, including any ways to double-check the correctness of the answer.

Voltage divider circuits may be constructed from reactive components just as easily as they may be constructed from resistors. Take this capacitive voltage divider, for instance:
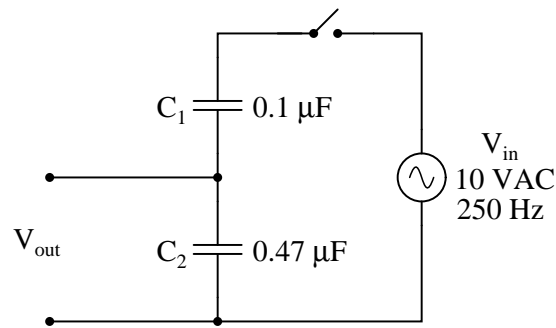
Calculate the magnitude and phase shift of V_{out}. Also, describe what advantages a capacitive voltage divider might have over a resistive voltage divider.

file 00638

Answer 21

$\mathbf{V_{out}} = 1.754 \text{ V} \angle 0^o$

Follow-up question #1: explain why the division ratio of a capacitive voltage divider remains constant with changes in signal frequency, even though we know that the reactance of the capacitors (X_{C1} and X_{C2}) will change.

Follow-up question #2: one interesting feature of capacitive voltage dividers is that they harbor the possibility of electric shock after being disconnected from the voltage source, if the source voltage is high enough and if the disconnection happens at just the right time. Explain why a capacitive voltage divider poses this threat whereas a resistive voltage divider does not. Also, identify what the *time* of disconnection from the AC voltage source has to do with shock hazard.

Notes 21

Capacitive voltage dividers find use in high-voltage AC instrumentation, due to some of the advantages they exhibit over resistive voltage dividers. Your students should take special note of the phase angle for the capacitor's voltage drop. Why it is 0 degrees, and not some other angle?

A technician needs to know the value of a capacitor, but does not have a capacitance meter nearby. In lieu of this, the technician sets up the following circuit to measure capacitance:
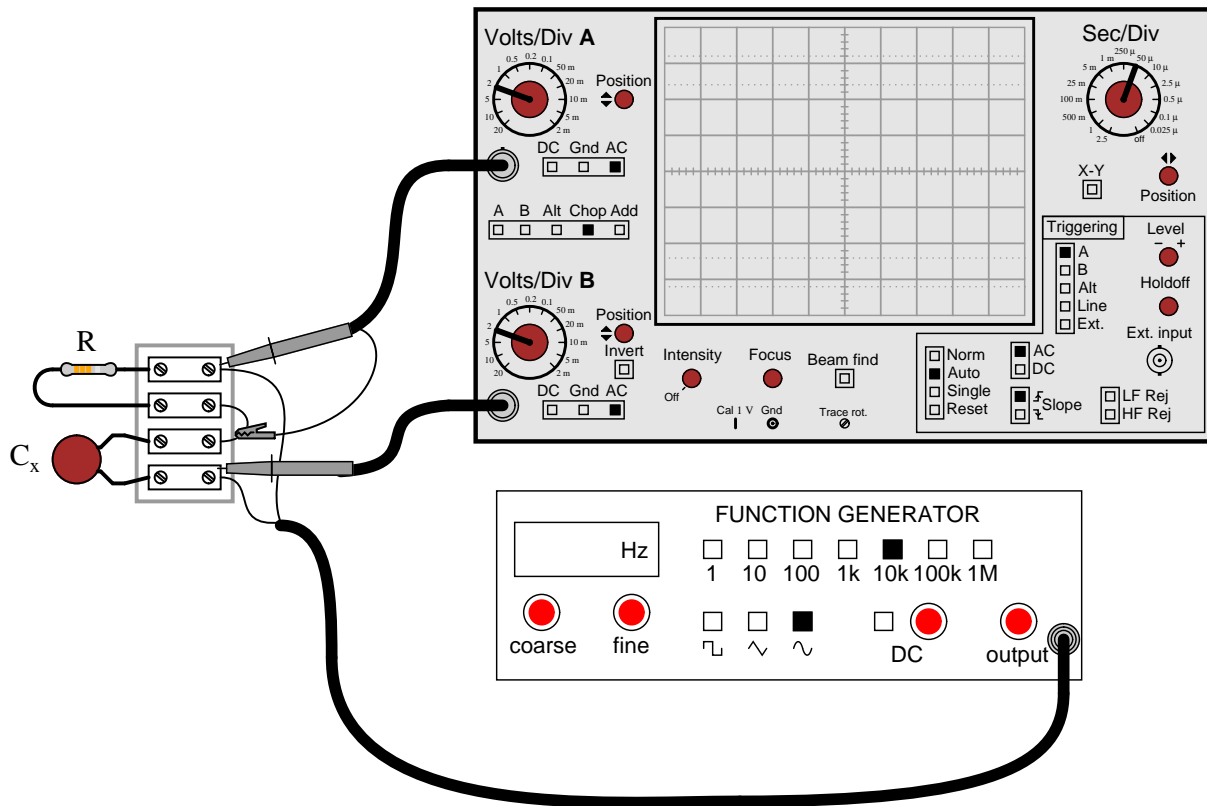
You happen to walk by this technician's workbench and ask, "How does this measurement setup work?" The technician responds, "You connect a resistor of known value (R) in series with the capacitor of unknown value (C_x), then adjust the generator frequency until the oscilloscope shows the two voltage drops to be equal, and then you calculate C_x."

Explain how this system works, in your own words. Also, write the formula you would use to calculate the value of C_x given f and R.

file 02114

Answer 22

I'll let you figure out how to explain the operation of this test setup. The formula you would use looks like this:

$$C_x = \frac{1}{2\pi f R}$$

Follow-up question: could you use a similar setup to measure the inductance of an unknown inductor L_x? Why or why not?

Challenge question: astute observers will note that this setup might not work in real life because the ground connection of the oscilloscope is *not* common with one of the function generator's leads. Explain why this might be a problem, and suggest a practical solution for it.

Notes 22

This method of measuring capacitance (or inductance for that matter) is fairly old, and works well if the unknown component has a high Q value.

A student measures voltage drops in an AC circuit using three voltmeters and arrives at the following measurements:
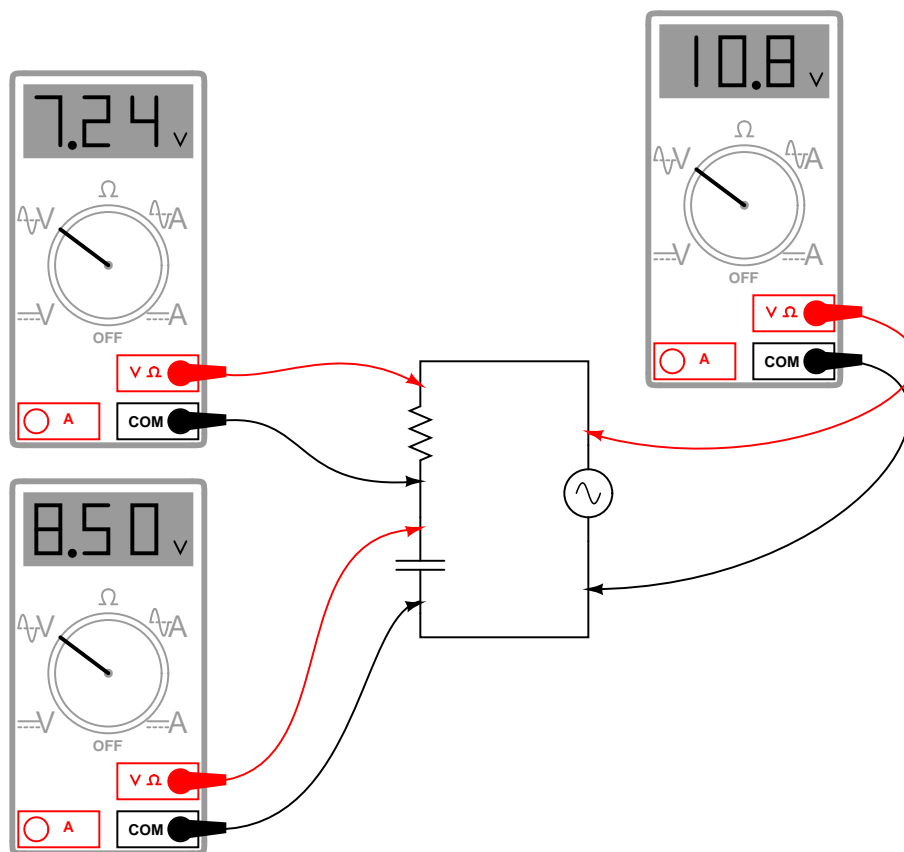
Upon viewing these measurements, the student becomes very perplexed. Aren't voltage drops supposed to *add* in series, just as in DC circuits? Why, then, is the total voltage in this circuit only 10.8 volts and not 15.74 volts? How is it possible for the total voltage in an AC circuit to be substantially less than the simple sum of the components' voltage drops?

Another student, trying to be helpful, suggests that the answer to this question might have something to do with RMS versus peak measurements. A third student disagrees, proposing instead that at least one of the meters is badly out of calibration and thus not reading correctly.

When you are asked for your thoughts on this problem, you realize that neither of the answers proposed thus far are correct. Explain the real reason for the "discrepancy" in voltage measurements, and also explain how you could experimentally disprove the other answers (RMS vs. peak, and bad calibration).

file 01566

Answer 23

AC voltages still add in series, but *phase* must also be accounted for when doing so. Unfortunately, multimeters provide no indication of phase whatsoever, and thus do not provide us with all the information we need. (Note: just by looking at this circuit's components, though, you should still be able to calculate the correct result for total voltage and validate the measurements.)

I'll let you determine how to disprove the two incorrect explanations offered by the other students!

Challenge question: calculate a set of possible values for the capacitor and resistor that would generate these same voltage drops in a real circuit. Hint: you must also decide on a value of frequency for the power source.

Notes 23

This question has two different layers: first, how to reconcile the "strange" voltage readings with Kirchhoff's Voltage Law; and second, how to experimentally validate the accuracy of the voltmeters and the fact that they are all registering the same type of voltage (RMS, peak, or otherwise, it doesn't matter). The first layer of this question regards the basic concepts of AC phase, while the second exercises troubleshooting and critical thinking skills. Be sure to discuss both of these topics in class with your students.

Question 24

Write an equation that solves for the impedance of this series circuit. The equation need not solve for the phase angle between voltage and current, but merely provide a scalar figure for impedance (in ohms):
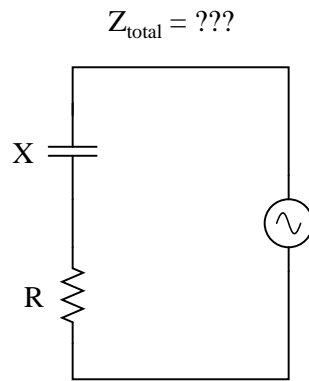
$$Z_{\text{total}} = \text{???}$$

Answer 24

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

Notes 24

Ask your students if this equation looks similar to any other mathematical equations they've seen before. If not, square both sides of the equation so it looks like $Z^2 = R^2 + X^2$ and ask them again.

Question 25

Use a triangle to calculate the total voltage of the source for this series RC circuit, given the voltage drop across each component:
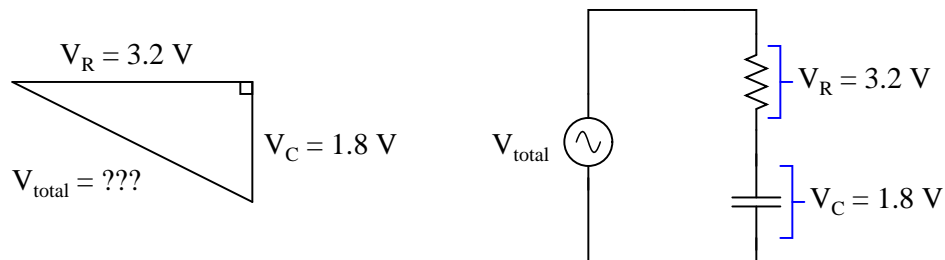
Explain what equation(s) you use to calculate V_{total}, as well as why we must geometrically add these voltages together.

file 02107

Answer 25

$V_{total} = 3.672$ volts, as calculated by the Pythagorean Theorem

Notes 25

Be sure to have students show you the form of the Pythagorean Theorem, rather than showing them yourself, since it is so easy for students to research on their own.

Question 26

Determine the phase angle (Θ) of the current in this circuit, with respect to the supply voltage:

file 01853

Answer 26

$\Theta = 26.51^{o}$
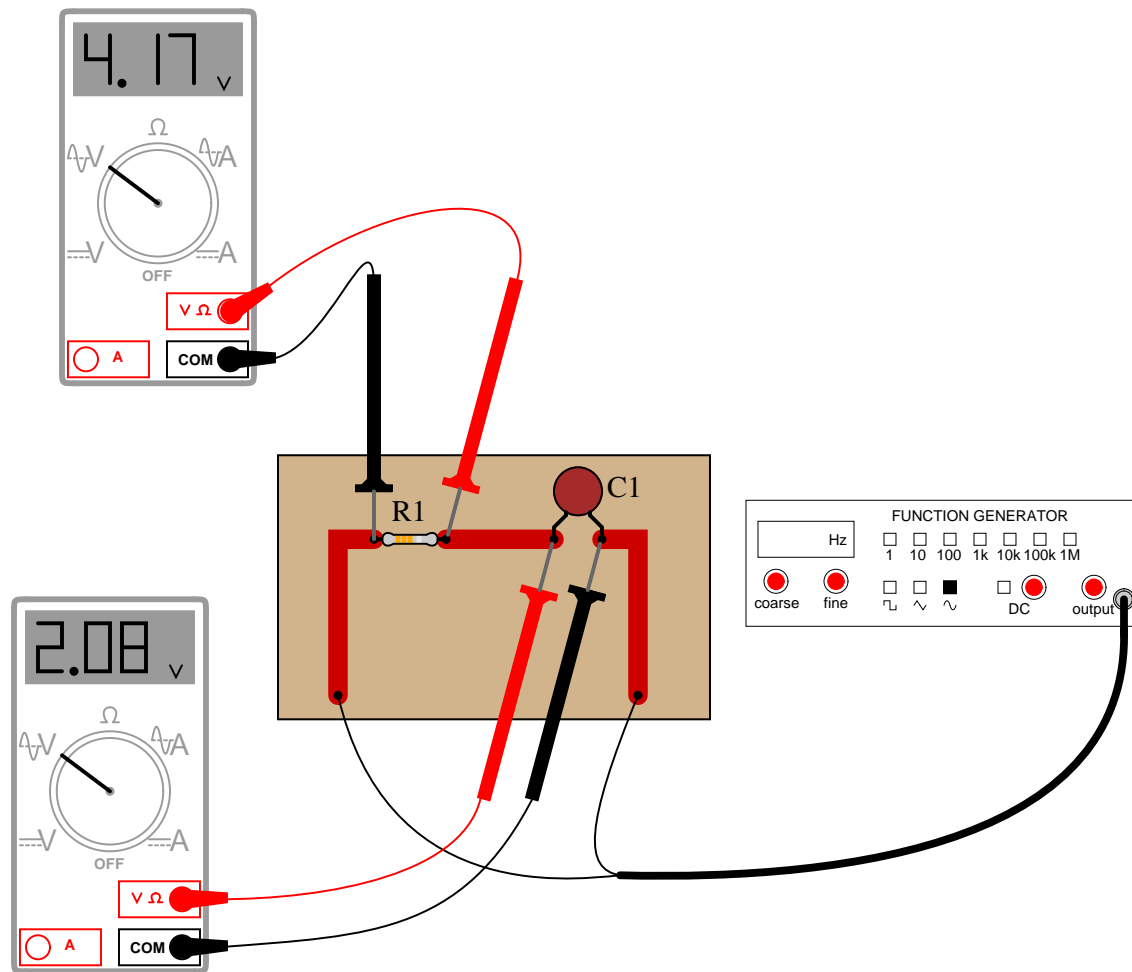
Challenge question: explain how the following phasor diagram was determined for this problem:
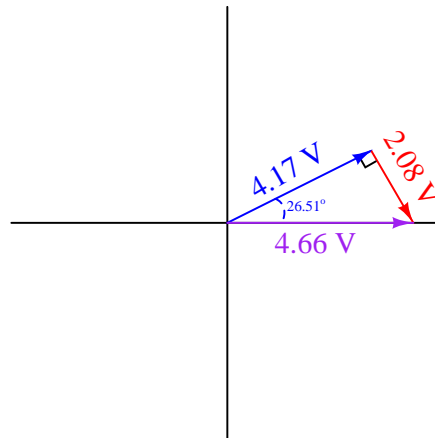
Notes 26

This is an interesting question for a couple of reasons. First, students must determine how they will measure phase shift with just the two voltage indications shown by the meters. This may present a significant challenge for some. Discuss problem-solving strategies in class so that students understand how and why it is possible to determine Θ.

Secondly, this is an interesting question because it shows how something as abstract as phase angle can be measured with just a voltmeter – no oscilloscope required! Not only that, but we don't even have to know the component values either! Note that this technique works only for simple circuits.

A practical point to mention here is that multimeters have frequency limits which must be considered when taking measurements on electronic circuits. Some high-quality handheld digital meters have frequency limits of hundred of kilohertz, while others fail to register accurately at only a few thousand hertz. Unless we knew these two digital voltmeters were sufficient for measuring at the signal frequency, their indications would be useless to us.

Question 27

Due to the effects of a changing electric field on the dielectric of a capacitor, some energy is dissipated in capacitors subjected to AC. Generally, this is not very much, but it is there. This dissipative behavior is typically modeled as a series-connected resistance:
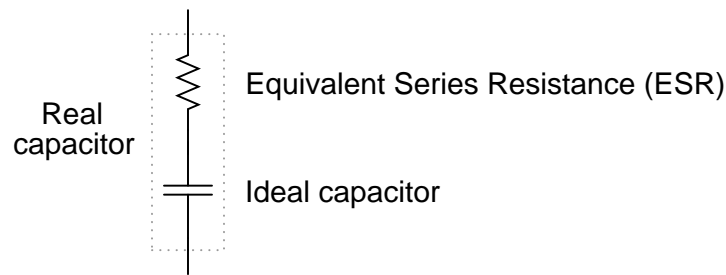
Calculate the magnitude and phase shift of the current through this capacitor, taking into consideration its equivalent series resistance (ESR):
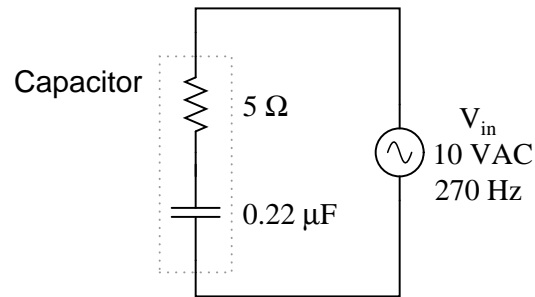
Compare this against the magnitude and phase shift of the current for an ideal 0.22 μF capacitor.
file 01847

Answer 27

$\mathbf{I} = 3.732206$ mA $\angle$ 89.89^o for the real capacitor with ESR.

$\mathbf{I} = 3.732212$ mA $\angle$ 90.00^o for the ideal capacitor.

Follow-up question #1: can this ESR be detected by a DC meter check of the capacitor? Why or why not?

Follow-up question #2: explain how the ESR of a capacitor can lead to physical heating of the component, especially under high-voltage, high-frequency conditions. What safety concerns might arise as a result of this?

Notes 27

Although capacitors do contain their own parasitic effects, ESR being one of them, they still tend to be much "purer" components than inductors for general use. This is another reason why capacitors are generally favored over inductors in applications where either will suffice.

36

Question 28

Solve for all voltages and currents in this series RC circuit:

0.01 µF

15 V RMS
1 kHz

4.7 kΩ
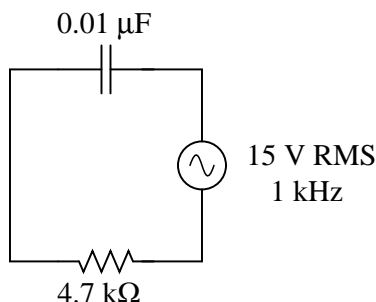
file 01848

Answer 28

$V_C = 14.39$ volts RMS
$V_R = 4.248$ volts RMS
$I = 903.9\,\mu A$ RMS

Follow-up question: identify the consequences of a shorted capacitor in this circuit, with regard to circuit current and component voltage drops.

Notes 28

Nothing special here – just a straightforward exercise in series AC circuit calculations.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them. The following is a sample of a written problem-solving strategy for analyzing a series resistive-reactive AC circuit:

Step 1: Calculate all reactances (X).
Step 2: Draw an impedance triangle $(Z \; ; \; R \; ; \; X)$, solving for Z
Step 3: Calculate circuit current using Ohm's Law: $I = \frac{V}{Z}$
Step 4: Calculate series voltage drops using Ohm's Law: $V = IZ$
Step 5: Check work by drawing a voltage triangle $(V_{total} \; ; \; V_1 \; ; \; V_2)$, solving for V_{total}

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Solve for all voltages and currents in this series RC circuit, and also calculate the phase angle of the total impedance:

220n

3k3

48 V peak
30 Hz
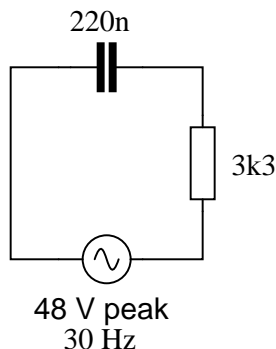
file 01849

Answer 29

$V_C = 47.56$ volts peak
$V_R = 6.508$ volts peak
$I = 1.972$ milliamps peak
$\Theta_Z = -82.21^o$

Follow-up question: what would we have to do to get these answers in units RMS instead of units "peak"?

Notes 29

Bring to your students' attention the fact that total voltage in this circuit is given in "peak" units rather than RMS, and what effect this has on our answers.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them. The following is a sample of a written problem-solving strategy for analyzing a series resistive-reactive AC circuit:

Step 1: Calculate all reactances (X).
Step 2: Draw an impedance triangle (Z ; R ; X), solving for Z
Step 3: Calculate circuit current using Ohm's Law: $I = \frac{V}{Z}$
Step 4: Calculate series voltage drops using Ohm's Law: $V = IZ$
Step 5: Check work by drawing a voltage triangle (V_{total} ; V_1 ; V_2), solving for V_{total}

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 30

Determine the total current and all voltage drops in this circuit, stating your answers the way a multimeter would register them:
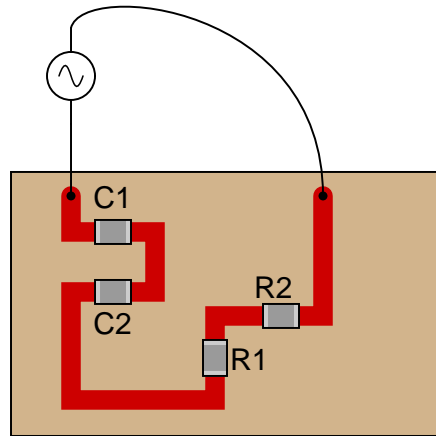
- $C_1 = 125$ pF
- $C_2 = 71$ pF
- $R_1 = 6.8$ kΩ
- $R_2 = 1.2$ kΩ
- $V_{supply} = 20$ V RMS
- $f_{supply} = 950$ kHz

Also, calculate the phase angle (Θ) between voltage and current in this circuit, and explain where and how you would connect an oscilloscope to measure that phase shift.

file 01851

Answer 30

- $I_{total} = 2.269$ mA
- $V_{C1} = 3.041$ V
- $V_{C2} = 5.354$ V
- $V_{R1} = 15.43$ V
- $V_{R2} = 2.723$ V
- $\Theta = -24.82^o$ (voltage lagging current)

I suggest using a dual-trace oscilloscope to measure total voltage (across the supply terminals) and voltage drop across resistor R_2. Theoretically, measuring the voltage dropped by either resistor would be fine, but R_2 works better for practical reasons (oscilloscope input lead grounding). Phase shift then could be measured either in the time domain or by a Lissajous figure analysis.

Some students many wonder what type of numerical result best corresponds to a multimeter's readings, if they do their calculations using complex numbers ("do I use polar or rectangular form, and if rectangular do I use the real or the imaginary part?"). The answers given for this question should clarify that point.

It is very important that students know how to apply this knowledge of AC circuit analysis to real-world situations. Asking students to determine how they would connect an oscilloscope to the circuit to measure Θ is an exercise in developing their abstraction abilities between calculations and actual circuit scenarios.

It is noteworthy that the low capacitances shown here approach parasitic capacitances between circuit board traces. In other words, whoever designs a circuit to operate at 950 kHz cannot simply place components at will on the board, but must consider the traces themselves to be circuit elements (both capacitive and inductive in nature!). The calculations used to obtain the given answers, of course, assume ideal conditions where the PC board is not considered to possess capacitance or inductance.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them. The following is a sample of a written problem-solving strategy for analyzing a series resistive-reactive AC circuit:

Step 1: Calculate all reactances (X).
Step 2: Draw an impedance triangle (Z ; R ; X), solving for Z
Step 3: Calculate circuit current using Ohm's Law: $I = \frac{V}{Z}$
Step 4: Calculate series voltage drops using Ohm's Law: $V = IZ$
Step 5: Check work by drawing a voltage triangle (V_{total} ; V_1 ; V_2), solving for V_{total}

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 31

Calculate the voltage drops across all components in this circuit, expressing them in complex (polar) form with magnitudes and phase angles each:

1.5 V
180 Hz

0.01 µF
C1

R1

7.1 kΩ

C2
0.15 µF
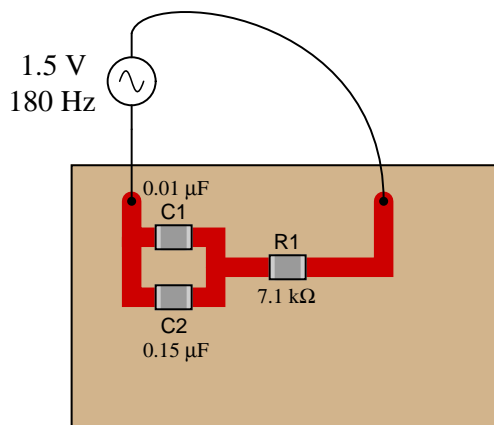
file 01852

Answer 31

$\mathbf{V_{C1}} = 0.921$ V $\angle -52.11^o$
$\mathbf{V_{C2}} = 0.921$ V $\angle -52.11^o$
$\mathbf{V_{R1}} = 1.184$ V $\angle 37.90^o$

Follow-up question: how much phase shift is there between the capacitors' voltage drop and the resistor's voltage drop? Explain why this value is what it is.

The first challenge of this question is for students to figure out how to reduce this series-parallel combination to something simpler. Fortunately, this is very easy to do if one remembers the properties of parallel capacitances.

Students may be surprised to discover the phase shift between V_C and V_R is the value it is. However, this should not remain a mystery. Discuss this with your class, taking time for all of them to understand why the voltage phasors of a resistor and a capacitor in a simple series circuit will always be orthogonal.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them. The following is a sample of a written problem-solving strategy for analyzing a series resistive-reactive AC circuit:

Step 1: Calculate all reactances (X).
Step 2: Draw an impedance triangle (Z ; R ; X), solving for Z
Step 3: Calculate circuit current using Ohm's Law: $I = \frac{V}{Z}$
Step 4: Calculate series voltage drops using Ohm's Law: $V = IZ$
Step 5: Check work by drawing a voltage triangle (V_{total} ; V_1 ; V_2), solving for V_{total}

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 32

In this circuit, a series resistor-capacitor network creates a phase-shifted voltage for the "gate" terminal of a power-control device known as a *TRIAC*. All portions of the circuit except for the RC network are "shaded" for de-emphasis:
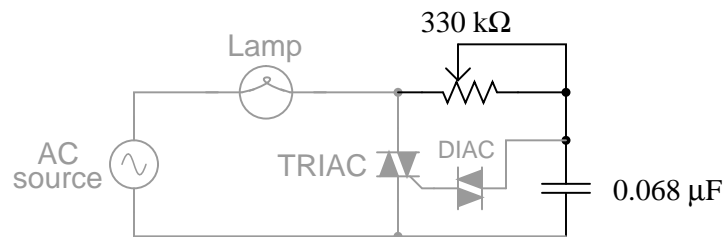
Calculate how many degrees of phase shift the capacitor's voltage is, compared to the total voltage across the series RC network, assuming a frequency of 60 Hz, and a 50% potentiometer setting.

file 00637

Answer 32

E_C phase shift = -76.7°

Challenge question: what effect will a change in potentiometer setting have on this phase angle? Specifically, will increasing the resistance make the phase shift approach -90° or approach 0°?

Notes 32

In this question, I purposely omitted any reference to voltage levels, so the students would have to set up part of the problem themselves. The goal here is to build problem-solving skills.

Question 33

A quantity sometimes used in DC circuits is *conductance*, symbolized by the letter G. Conductance is the reciprocal of resistance $(G = \frac{1}{R})$, and it is measured in the unit of siemens.

Expressing the values of resistors in terms of conductance instead of resistance has certain benefits in parallel circuits. Whereas resistances (R) add in series and "diminish" in parallel (with a somewhat complex equation), conductances (G) add in parallel and "diminish" in series. Thus, doing the math for series circuits is easier using resistance and doing math for parallel circuits is easier using conductance:

$$R_{total} = R_1 + R_2 + R_3$$
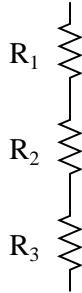
$$G_{total} = G_1 + G_2 + G_3$$
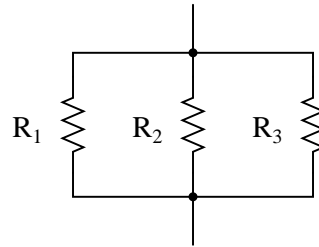
$$G_{total} = \cfrac{1}{\cfrac{1}{G_1} + \cfrac{1}{G_2} + \cfrac{1}{G_3}}$$

$$R_{total} = \cfrac{1}{\cfrac{1}{R_1} + \cfrac{1}{R_2} + \cfrac{1}{R_3}}$$

In AC circuits, we also have reciprocal quantities to reactance (X) and impedance (Z). The reciprocal of reactance is called *susceptance* $(B = \frac{1}{X})$, and the reciprocal of impedance is called *admittance* $(Y = \frac{1}{Z})$. Like conductance, both these reciprocal quantities are measured in units of siemens.

Write an equation that solves for the admittance (Y) of this parallel circuit. The equation need not solve for the phase angle between voltage and current, but merely provide a scalar figure for admittance (in siemens):

$$Y_{total} = ???$$

file 01845

44
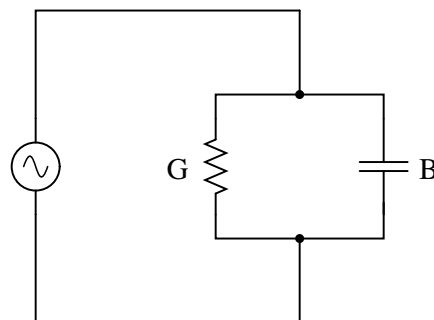
Answer 33

$$Y_{total} = \sqrt{G^2 + B^2}$$

Follow-up question #1: draw a phasor diagram showing how Y, G, and B relate.

Follow-up question #2: re-write this equation using quantities of resistance (R), reactance (X), and impedance (Z), instead of conductance (G), susceptance (B), and admittance (Y).

Notes 33

Ask your students if this equation looks familiar to them. It should!

The answer to the challenge question is a matter of algebraic substitution. Work through this process with your students, and then ask them to compare the resulting equation with other equations they've seen before. Does its form look familiar to them in any way?

Question 34

Calculate the total impedance offered by these three capacitors to a sinusoidal signal with a frequency of 4 kHz:

- $C_1 = 0.1\,\mu\text{F}$
- $C_2 = 0.047\,\mu\text{F}$
- $C_3 = 0.033\,\mu\text{F}$

State your answer in the form of a scalar number (not complex), but calculate it using two different strategies:

- Calculate total capacitance (C_{total}) first, then total impedance (Z_{total}).
- Calculate individual admittances first (Y_{C1}, Y_{C2}, and Y_{C3}), then total impedance (Z_{total}).

file 01846

Answer 34

First strategy:

$C_{total} = 0.18\,\mu\text{F}$

$Z_{total} = 221\,\Omega$

Second strategy:

$Y_{C1} = 2.51\text{ mS}$

$Y_{C2} = 1.18\ \text{ mS}$

$Y_{C3} = 829\,\mu\text{S}$

$Y_{total} = 4.52\text{ mS}$

$Z_{total} = 221\,\Omega$

Notes 34

This question is another example of how multiple means of calculation will give you the same answer (if done correctly!). Make note to your students that this indicates an answer-checking strategy!

Question 35

Calculate the total impedance of these parallel-connected components, expressing it in polar form (magnitude and phase angle):

Surface-mount components on a printed-circuit board

C1 33n   R1 510

Z_{total} @ 7.9 kHz = ???
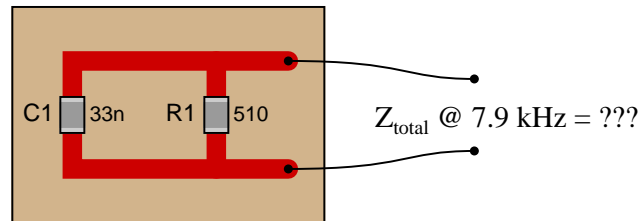
Also, draw an admittance triangle for this circuit.

<u>file 02108</u>

Answer 35

$Z_{total} = 391.4 \ \Omega \ \angle \ \text{-}39.9^o$

Y_{total} = 2.555 mS

Y_{C1} = 1.638 mS

39.9°

Y_{R1} = 1.961 mS
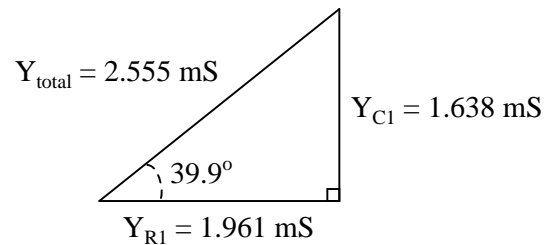
Notes 35

Some students may wonder why every side of the triangle is represented by a Y term, rather than Y for the hypotenuse, G for the adjacent, and B for the opposite. If students ask about this, remind them that conductance (G) and susceptance (B) are simple two different *types* of admittances (Y), just as resistance (R) and reactance (X) are simply two different types of impedances (Z).

Question 36

Calculate the total impedances (complete with phase angles) for each of the following capacitor-resistor circuits:
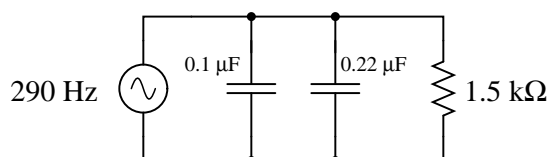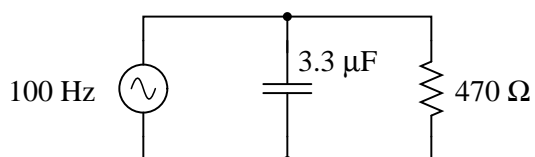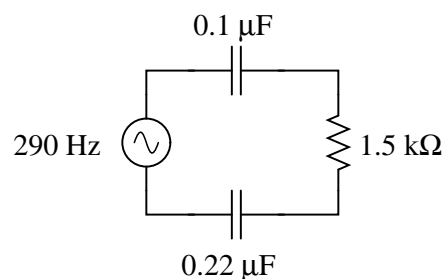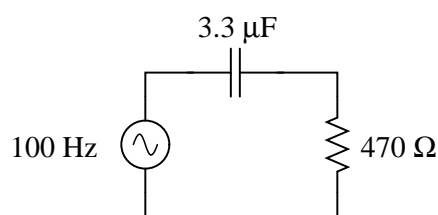
3.3 μF

100 Hz   470 Ω

0.1 μF

290 Hz   1.5 kΩ

0.22 μF

3.3 μF

100 Hz   470 Ω

0.1 μF   0.22 μF

290 Hz   1.5 kΩ

file 02109

Answer 36

3.3 μF

100 Hz   470 Ω

$Z_{total} = 673.4 \ \Omega \ \angle \ -45.74^o$

0.1 μF

290 Hz   1.5 kΩ

0.22 μF
$Z_{total} = 8.122 \ k\Omega \ \angle \ -79.36^o$

3.3 μF

100 Hz   470 Ω

$Z_{total} = 336.6 \ \Omega \ \angle \ -44.26^o$

0.1 μF   0.22 μF

290 Hz   1.5 kΩ
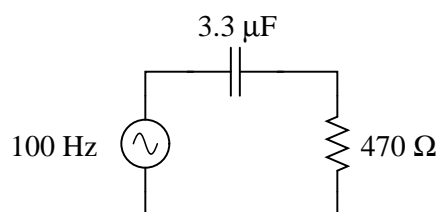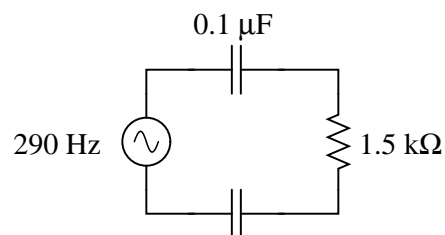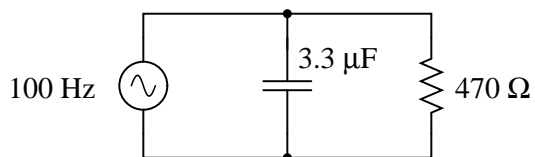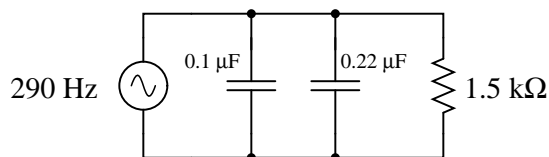
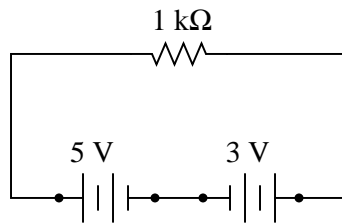$Z_{total} = 1.129 \ k\Omega \ \angle \ -41.17^o$

Notes 36

Have your students explain how they solved for each impedance, step by step. You may find different approaches to solving the same problem(s), and your students will benefit from seeing the diversity of solution techniques.
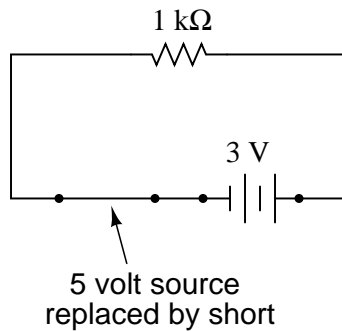
Question 37

If the source voltage in this circuit is assumed to be the phase reference (that is, the voltage is defined to be at an angle of 0 degrees), determine the relative phase angles of each current in this parallel circuit:
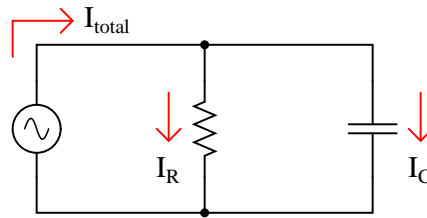
- $\Theta_{I(R)} =$
- $\Theta_{I(C)} =$
- $\Theta_{I(total)} =$

file 02112

Answer 37

- $\Theta_{I(R)} = 0^o$
- $\Theta_{I(C)} = 90^o$
- $\Theta_{I(total)} =$ some positive angle between 0° and 90°, exclusive

Notes 37

Some students will be confused about the positive phase angles, since this is a capacitive circuit and they have learned to associate negative angles with capacitors. It is important for these students to realize, though, that the negative angles they immediately associate with capacitors are in reference to *impedance* and not necessarily to other variables in the circuit!

Question 38

If the dielectric substance between a capacitor's plates is not a perfect insulator, there will be a path for direct current (DC) from one plate to the other. This is typically called *leakage resistance*, and it is modeled as a shunt resistance to an ideal capacitance:

Real
capacitor

Ideal capacitor   Leakage resistance
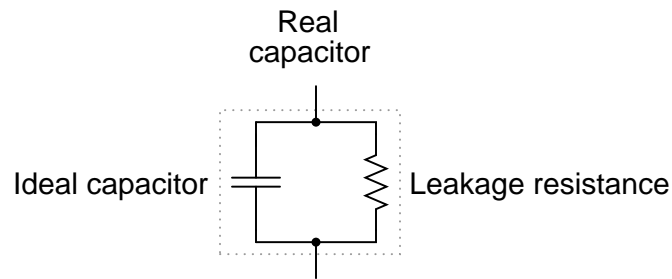
Calculate the magnitude and phase shift of the current drawn by this real capacitor, if powered by a sinusoidal voltage source of 30 volts RMS at 400 Hz:

$0.75 \ \mu F$ $R_{leakage} = 1.5 \ M\Omega$ 30 V RMS
400 Hz
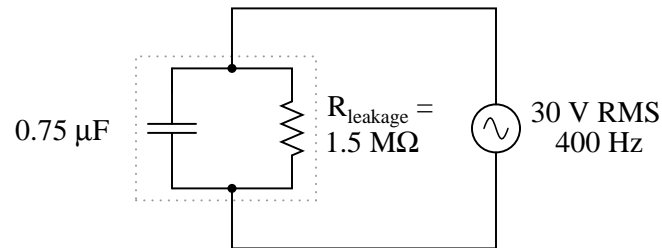
Compare this against the magnitude and phase shift of the current for an ideal capacitor (no leakage).
file 01850

Answer 38

$\mathbf{I} = 56.548671$ mA $\angle \ 89.98^o$ for the real capacitor with leakage resistance.
$\mathbf{I} = 56.548668$ mA $\angle \ 90.00^o$ for the ideal capacitor.

Discuss with your students the fact that electrolytic capacitors typically have more leakage (less $R_{leakage}$) than most other capacitor types, due to the thinness of the dielectric oxide layer.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them. The following is a sample of a written problem-solving strategy for analyzing a series resistive-reactive AC circuit:

Step 1: Calculate all reactances (X).
Step 2: Draw an impedance triangle (Z ; R ; X), solving for Z
Step 3: Calculate circuit current using Ohm's Law: $I = \frac{V}{Z}$
Step 4: Calculate series voltage drops using Ohm's Law: $V = IZ$
Step 5: Check work by drawing a voltage triangle (V_{total} ; V_1 ; V_2), solving for V_{total}

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 39

The *input impedance* of an electrical test instrument is a very important parameter in some applications, because of how the instrument may *load* the circuit being tested. Oscilloscopes are no different from voltmeters in this regard:
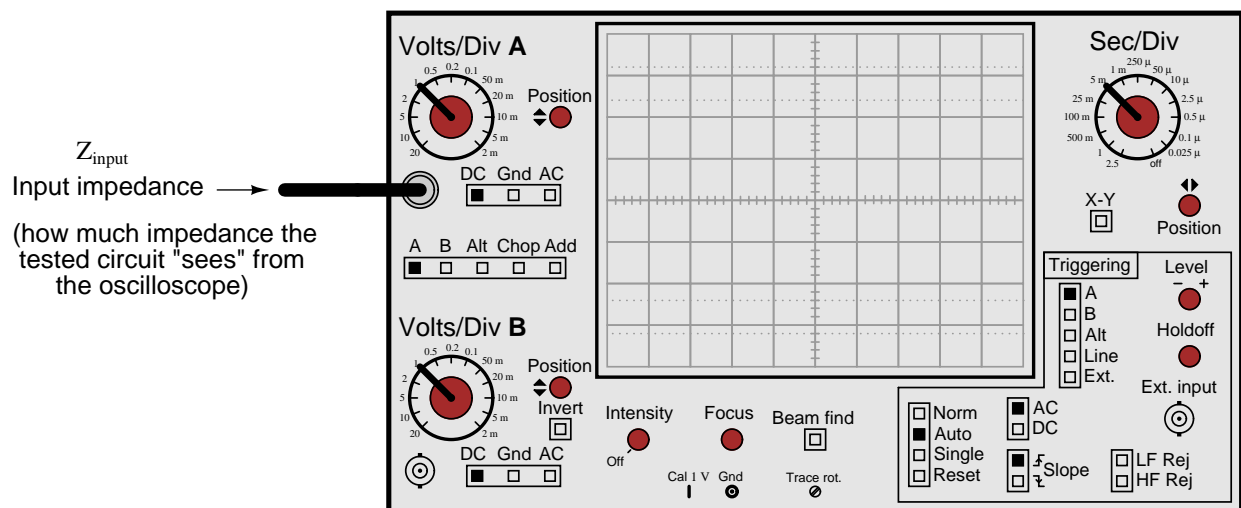
Typical input impedance for an oscilloscope is 1 MΩ of resistance, in parallel with a small amount of capacitance. At low frequencies, the reactance of this capacitance is so high that it may be safely ignored. At high frequencies, though, it may become a substantial load to the circuit under test:

Oscilloscope input (typical)
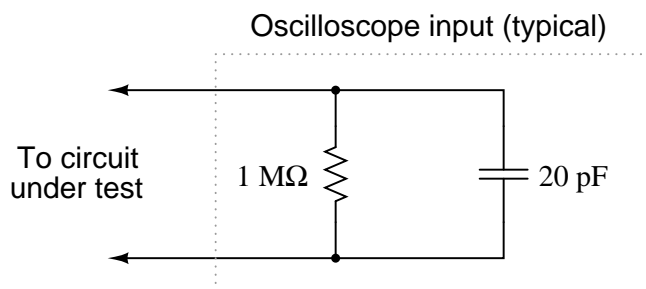
Calculate how many ohms of impedance this oscilloscope input (equivalent circuit shown in the above schematic) will impose on a circuit with a signal frequency of 150 kHz.

file 02111

Answer 39

$Z_{input} = 52.98$ kΩ at 150 kHz

Follow-up question: what are the respective input impedances for ideal voltmeters and ideal ammeters? Explain why each ideal instrument needs to exhibit these impedances in order to accurately measure voltage and current (respectively) with the least "impact" to the circuit under test.

Notes 39

Mention to your students that this capacitive loading effect only gets worse when a cable is attached to the oscilloscope input. The calculation performed for this question is only for the *input* of the oscilloscope itself, not including whatever capacitance may be included in the test probe cable!

This is one of the reasons why ×10 probes are used with oscilloscopes: to minimize the loading effect on the tested circuit.

Question 40

Determine the size of capacitor (in Farads) necessary to create a total current of 11.3 mA in this parallel RC circuit:
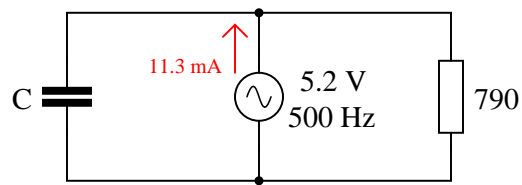
Answer 40

$C = 562.2$ nF

Notes 40

Have your students explain how they solved for each impedance, step by step. You may find different approaches to solving the same problem(s), and your students will benefit from seeing the diversity of solution techniques.

Suppose we have a single resistor powered by two series-connected voltage sources. Each of the voltage sources is "ideal," possessing no internal resistance:

1 kΩ

5 V   3 V

Calculate the resistor's voltage drop and current in this circuit.

Now, suppose we were to remove one voltage source from the circuit, replacing it with its internal resistance (0 Ω). Re-calculate the resistor's voltage drop and current in the resulting circuit:

1 kΩ

3 V

5 volt source
replaced by short

Now, suppose we were to remove the other voltage source from the circuit, replacing it with its internal resistance (0 Ω). Re-calculate the resistor's voltage drop and current in the resulting circuit:

1 kΩ

5 V

3 volt source
replaced by short

One last exercise: "superimpose" (add) the resistor voltages and superimpose (add) the resistor currents in the last two circuit examples, and compare these voltage and current figures with the calculated values of the original circuit. What do you notice?

file 00691

Answer 41

Original circuit: $E_R = 2$ volts ; $I_R = 2$ mA

With 3 volt voltage source only: $E_R = 3$ volts ; $I_R = 3$ mA

With 5 volt voltage source only: $E_R = 5$ volts ; $I_R = 5$ mA

5 volts - 3 volts = 2 volts
5 mA - 3 mA = 2 mA

Notes 41

This circuit is so simple, students should not even require the use of a calculator to determine the current figures. The point of it is, to get students to see the concept of *superposition* of voltages and currents.

Ask your students if they think it is important to keep track of voltage polarities and current directions in the superposition process. Why or why not?

Question 42

Suppose we have a single resistor powered by two parallel-connected current sources. Each of the current sources is "ideal," possessing infinite internal resistance:

Calculate the resistor's voltage drop and current in this circuit.

Now, suppose we were to remove one current source from the circuit, replacing it with its internal resistance (∞ Ω). Re-calculate the resistor's voltage drop and current in the resulting circuit:

Now, suppose we were to remove the other current source from the circuit, replacing it with its internal resistance (∞ Ω). Re-calculate the resistor's voltage drop and current in the resulting circuit:

One last exercise: "superimpose" (add) the resistor voltages and superimpose (add) the resistor currents in the last two circuit examples, and compare these voltage and current figures with the calculated values of the original circuit. What do you notice?

file 00692

Answer 42

Original circuit: $E_R = 55$ volts ; $I_R = 11$ A

With 7 amp current source only: $E_R = 35$ volts ; $I_R = 7$ A

With 4 amp current source only: $E_R = 20$ volts ; $I_R = 4$ A

35 volts + 20 volts = 55 volts
7 A + 4 A = 11 A

Notes 42

This circuit is so simple, students should not even require the use of a calculator to determine the current figures. If students are not familiar with current sources, this question provides an excellent opportunity to review them. The main point of the question is, however, to get students to see the concept of *superposition* of voltages and currents.

Question 43

The *Superposition Theorem* is a very important concept used to analyze both DC and AC circuits. Define this theorem in your own words, and also state the necessary conditions for it to be freely applied to a circuit.

file 02036

Answer 43

There are plenty of textbook references to the Superposition Theorem and where it may be applied. I'll let you do your own research here!

Notes 43

As the answer states, students have a multitude of resources to consult on this topic. It should not be difficult for them to ascertain what this important theorem is and how it is applied to the analysis of circuits.

Be sure students understand what the terms *linear* and *bilateral* mean with reference to circuit components and the necessary conditions for Superposition Theorem to be applied to a circuit. Point out that it is still possible to apply the Superposition Theorem to a circuit containing nonlinear or unilateral components if we do so carefully (i.e. under narrowly defined conditions).

Question 44

Note that this circuit is impossible to reduce by regular series-parallel analysis:
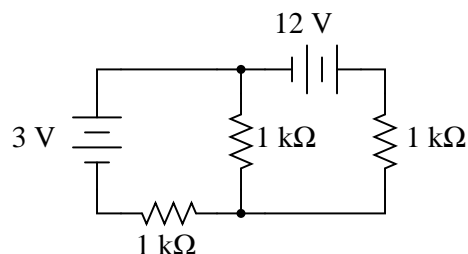
However, the Superposition Theorem makes it almost trivial to calculate all the voltage drops and currents:
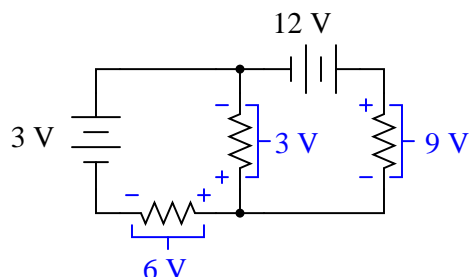
(Currents not shown for simplicity)

Explain the procedure for applying the Superposition Theorem to this circuit.
file 01855

Answer 44

This is easy enough for you to research on your own!

Notes 44

I really enjoy covering the Superposition Theorem in class with my students. It's one of those rare analysis techniques that is intuitively obvious and yet powerful at the same time. Because the principle is so easy to learn, I highly recommend you leave this question for your students to research, and let *them* fully present the answer in class rather than you explain any of it.

Question 45

Explain in your own words how to apply the *Superposition Theorem* to calculate the amount of current through the load resistor in this circuit:
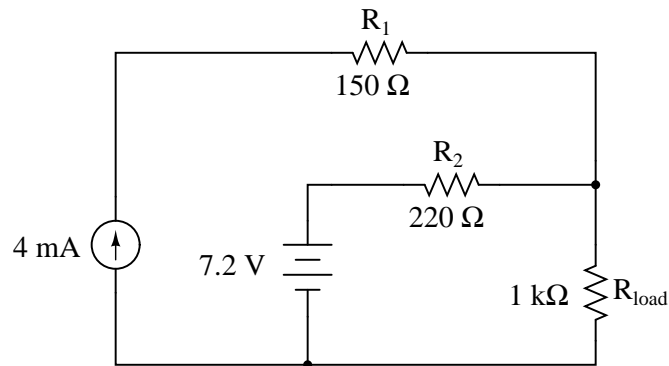
file 02035

Answer 45

To apply the Superposition Theorem to the analysis of R_{load}'s current, you must consider each source acting alone, then algebraically combine the results of each analysis.

$I_{load} = 6.623$ mA

Notes 45

Here is a circuit students will not be able to analyze by series-parallel analysis, since it is impossible to reduce all the resistors in it to a single equivalent resistance. It is cases like this that really showcase the power of Superposition as an analysis technique.

Question 46

The *Superposition Theorem* works nicely to calculate voltages and currents in resistor circuits. But can it be used to calculate power dissipations as well? Why or why not? Be specific with your answer.

<u>file 00694</u>

Answer 46

The Superposition Theorem cannot be directly used to calculate power.

Notes 46

In order to answer this question correctly (without just looking up the answer in a book), students will have to perform a few power calculations in simple, multiple-source circuits. It may be worthwhile to work through a couple of example problems during discussion time, to illustrate the answer.

Despite the fact that resistor power dissipations cannot be superimposed to obtain the answer(s), it is still possible to use the Superposition Theorem to calculate resistor power dissipations in a multiple-source circuit. Challenge your students with the task of applying this theorem for solving power dissipations in a circuit.

Calculate the charging current through each battery, using the Superposition Theorem (ignore all wire and connection resistances – only consider the resistance of each fuse):
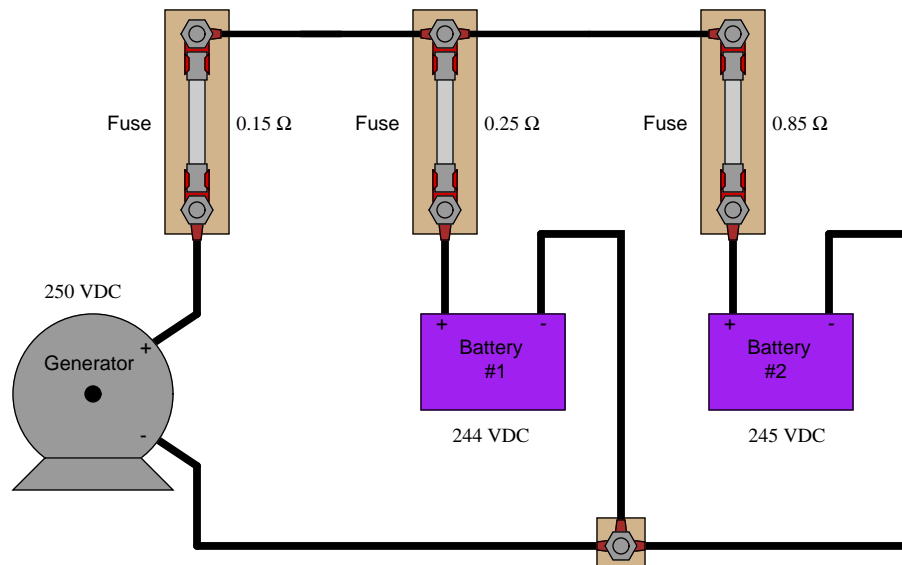
file 00695

Answer 47

$I_{generator} = 16.82$ A

$I_{battery1} = 13.91$ A

$I_{battery2} = 2.91$ A

Follow-up question: identify any safety hazards that could arise as a result of excessive resistance in the fuse holders (e.g., corrosion build-up on the metal tabs where the fuse clips in to the fuse-holder).

Notes 47

Though there are other methods of analysis for this circuit, it is still a good application of Superposition Theorem.

A remote speaker for an audio system is connected to the amplifier by means of a long, 2-conductor cable:
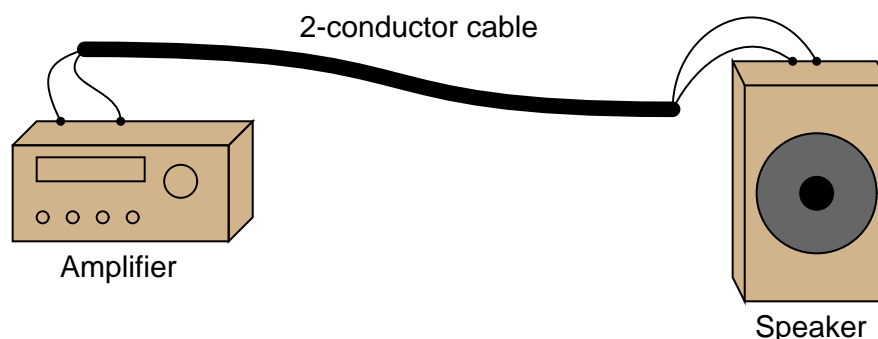
This system may be schematically modeled as an AC voltage source connected to a load resistor:
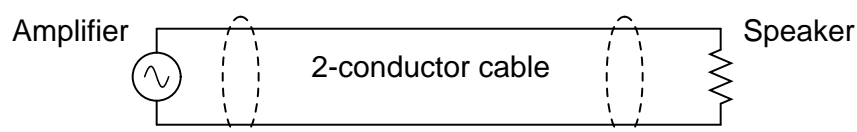
Suppose we decided to use the 2-conductor cable for more than just conveying an audio (AC) signal – we want to use it to carry DC power as well to energize a small lamp. However, if we were to simply connect the DC power source in parallel with the amplifier output at one end, and the lamp in parallel with the speaker at the other, bad things would happen:
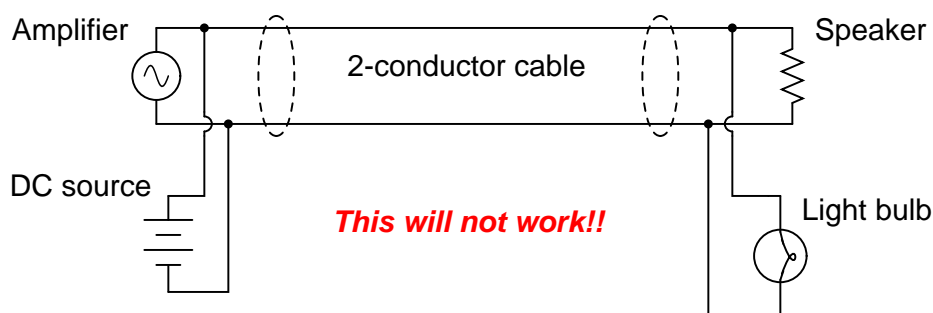
If we were to connect the components together as shown above, the DC power source will likely damage the amplifier by being directly connected to it, the speaker will *definitely* be damaged by the application of significant DC voltage to its coil, and the light bulb will waste audio power by acting as a second (non-audible) load. Suffice to say, this is a bad idea.

Using inductors and capacitors as "filtering" components, though, we can make this system work:
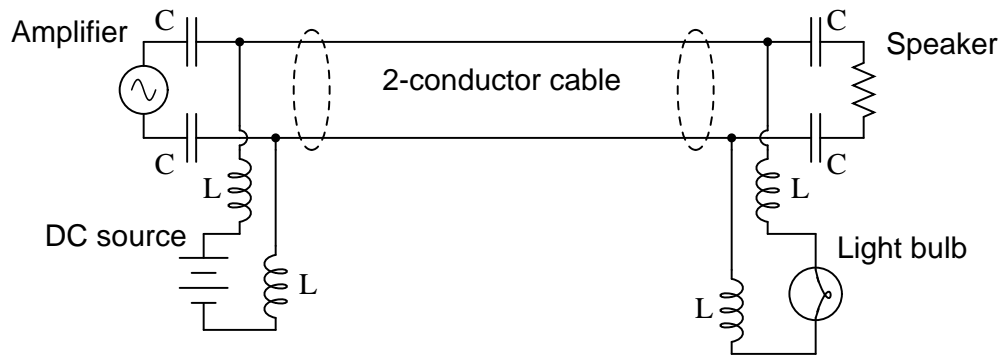
Apply the Superposition Theorem to this circuit to demonstrate that the audio and DC signals will not interfere with each other as they would if directly connected. Assume that the capacitors are of such large value that they present negligible impedance to the audio signal ($Z_C \approx 0\,\Omega$) and that the inductors are sufficiently large that they present infinite impedance to the audio signal ($Z_L \approx \infty$).

file 01856

Answer 48

As each source is considered separately, the reactive components ensure each load receives the correct source voltage, with no interference.

Notes 48

Such "power-plus-data" strategies are made possible by the Superposition Theorem and the linearity of resistors, capacitors, and inductors. If time permits, this would be a good opportunity to discuss "power-line carrier" systems, where high-frequency data is transmitted over power line conductors. The venerable X10 network system is an example for residential power wiring, while power distribution utilities have been using this "PLC" technology (the acronym not to be confused with *Programmable Logic Controllers*) for decades over high-voltage transmission lines.

The following circuit is a simple *mixer* circuit, combining three AC voltage signals into one, to be measured by an oscilloscope:
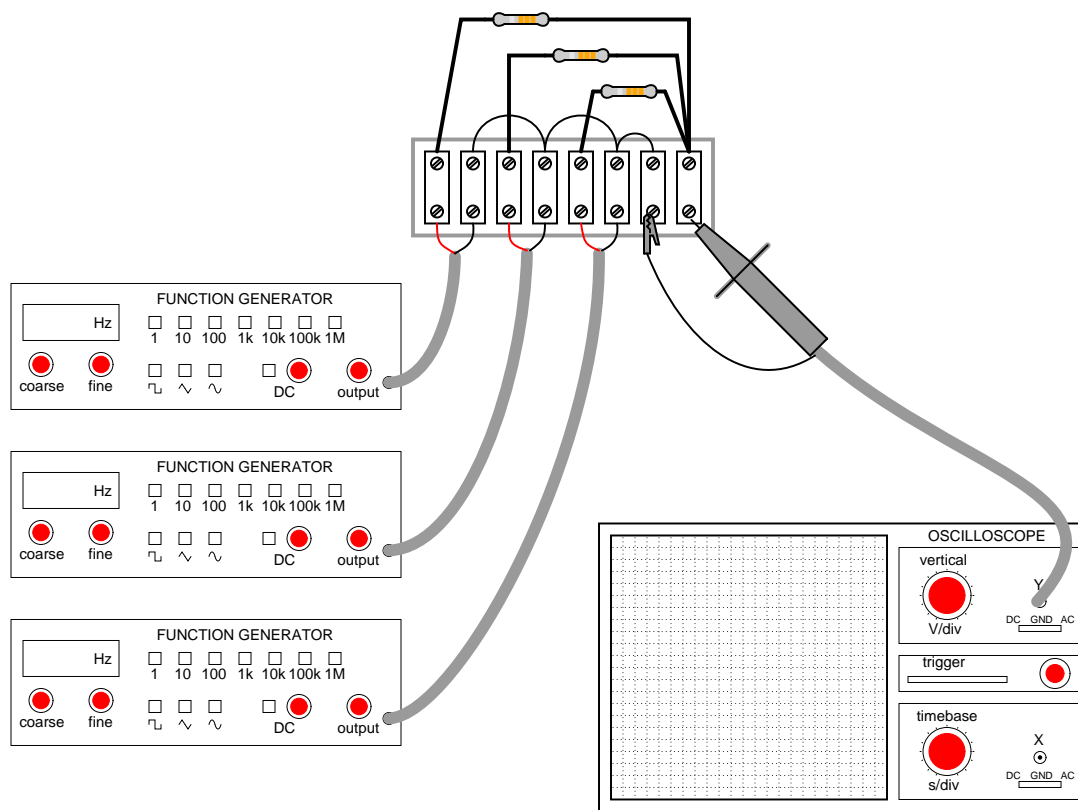
Draw a schematic diagram of this circuit, to make it easier to analyze.

Is it possible to filter the three constituent input signals from each other in the resulting output signal, or are they irrevocably affected by one another when they "mix" together in this resistor network? How does the *superposition principle* relate to the operation of a mixer circuit like this?

What if the mixing circuit contains capacitors and inductors rather than resistors? Does the same principle apply? Why or why not?

file 00648

Answer 49
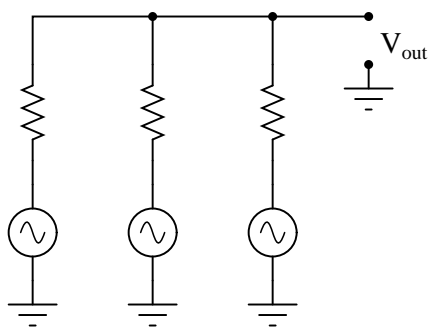
The "superposition principle" states that when two or more waveforms mix together in a linear network, the result is the sum of the waveforms. That is, the waveforms simply add up to make a total, and are not "irrevocably affected" by one another. The question, then, is really: what constitutes a *linear* network?

Notes 49

It is no coincidence that the "superposition principle" sounds a lot like the "superposition theorem" learned as a network analysis technique: consider the effects of all power sources one at a time, and add those effects together to determine the final result.

The matter of "irrevocable influence" is important to us because it dictates how difficult it would be to separate the mixed signals from each other. When external noise couples to a circuit through capacitive or inductive coupling, can we filter out the noise and obtain the true signal again, or has the signal been corrupted in such a way that restoration is impossible by mere filtering? The key to answering this question is whether or not the "network" formed from parasitic capacitive/inductive coupling is linear. Discuss with your students what determines linearity in a math equation, and apply these criteria to the equations describing resistor, capacitor, and inductor behavior.

Question 50

What is a musical *chord*? If viewed on an oscilloscope, what would the signal for a chord look like?

file 00647

Answer 50

A *chord* is a mixture of three of more notes. On an oscilloscope, it would appear to be a very complex waveform, very non-sinusoidal.

Note: if you want to see this form yourself without going through the trouble of setting up a musical keyboard (or piano) and oscilloscope, you may simulate it using a graphing calculator or computer program. Simply graph the sum of three waveforms with the following frequencies:

- 261.63 Hz (middle "C")
- 329.63 Hz ("E")
- 392.00 Hz ("G")

Notes 50

Students with a musical background (especially piano) should be able to add substantially to the discussion on this question. The important concept to discuss here is that multiple frequencies of any signal form (AC voltage, current, sound waves, light waves, etc.) are able to exist simultaneously along the same signal path without interference.

Question 51

Identify the type of electronic instrument that displays the relative amplitudes of a range of signal frequencies on a graph, with amplitude on the vertical axis and frequency on the horizontal.

file 00649

Answer 51

A *spectrum analyzer*.

Challenge questions: two similar instruments are the *wave analyzer* and the *Fourier analyzer*. Explain how both these instruments are similar in function to a spectrum analyzer, and also how both differ.

Notes 51

Spectrum analyzers capable of analyzing radio-frequency signals are very expensive, but low-cost personal computer hardware and software does a good job of analyzing complex audio signals. It would be a benefit to your class to have a low-frequency spectrum analyzer setup available for student use, and possible demonstration during discussion.

Question 52

If an oscilloscope is connected to a series combination of AC and DC voltage sources, what is displayed on the oscilloscope screen depends on where the "coupling" control is set.

With the coupling control set to "DC", the waveform displayed will be elevated above (or depressed below) the "zero" line:
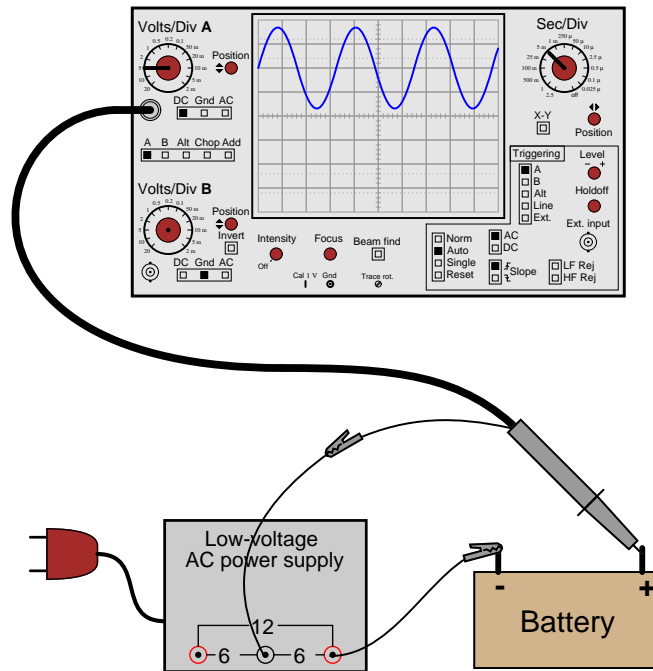
Setting the coupling control to "AC", however, results in the waveform automatically centering itself on the screen, about the zero line.
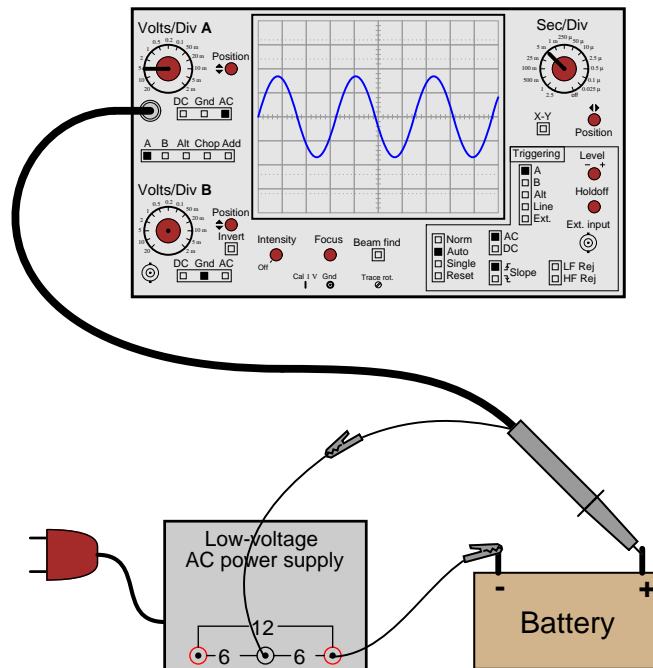
Based on these observations, explain what the "DC" and "AC" settings on the coupling control actually mean.

file 00538

Answer 52

The "DC" setting allows the oscilloscope to display *all* components of the signal voltage, both AC and DC, while the "AC" setting blocks all DC within the signal, to only display the varying (AC) portion of the signal on the screen.

Notes 52

A common misconception among students is that the "DC" setting is used for measuring DC signals only, and that the "AC" setting is used for measuring AC signals only. I often refer to the "DC" setting as *direct coupling* in order to avoid the connotation of "direct current," in an attempt to reinforce the idea that with "DC" coupling, what you see is all that's really there. With "AC" coupling, only part of the signal is being coupled to the input amplifier circuitry.

Question 53

Explain what happens inside an oscilloscope when the "coupling" switch is moved from the "DC" position to the "AC" position.

Answer 53

Switch shown in "AC" position

Signal input

Signal output
to vertical amplifier
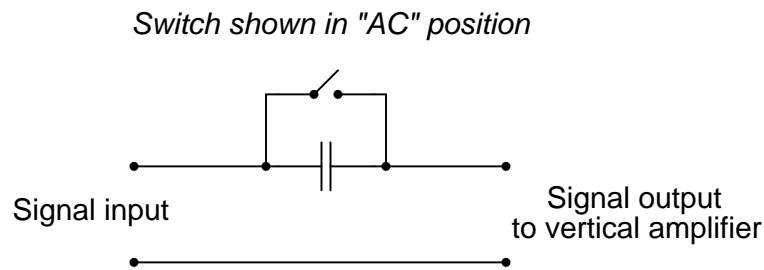
Notes 53

In order for students to answer this question, they must review the internal operation of an oscilloscope. This does not have to be rigorous – a block-diagram understanding is good enough. The important thing is that they understand what the capacitor does for the oscilloscope input. Once this is understood, students will have a much better understanding of *why* and *where* the coupling control is used.

Question 54

Suppose a technician measures the voltage output by an AC-DC power supply circuit:
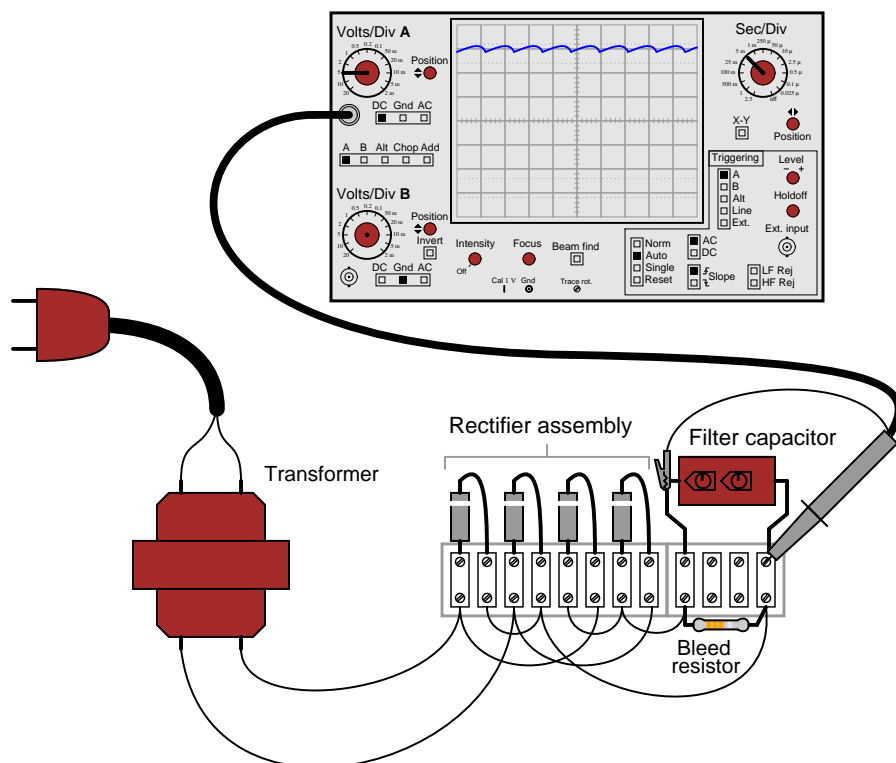
The waveform shown by the oscilloscope is mostly DC, with just a little bit of AC "ripple" voltage appearing as a ripple pattern on what would otherwise be a straight, horizontal line. This is quite normal for the output of an AC-DC power supply.

Suppose we wished to take a closer view of this "ripple" voltage. We want to make the ripples more pronounced on the screen, so that we may better discern their shape. Unfortunately, though, when we decrease the number of volts per division on the "vertical" control knob to magnify the vertical amplification of the oscilloscope, the pattern completely disappears from the screen!

Explain what the problem is, and how we might correct it so as to be able to magnify the ripple voltage waveform without having it disappear off the oscilloscope screen.

file 00539

Answer 54

The problem is that the vertical axis input is DC-coupled.

Follow-up question: predict the *frequency* of the ripple voltage in this power supply circuit.

Notes 54

As usual, what I'm looking for in an answer here is an *explanation* for what is happening. If a student simply tells you, "the vertical input is DC-coupled," press them for more detail. What does it mean for the input to be "DC-coupled," and why does this cause the line to disappear from the screen when we increase the vertical sensitivity? What alternative do we have to "DC coupling" on an oscilloscope?

One nice thing about oscilloscopes is that they cannot be damaged by "pegging" the display, as can analog multimeters. The same concept applies, though, and is useful in explaining to students why waveforms disappear from the screen when the vertical sensitivity is too great.

A student just learning to use oscilloscopes connects one directly to the output of a signal generator, with these results:
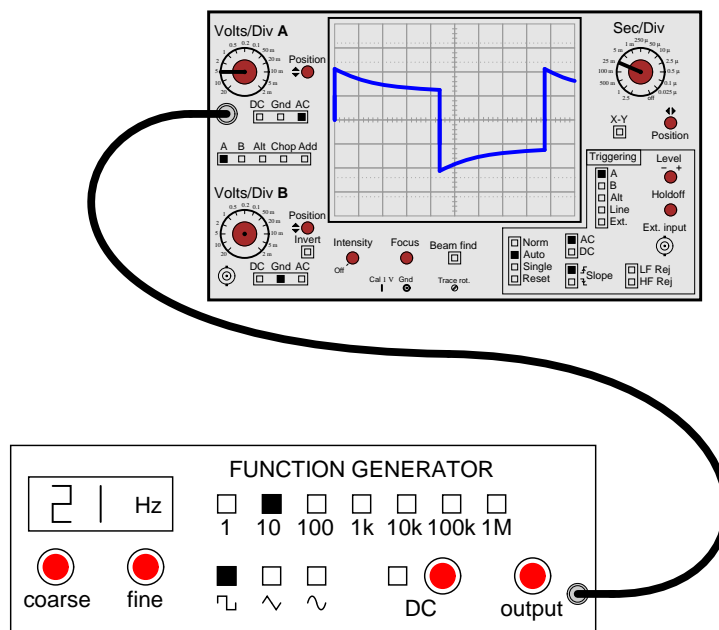
As you can see, the function generator is configured to output a square wave, but the oscilloscope does not register a square wave. Perplexed, the student takes the function generator to a different oscilloscope. At the second oscilloscope, the student sees a proper square wave on the screen:
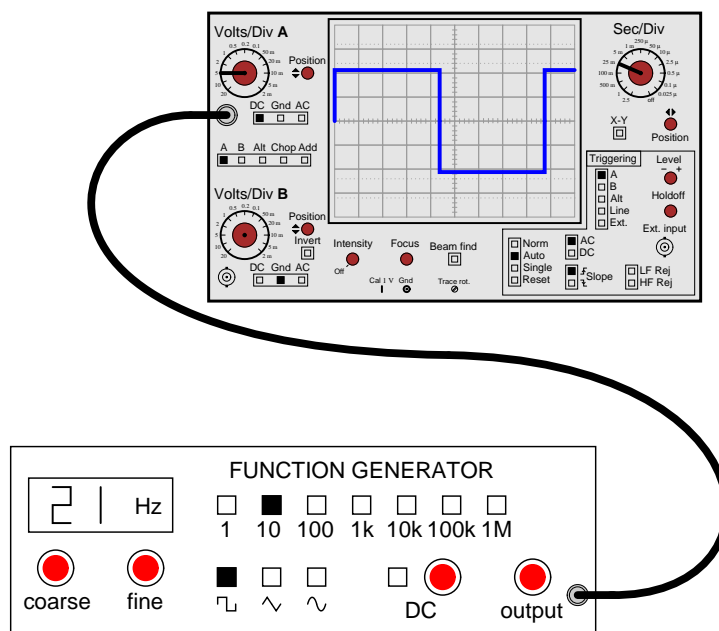
It is then that the student realizes the first oscilloscope has its "coupling" control set to AC, while the second oscilloscope was set to DC. Now the student is really confused! The signal is obviously AC, as it

oscillates above and below the centerline of the screen, but yet the "DC" setting appears to give the most accurate results: a true-to-form square wave.

How would you explain what is happening to this student, and also describe the appropriate uses of the "AC" and "DC" coupling settings so he or she knows better how to use it in the future?

file 01854

Answer 55

"DC" does *not* imply that the oscilloscope can only show DC signals and not AC signals, as many beginning students think. Rather, the "DC" setting is the one that should be first used to measure all signals, with the "AC" setting engaged only as needed.

Notes 55

The answer I give here is correct, but does not address *why* the coupling control does what it does, nor does it describe why the square wave signal appears all distorted on the first oscilloscope's screen. I leave this for your students to research and for you and your students to discuss together in class.

Question 56

In very simple, qualitative terms, rate the impedance of capacitors and inductors as "seen" by low-frequency and high-frequency signals alike:

- Capacitor as it "appears" to a low frequency signal: (<u>high</u> or <u>low</u>) impedance?
- Capacitor as it "appears" to a high frequency signal: (<u>high</u> or <u>low</u>) impedance?

- Inductor as it "appears" to a low frequency signal: (<u>high</u> or <u>low</u>) impedance?
- Inductor as it "appears" to a high frequency signal: (<u>high</u> or <u>low</u>) impedance?

<u>file 00616</u>

Answer 56

- Capacitor as it "appears" to a low frequency signal: *high* impedance.
- Capacitor as it "appears" to a high frequency signal: *low* impedance.

- Inductor as it "appears" to a low frequency signal: *low* impedance.
- Inductor as it "appears" to a high frequency signal: *high* impedance.

Challenge question: what does a capacitor "appear" as to a DC signal?

Notes 56

Ask your students how they arrived at their answers for these qualitative assessments. If they found difficulty understanding the relationship of frequency to impedance for reactive components, I suggest you work through the reactance equations qualitatively with them. In other words, evaluate each of the reactance formulae ($X_L = 2\pi f L$ and $X_C = \frac{1}{2\pi f C}$) in terms of f increasing and decreasing, to understand how each of these components reacts to low- and high-frequency signals.

Question 57

Identify these filters as either being "low-pass" or "high-pass", and be prepared to explain your answers:
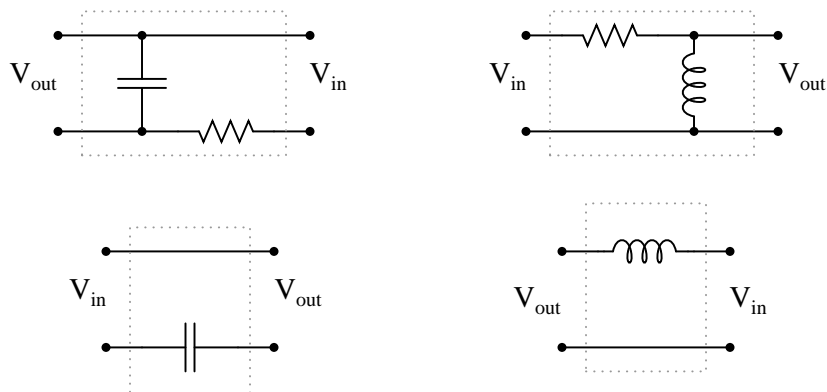
Answer 57
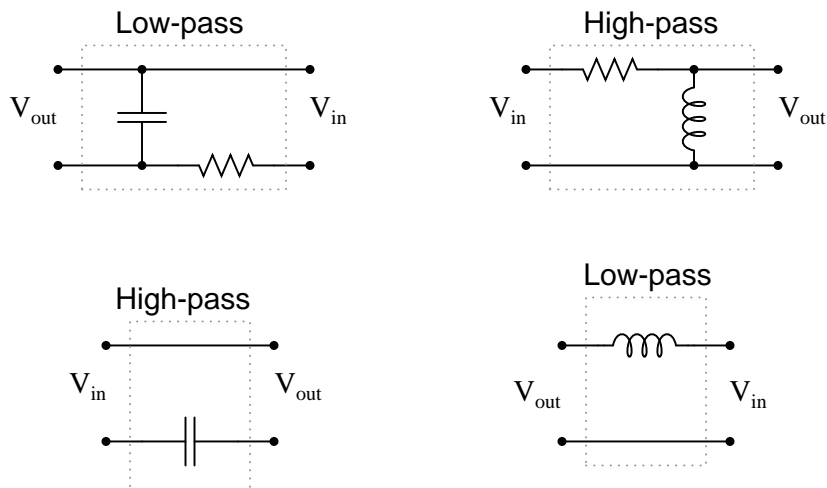
Notes 57

Low-pass and high-pass filter circuit are really easy to identify if you consider the input frequencies in terms of extremes: radio frequency (very high), and DC ($f = 0$ Hz). Ask your students to identify the respective impedances of all components in a filter circuit for these extreme frequency examples, and the functions of each filter circuit should become very clear to see.

Question 58

Suppose you were installing a high-power stereo system in your car, and you wanted to build a simple filter for the "tweeter" (high-frequency) speakers so that no bass (low-frequency) power is wasted in these speakers. Modify the schematic diagram below with a filter circuit of your choice:
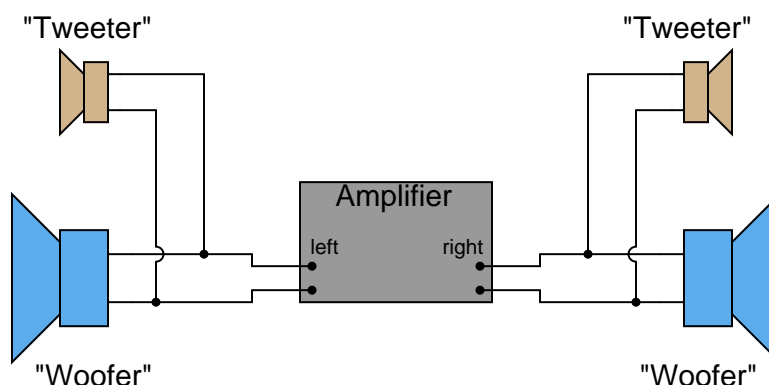
Hint: this only requires a single component per tweeter!

file 00613

Answer 58
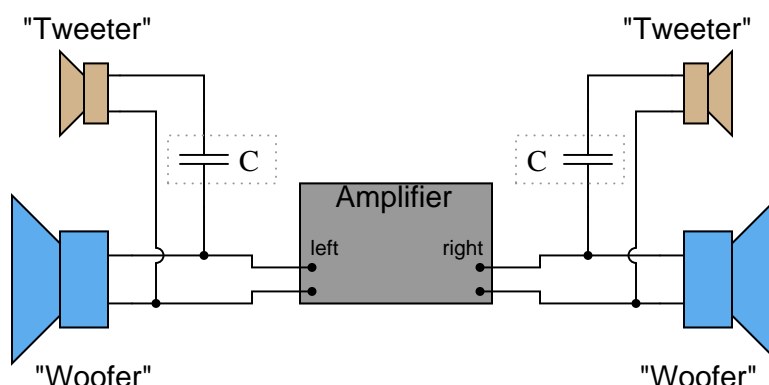
Follow-up question: what type of capacitor would you recommend using in this application (electrolytic, mylar, ceramic, etc.)? Why?

Notes 58

Ask your students to describe what type of filter circuit a series-connected capacitor forms: low-pass, high-pass, band-pass, or band-stop? Discuss how the name of this filter should describe its intended function in the sound system.

Regarding the follow-up question, it is important for students to recognize the practical limitations of certain capacitor types. One thing is for sure, ordinary (polarized) electrolytic capacitors will not function properly in an application like this!

The *superposition principle* describes how AC signals of different frequencies may be "mixed" together and later separated in a linear network, without one signal distorting another. DC may also be similarly mixed with AC, with the same results.

This phenomenon is frequently exploited in computer networks, where DC power and AC data signals (on-and-off pulses of voltage representing 1-and-0 binary bits) may be combined on the same pair of wires, and later separated by filter circuits, so that the DC power goes to energize a circuit, and the AC signals go to another circuit where they are interpreted as digital data:
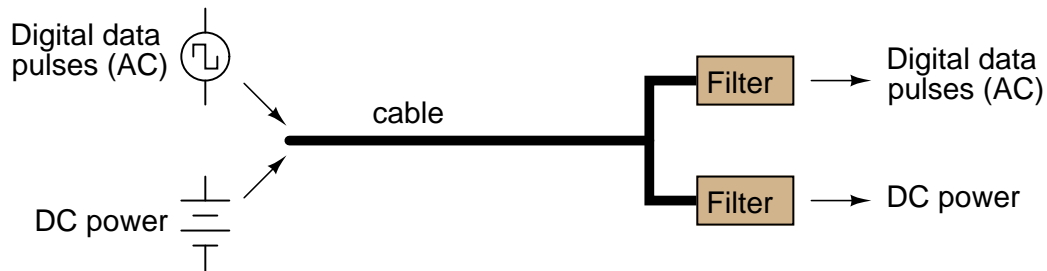
Filter circuits are also necessary on the transmission end of the cable, to prevent the AC signals from being shunted by the DC power supply's capacitors, and to prevent the DC voltage from damaging the sensitive circuitry generating the AC voltage pulses.

Draw some filter circuits on each end of this two-wire cable that perform these tasks, of separating the two sources from each other, and also separating the two signals (DC and AC) from each other at the receiving end so they may be directed to different loads:
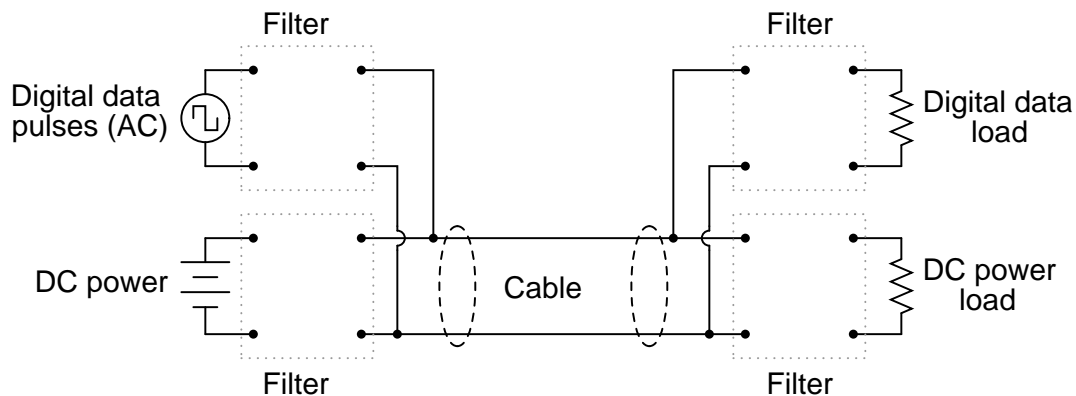
file 00612
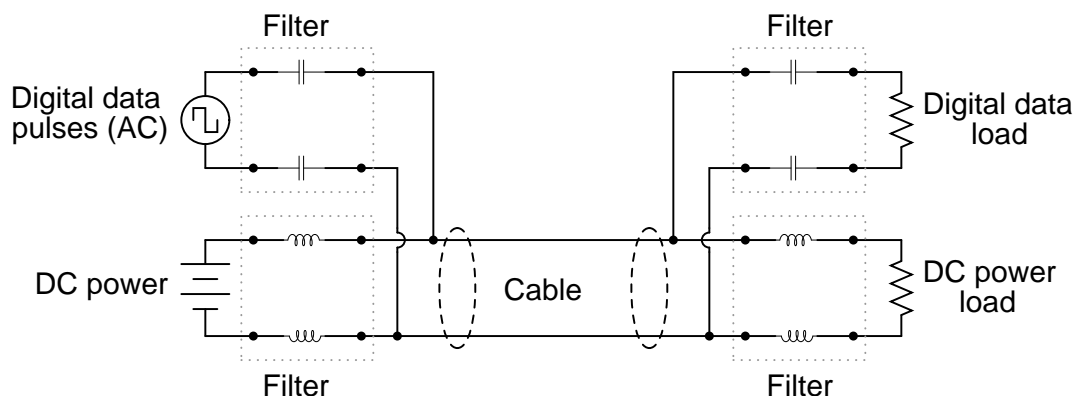
Follow-up question #1: how might the *superposition theorem* be applied to this circuit, for the purposes of analyzing its function?

Follow-up question #2: suppose one of the capacitors were to fail shorted. Identify what effect, if any, this would have on the operation of the circuit. What if two capacitors were to fail shorted? Would it matter if those two capacitors were both on either the transmitting or the receiving side, or if one of the failed capacitors was on the transmitting side and the other was on the receiving side?

Notes 59

Discuss with your students why inductors were chosen as filtering elements for the DC power, while capacitors were chosen as filtering elements for the AC data signals. What are the relative reactances of these components when subjected to the respective frequencies of the AC data signals (many kilohertz or megahertz) versus the DC power supply (frequency = 0 hertz).

This question is also a good review of the "superposition theorem," one of the most useful and easiest-to-understand of the network theorems. Note that no quantitative values need be considered to grasp the function of this communications network. Analyze it *qualitatively* with your students instead.

Question 60

Draw the Bode plot for an *ideal* high-pass filter circuit:
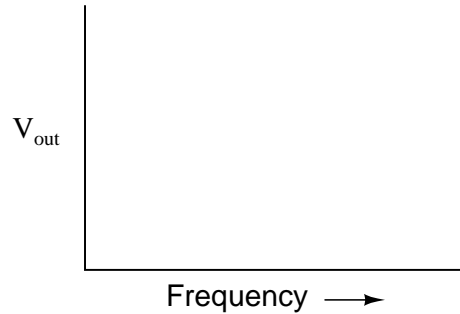
Be sure to note the "cutoff frequency" on your plot.
<u>file 00618</u>

Answer 60
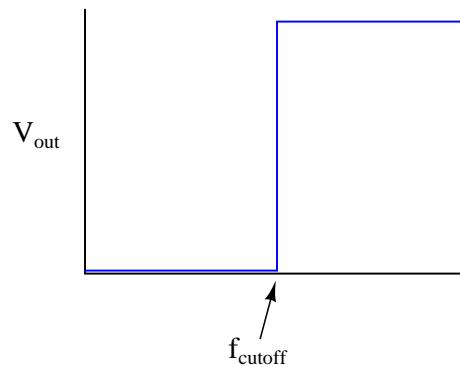
Follow-up question: a theoretical filter with this kind of idealized response is sometimes referred to as a "brick wall" filter. Explain why this name is appropriate.

Notes 60

The plot given in the answer, of course, is for an ideal high-pass filter, where all frequencies below f_{cutoff} are blocked and all frequencies above f_{cutoff} are passed. In reality, filter circuits never attain this ideal "square-edge" response. Discuss possible applications of such a filter with your students.

Challenge them to draw the Bode plots for ideal *band-pass* and *band-stop* filters as well. Exercises such as this really help to clarify the purpose of filter circuits. Otherwise, there is a tendency to lose perspective of what real filter circuits, with their correspondingly complex Bode plots and mathematical analyses, are supposed to do.

Question 61

Draw the Bode plot for an *ideal* low-pass filter circuit:

V$_{out}$
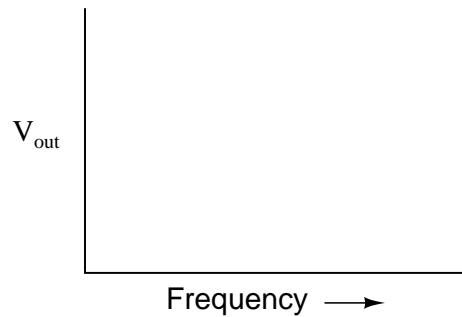
Frequency $\longrightarrow$

Be sure to note the "cutoff frequency" on your plot.
file 01245

Answer 61
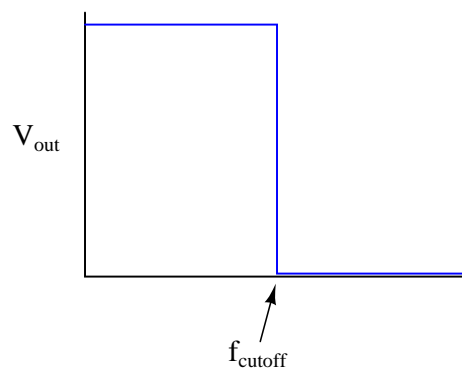
V$_{out}$

f$_{cutoff}$

Follow-up question: a theoretical filter with this kind of idealized response is sometimes referred to as a "brick wall" filter. Explain why this name is appropriate.

Notes 61

The plot given in the answer, of course, is for an ideal low-pass filter, where all frequencies below f_{cutoff} are passed and all frequencies above f_{cutoff} are blocked. In reality, filter circuits never attain this ideal "square-edge" response. Discuss possible applications of such a filter with your students.

Challenge them to draw the Bode plots for ideal *band-pass* and *band-stop* filters as well. Exercises such as this really help to clarify the purpose of filter circuits. Otherwise, there is a tendency to lose perspective of what real filter circuits, with their correspondingly complex Bode plots and mathematical analyses, are supposed to do.

Question 62

Identify what type of filter this circuit is, and calculate its cutoff frequency given a resistor value of 1 kΩ and a capacitor value of 0.22 μF:
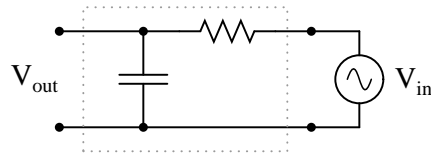
Calculate the impedance of both the resistor and the capacitor at this frequency. What do you notice about these two impedance values?

file 00617

Answer 62

This is a *low-pass* filter.

$f_{cutoff} = 723.4$ Hz

Notes 62

Be sure to ask students where they found the cutoff frequency formula for this filter circuit.

When students calculate the impedance of the resistor and the capacitor at the cutoff frequency, they should notice something unique. Ask your students why these values are what they are at the cutoff frequency. Is this just a coincidence, or does this tell us more about how the "cutoff frequency" is defined for an RC circuit?

Question 63

The formula for determining the cutoff frequency of a simple LR filter circuit looks substantially different from the formula used to determine cutoff frequency in a simple RC filter circuit. Students new to this subject often resort to memorization to distinguish one formula from the other, but there is a better way.

In simple filter circuits (comprised of one reactive component and one resistor), cutoff frequency is that frequency where circuit reactance equals circuit resistance. Use this simple definition of cutoff frequency to derive both the RC and the LR filter circuit cutoff formulae, where f_{cutoff} is defined in terms of R and either L or C.

file 02075

Answer 63

$$f_{cutoff} = \frac{1}{2\pi RC} \qquad \text{(For simple RC filter circuits)}$$

$$f_{cutoff} = \frac{R}{2\pi L} \qquad \text{(For simple LR filter circuits)}$$

Notes 63

This is an exercise in algebraic substitution, taking the formula $X = R$ and introducing f into it by way of substitution, then solving for f. Too many students try to memorize every new thing rather than build their knowledge upon previously learned material. It is surprising how many electrical and electronic formulae one may derive from just a handful of fundamental equations, if one knows how to use algebra.

Some textbooks present the LR cutoff frequency formula like this:

$$f_{cutoff} = \frac{1}{2\pi \frac{L}{R}}$$

If students present this formula, you can be fairly sure they simply found it somewhere rather than derived it using algebra. Of course, this formula is exactly equivalent to the one I give in my answer – and it is good to show the class how these two are equivalent – but the real point of this question is to get your students using algebra as a practical tool in their understanding of electrical theory.

Question 64

Identify what type of filter this circuit is, and calculate the size of resistor necessary to give it a cutoff frequency of 3 kHz:
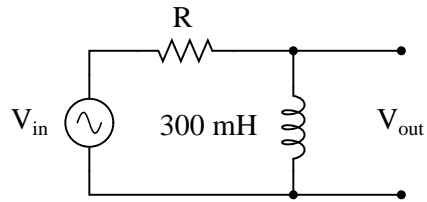
file 00619

Answer 64

This is a *high-pass* filter.

$$R = 2\pi f L$$

$$R = 5.65 \text{ k}\Omega$$

Notes 64

The most important part of this question, as usual, is to have students come up with methods of solution for determining R's value. Ask them to explain how they arrived at their answer, and if their method of solution made use of any formula or principle used in *capacitive* filter circuits.

Question 65

Calculate the power dissipated by this circuit's load at two different source frequencies: 0 Hz (DC), and f_{cutoff}.
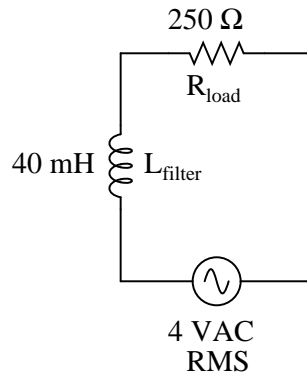
What do these figures tell you about the nature of this filter circuit (whether it is a low-pass or a high-pass filter), and also about the definition of *cutoff frequency* (also referred to as f_{-3dB})?

file 00646

Answer 65

P_{load} @ $f = 0$ Hz $= 64$ mW

P_{load} @ $f_{cutoff} = 32$ mW

These load dissipation figures prove this circuit is a *low-pass* filter. They also demonstrate that the load dissipation at f_{cutoff} is exactly half the amount of power the filter is capable of passing to the load under ideal (maximum) conditions.

Notes 65

If your students have never encountered decibel (dB) ratings before, you should explain to them that -3 dB is an expression meaning "one-half power," and that this is why the cutoff frequency of a filter is often referred to as the *half-power point*.

The important lesson to be learned here about cutoff frequency is that its definition means something in terms of load power. It is not as though someone decided to arbitrarily define f_{cutoff} as the point at which the load receives 70.7% of the source voltage!

Question 66

Real filters never exhibit perfect "square-edge" Bode plot responses. A typical low-pass filter circuit, for example, might have a frequency response that looks like this:
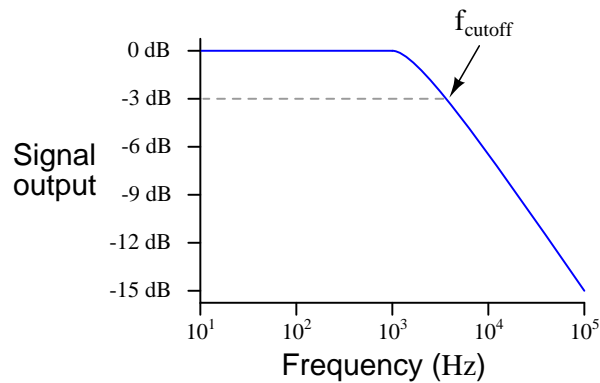
What does the term *rolloff* refer to, in the context of filter circuits and Bode plots? Why would this parameter be important to a technician or engineer?

file 01246

Answer 66

"Rolloff" refers to the *slope* of the Bode plot in the attenuating range of the filter circuit, usually expressed in units of decibels per octave (dB/octave) or decibels per decade (dB/decade):
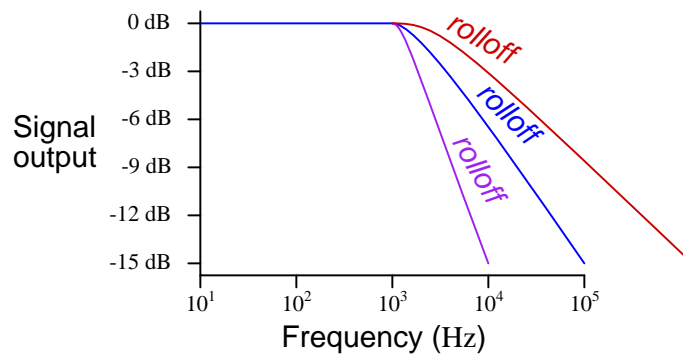
Notes 66

Point students' attention to the scale used on this particular Bode plot. This is called a *log-log* scale, where neither vertical nor horizontal axis is linearly marked. This scaling allows a very wide range of conditions to be shown on a relatively small plot, and is very common in filter circuit analysis.

Question 67

Explain what a *band-pass* filter is, and how it differs from either a low-pass or a high-pass filter circuit. Also, explain what a *band-stop* filter is, and draw Bode plots representative of both band-pass and band-stop filter types.

<u>file 01859</u>

Answer 67

A band-pass filter passes only those frequencies falling within a specified range, or "band." A band-stop filter, sometimes referred to as a *notch filter*, does just the opposite: it attenuates frequencies falling within a specified band.

Challenge question: what type of filter, band-pass or band-stop, do you suppose is used in a radio receiver (tuner)? Explain your reasoning.

Notes 67

In this question, I've opted to let students draw Bode plots, only giving them written descriptions of each filter type.

A common way of representing complex electronic systems is the *block diagram*, where specific functional sections of a system are outlined as squares or rectangles, each with a certain purpose and each having input(s) and output(s). For an example, here is a block diagram of an analog ("Cathode Ray") oscilloscope, or *CRO*:

Block diagram of Cathode-Ray Oscilloscope
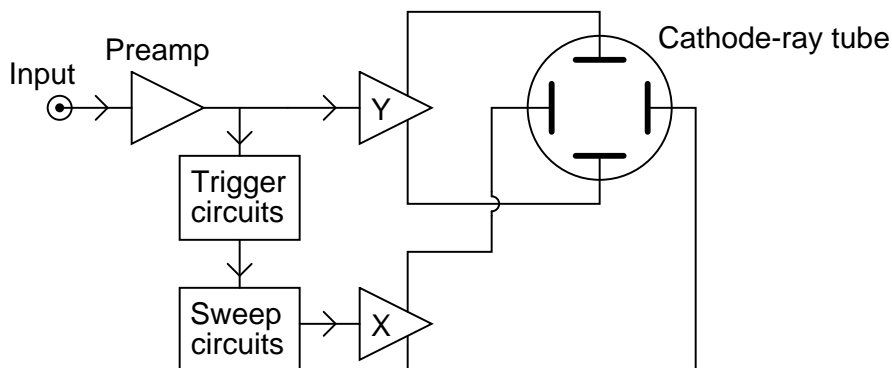
Block diagrams may also be helpful in representing and understanding filter circuits. Consider these symbols, for instance:

Which of these represents a *low-pass* filter, and which represents a *high-pass filter*? Explain your reasoning.

Also, identify the new filter functions created by the compounding of low- and high-pass filter "blocks":

file 01858

88

Band-stop filter
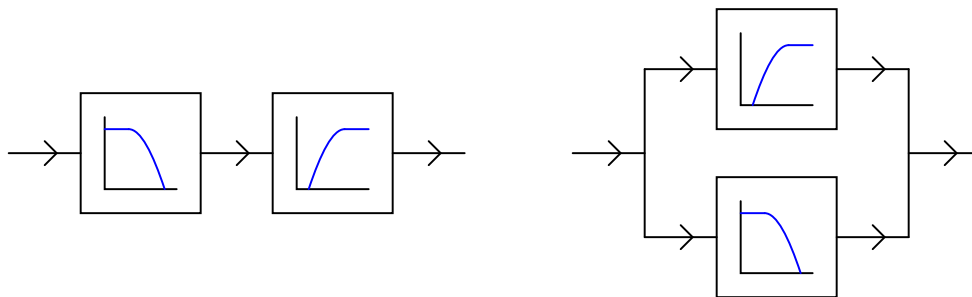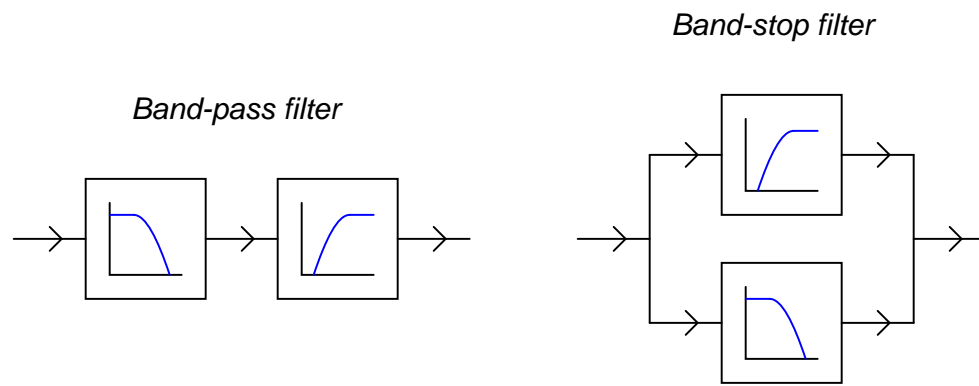
Band-pass filter

Notes 68

Aside from getting students to understand that band-function filters may be built from sets of low- and high-pass filter blocks, this question is really intended to initiate problem-solving activity. Discuss with your students how they might approach a problem like this to see how the circuits respond. What "thought experiments" did they try in their minds to investigate these circuits?

Question 69

Plot the typical response of a band-pass filter circuit, showing signal output (amplitude) on the vertical axis and frequency on the horizontal axis:

Amplitude
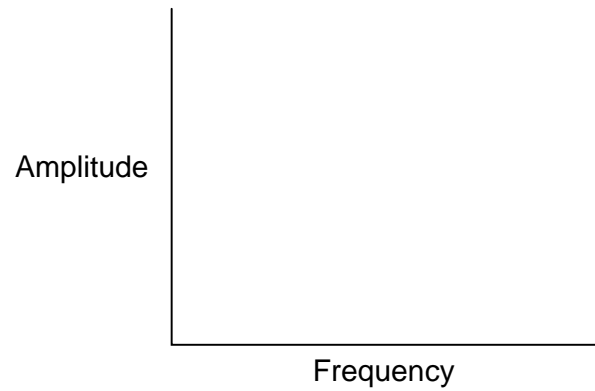
Frequency

Also, identify and label the *bandwidth* of the circuit on your filter plot.
file 01564

Answer 69

Amplitude
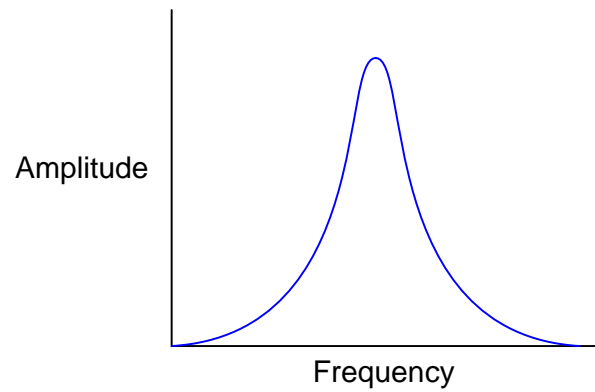
Frequency

The bandwidth of a band-pass filter circuit is that range of frequencies where the output amplitude is at least 70.7% of maximum:
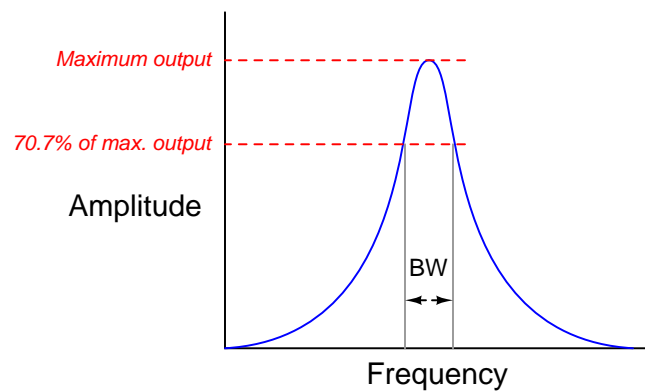
Maximum output

70.7% of max. output

Amplitude

BW

Frequency

90

Bandwidth is an important concept in electronics, for more than just filter circuits. Your students may discover references to bandwidth of amplifiers, transmission lines, and other circuit elements as they do their research. Despite the many and varied applications of this term, the principle is fundamentally the same.

Question 70

Suppose this band-stop filter were to suddenly start acting as a high-pass filter. Identify a single component failure that could cause this problem to occur:
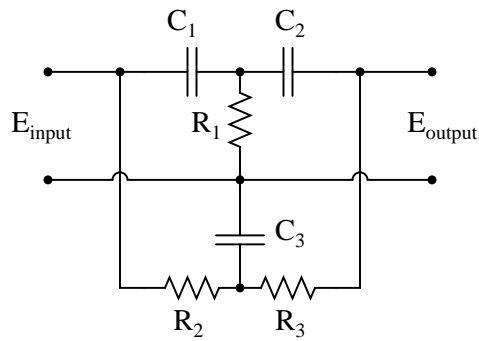
Answer 70
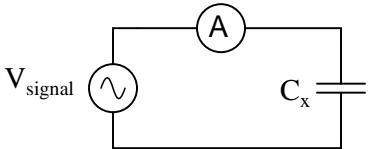
If resistor R_3 failed open, it would cause this problem. However, this is not the *only* failure that could cause the same type of problem!

Notes 70

Ask your students to explain why an open R_2 would cause this filter to act as a high-pass instead of a band-stop. Then, ask them to identify other possible component failures that could cause a similar effect.

By the way, this filter circuit illustrates the popular *twin-tee* filter topology.

Competency: **Measuring capacitance by AC reactance**   Version:

Schematic

Given conditions

$V_{signal} =$

Parameters

Measured		Calculated

I_C [ ]   at f = $\longrightarrow$ C_x [ ]

I_C [ ]   at f = $\longrightarrow$ C_x [ ]

I_C [ ]   at f = $\longrightarrow$ C_x [ ]

C_x [ ] (With C meter) C_x [ ] (Average)
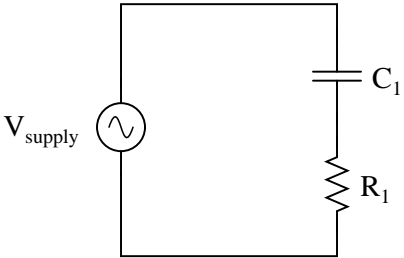
Answer 71

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

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 a standard capacitor value.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

Competency: **Series RC circuit** Version:

Schematic

Given conditions

$V_{supply} =$ $C_1 =$ $R_1 =$

$f_{supply} =$

Parameters

	Predicted	Measured
V_{C1}		
V_{R1}		
I_{total}		

Calculations

Fault analysis

Suppose component [ ] fails ☐ open ☐ other _____

☐ shorted

What will happen in the circuit?

file 01664

Answer 72

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

Notes 72

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.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Parallel RC circuit**   Version:

Schematic

Given conditions

$V_{supply} =$ $C_1 =$ $R_1 =$

$f_{supply} =$

Parameters

	Predicted	Measured
I_{C1}		
I_{R1}		
I_{total}		

Calculations

Fault analysis

Suppose component ☐ fails   ☐ open   ☐ other _____

☐ shorted

What will happen in the circuit?

Answer 73

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

Notes 73

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.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Time-domain phase shift measurement**   Version:

Schematic

Given conditions

$f_{supply} =$ $C_1 =$ $R_1 =$

Parameters

Predicted

θ [   ]

Measured

Shift (divisions) [   ]

Period (divisions) [   ]

θ [   ]

Dual oscilloscope trace

file 01688

Answer 74

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

Notes 74

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.

One way for students to do this assessment is to have them predict what the sine waves will look like, based on circuit component values. They sketch the predicted waveforms on the grid provided before actually hooking up an oscilloscope, then the instructor assesses them based on the conformity of the real oscilloscope display to their prediction.

Competency: **Variable phase shift bridge circuit**   Version:

Schematic

Given conditions

Recommendations

$V_{signal} =$

$R_1 = R_2 =$

$C_1 = C_2 =$

$f_{signal} =$

$R_{pot} =$

$R \approx \dfrac{1}{2\pi fC}$

$R_{pot} \gg R_1 , R_2$

Parameters

	Predicted	Measured	
$\theta_{V_{out}}$			*Potentiometer at full-left position*
$\theta_{V_{out}}$			*Potentiometer at full-right position*

	Predicted	Measured	
V_{out}			*Potentiometer at full-left position*
V_{out}			*Potentiometer at full-right position*

file 03468

101

Answer 75

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

Notes 75

This is a very interesting circuit to built and test. You may build one using 1 μF capacitors, 2.7 kΩ resistors, and a 100 kΩ potentiometer that will successfully operate on 60 Hz power-line excitation. If you prefer to use audio frequency power, try 0.047 μF capacitors, 1 kΩ resistors, a 100 kΩ potentiometer, and 3.386 kHz for the source frequency.

An interesting thing to note about using line power is that any distortions in the excitation sine-wave will become obvious when the potentiometer wiper is turned toward the differentiating position (where Θ is positive). If listened to with an audio detector, you may even hear the change in timbre while moving the wiper from one extreme to the other. If excited by a "clean" sine-wave, however, no change in timbre should be heard because there are no harmonics present.

Troubleshooting log

Actions / Measurements / Observations (i.e. *What I did and/or noticed . . .*)	Conclusions (i.e. *What this tells me . . .*)

file 03933

Answer 76

I do not provide a grading rubric here, but elsewhere.

Notes 76

The idea of a troubleshooting log is three-fold. First, it gets students in the habit of documenting their troubleshooting procedure and thought process. This is a valuable habit to get into, as it translates to more efficient (and easier-followed) troubleshooting on the job. Second, it provides a way to document student steps for the assessment process, making your job as an instructor easier. Third, it reinforces the notion that each and every measurement or action should be followed by reflection (conclusion), making the troubleshooting process more efficient.

NAME: _____ **Troubleshooting Grading Criteria**

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

<u>100 %</u> *(Must meet or exceed all criteria listed)*
A. Absolutely flawless procedure
B. No unnecessary actions or measurements taken

<u>90 %</u> *(Must meet or exceed these criteria in addition to all criteria for 85% and below)*
A. No reversals in procedure (i.e. changing mind without sufficient evidence)
B. Every single action, measurement, and relevant observation properly documented

<u>80 %</u> *(Must meet or exceed these criteria in addition to all criteria for 75% and below)*
A. No more than one unnecessary action or measurement
B. No false conclusions or conceptual errors
C. No missing conclusions (i.e. at least one documented conclusion for action / measurement / observation)

<u>70 %</u> *(Must meet or exceed these criteria in addition to all criteria for 65%)*
A. No more than one false conclusion or conceptual error
B. No more than one conclusion missing (i.e. an action, measurement, or relevant observation without a corresponding conclusion)

<u>65 %</u> *(Must meet or exceed these criteria in addition to all criteria for 60%)*
A. No more than two false conclusions or conceptual errors
B. No more than two unnecessary actions or measurements
C. No more than one undocumented action, measurement, or relevant observation
D. Proper use of all test equipment

<u>60 %</u> *(Must meet or exceed these criteria)*
A. Fault accurately identified
B. Safe procedures used at all times

<u>50 %</u> *(Only applicable where students performed significant development/design work – i.e. not a proven circuit provided with all component values)*
A. Working prototype circuit built and demonstrated

<u>0 %</u> *(If <u>any</u> of the following conditions are true)*
A. Unsafe procedure(s) used at any point

<u>file 03932</u>

Answer 77

Be sure to document all steps taken and conclusions made in your troubleshooting!

Notes 77

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.

Question 78

Suppose someone were to ask you to differentiate electrical reactance (X) from electrical resistance (R). How would you distinguish these two similar concepts from one another, using your own words?

file 03301

Answer 78

It is really important for you to frame this concept in your own words, so be sure to check with your instructor on the accuracy of your answer to this question! To give you a place to start, I offer this distinction: resistance is electrical *friction*, whereas reactance is electrical *energy storage*. Fundamentally, the difference between X and R is a matter of energy exchange, and it is understood most accurately in those terms.
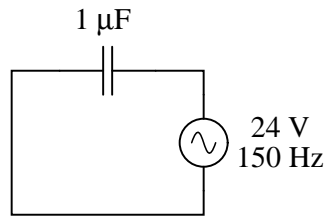
Notes 78

This is an excellent point of crossover with your students' studies in elementary physics, if they are studying physics now or have studied physics in the past. The energy-storing actions of inductors and capacitors are quite analogous to the energy-storing actions of masses and springs (respectively, if you associate velocity with current and force with voltage). In the same vein, resistance is analogous to kinetic friction between a moving object and a stationary surface. The parallels are so accurate, in fact, that the electrical properties of R, L, and C have been exploited to model mechanical systems of friction, mass, and resilience in circuits known as *analog computers*.

Question 79

Explain all the steps necessary to calculate the amount of current in this capacitive AC circuit:

1 μF

24 V
150 Hz

<u>file 01551</u>

Answer 79

$I = 22.6$ mA

Notes 79

The current is not difficult to calculate, so obviously the most important aspect of this question is not the math. Rather, it is the *procedure* of calculation: what to do first, second, third, etc., in obtaining the final answer.

Question 80

Calculate the total impedance offered by these two capacitors to a sinusoidal signal with a frequency of 900 Hz:

Z_{total} @ 900 Hz = ???
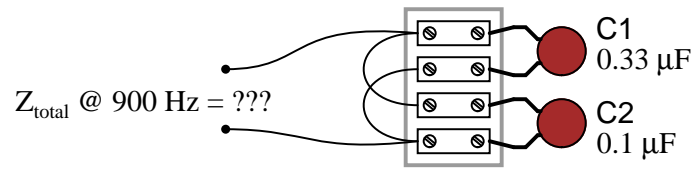
Show your work using three different problem-solving strategies:

- Calculating total capacitance (C_{total}) first, then total impedance (Z_{total}).
- Calculating individual admittances first (Y_{C1} and Y_{C2}), then total admittance (Y_{total}), then total impedance (Z_{total}).
- Using complex numbers: calculating individual impedances first ($\mathbf{Z_{C1}}$ and $\mathbf{Z_{C2}}$), then total impedance ($\mathbf{Z_{total}}$).

Do these two strategies yield the same total impedance value? Why or why not?

<u>file 01835</u>

Answer 80

First strategy:

$C_{total} = 0.43\,\mu\text{F}$

$X_{total} = 411.3\,\Omega$

$\mathbf{Z_{total}} = 411.3\,\Omega \angle -90^o$ or $\mathbf{Z_{total}} = 0 - j411.3\,\Omega$

Second strategy:

$Z_{C1} = X_{C1} = 535.9\,\Omega$

$Y_{C1} = \frac{1}{Z_{C1}} = 1.866\,\text{mS}$

$Z_{C1} = X_{C2} = 1.768\,\text{k}\Omega$

$Y_{C2} = \frac{1}{Z_{C2}} = 565.5\,\mu\text{S}$

$Y_{total} = 2.432\,\text{mS}$

$Z_{total} = \frac{1}{Y_{total}} = 411.3\,\Omega$

Third strategy: (using complex numbers)

$X_{C1} = 535.9\,\Omega \quad \mathbf{Z_{C1}} = 535.9\,\Omega \angle -90^o$

$X_{C2} = 1.768\,\text{k}\Omega \quad \mathbf{Z_{C1}} = 1.768\,\text{k}\Omega \angle -90^o$

$\mathbf{Z_{total}} = 411.3\,\Omega \angle -90^o$ or $\mathbf{Z_{total}} = 0 - j411.3\,\Omega$

A common misconception many students have about capacitive reactances and impedances is that they must interact "oppositely" to how one would normally consider electrical opposition. That is, many students believe capacitive reactances and impedances should add in parallel and diminish in series, because that's what capacitance (in Farads) does! This is not true, however. Impedances *always* add in series and diminish in parallel, at least from the perspective of complex numbers. This is one of the reasons I favor AC circuit calculations using complex numbers: because then students may conceptually treat impedance just like they treat DC resistance.

The purpose of this question is to get students to realize that *any* way they can calculate total impedance is correct, whether calculating total capacitance and then calculating impedance from that, or by calculating the impedance of each capacitor and then combining impedances to find a total impedance. This should be reassuring, because it means students have a way to check their work when analyzing circuits such as this!
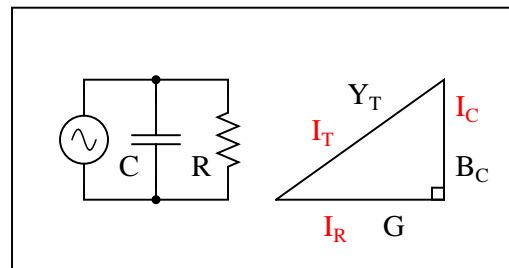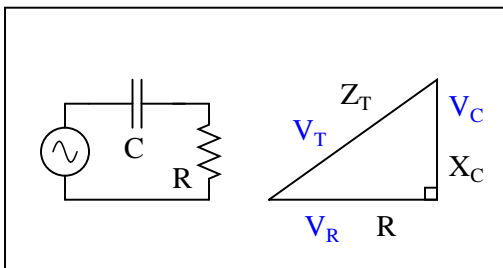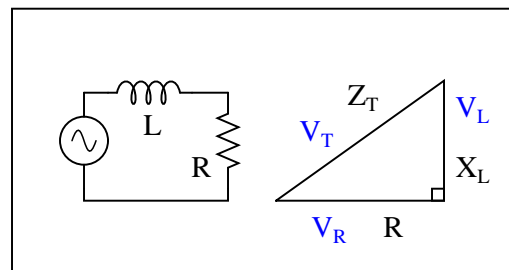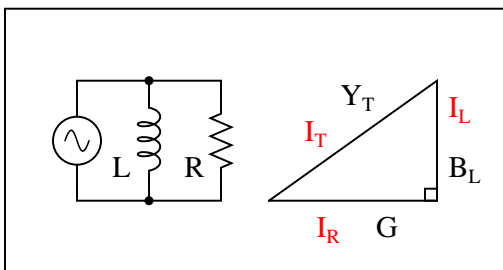
Question 81

Examine the following circuits, then label the sides of their respective triangles with all the variables that are trigonometrically related in those circuits:
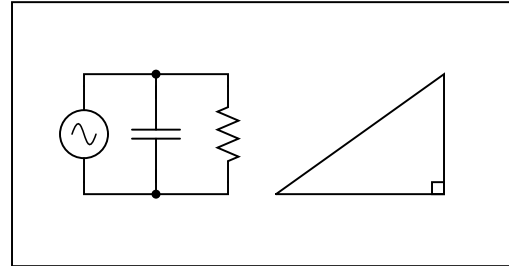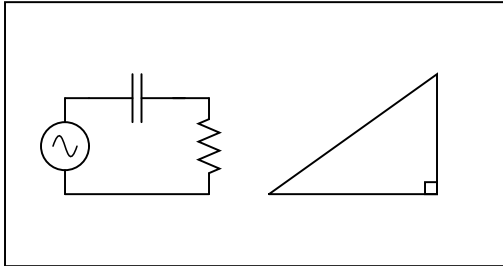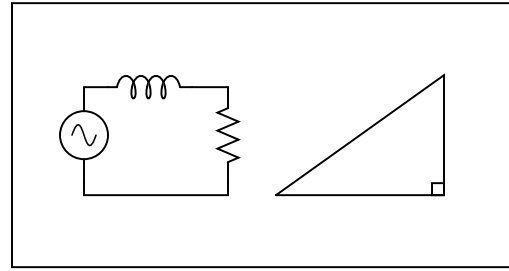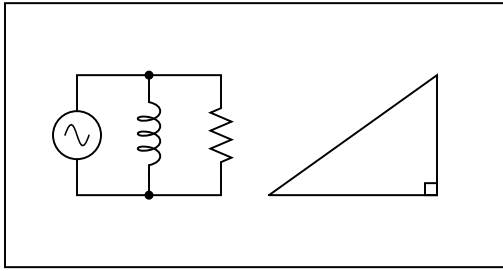
Answer 81

This question asks students to identify those variables in each circuit that vectorially *add*, discriminating them from those variables which do not add. This is extremely important for students to be able to do if they are to successfully apply "the triangle" to the solution of AC circuit problems.

Note that some of these triangles should be drawn upside-down instead of all the same as they are shown in the question, if we are to properly represent the vertical (imaginary) phasor for capacitive impedance and for inductor admittance. However, the point here is simply to get students to recognize what quantities add and what do not. Attention to the direction (up or down) of the triangle's opposite side can come later.

Question 82

Draw a phasor diagram showing the trigonometric relationship between resistance, reactance, and impedance in this series circuit:

2.2 kΩ

R

5 V RMS
350 Hz

C

0.22 µF
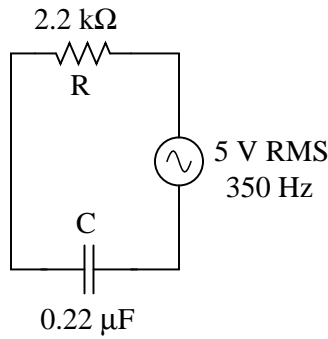
Show mathematically how the resistance and reactance combine in series to produce a total impedance (scalar quantities, all). Then, show how to analyze this same circuit using complex numbers: regarding each of the component as having its own impedance, demonstrating mathematically how these impedances add up to comprise the total impedance (in both polar and rectangular forms).

file 01828

Answer 82

$R = 2.2$ kΩ

$X_C = 2.067$ kΩ

$Z_{total} = 3.019$ kΩ
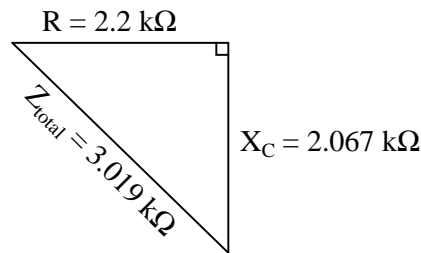
Scalar calculations

$R = 2.2$ kΩ $X_C = 2.067$ kΩ

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

$Z_{series} = \sqrt{2200^2 + 2067^2} = 3019$ Ω

Complex number calculations

$\mathbf{Z_R} = 2.2$ kΩ $\angle\ 0^o$ $\mathbf{Z_C} = 2.067$ kΩ $\angle -90^o$ (Polar form)

$\mathbf{Z_R} = 2.2$ kΩ $+ j0$ Ω $\mathbf{Z_C} = 0$ Ω $- j2.067$ kΩ   (Rectangular form)

$\mathbf{Z_{series}} = \mathbf{Z_1} + \mathbf{Z_2} + \cdots \mathbf{Z_n}$ (General rule of series impedances)

$\mathbf{Z_{series}} = \mathbf{Z_R} + \mathbf{Z_C}$ (Specific application to this circuit)

$\mathbf{Z_{series}} = 2.2$ kΩ $\angle\ 0^o + 2.067$ kΩ $\angle -90^o = 3.019$ kΩ $\angle -43.2^o$

$\mathbf{Z_{series}} = (2.2$ kΩ $+ j0$ Ω$) + (0$ Ω $- j2.067$ kΩ$) = 2.2$ kΩ $- j2.067$ kΩ

I want students to see that there are two different ways of approaching a problem such as this: with *scalar* math and with *complex number* math. If students have access to calculators that can do complex-number arithmetic, the "complex" approach is actually simpler for series-parallel combination circuits, and it yields richer (more informative) results.

Ask your students to determine which of the approaches most resembles DC circuit calculations. Incidentally, this is why I tend to prefer complex-number AC circuit calculations over scalar calculations: because of the conceptual continuity between AC and DC. When you use complex numbers to represent AC voltages, currents, and impedances, almost all the rules of DC circuits still apply. The big exception, of course, is calculations involving *power*.

Question 83

Calculate the total impedance of this RC circuit, once using nothing but scalar numbers, and again using complex numbers:

$$Z_{total} \text{ @ } 400 \text{ Hz} = ???$$
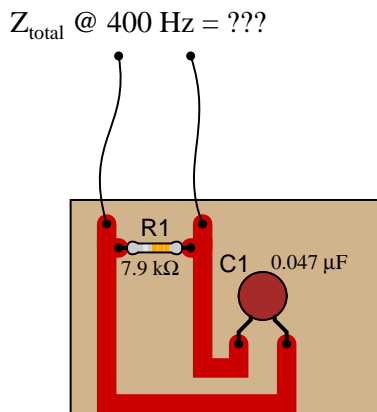
file 01838

Answer 83

Scalar calculations

$R_1 = 7.9 \text{ k}\Omega \quad G_{R1} = 126.6 \ \mu\text{S}$

$X_{C1} = 8.466 \text{ k}\Omega \quad B_{C1} = 118.1 \ \mu\text{S}$

$Y_{total} = \sqrt{G^2 + B^2} = 173.1 \ \mu\text{S}$

$Z_{total} = \frac{1}{Y_{total}} = 5.776 \text{ k}\Omega$

Complex number calculations

$R_1 = 7.9 \text{ k}\Omega \quad \mathbf{Z_{R1}} = 7.9 \text{ k}\Omega \angle 0^o$

$X_{C1} = 8.466 \text{ k}\Omega \quad \mathbf{Z_{C1}} = 8.466 \text{ k}\Omega \angle -90^o$

$\mathbf{Z_{total}} = \frac{1}{\frac{1}{\mathbf{Z_{R1}}} + \frac{1}{\mathbf{Z_{C1}}}} = 5.776 \text{ k}\Omega \angle -43.02^o$

Notes 83

Some electronics textbooks (and courses) tend to emphasize scalar impedance calculations, while others emphasize complex number calculations. While complex number calculations provide more informative results (a phase shift given in *every* variable!) and exhibit conceptual continuity with DC circuit analysis (same rules, similar formulae), the scalar approach lends itself better to conditions where students do not have access to calculators capable of performing complex number arithmetic. Yes, of course, you can do complex number arithmetic without a powerful calculator, but it's a *lot* more tedious and prone to errors than calculating with admittances, susceptances, and conductances (primarily because the phase shift angle is omitted for each of the variables).

Question 84

A student is asked to calculate the phase shift for the following circuit's output voltage, relative to the phase of the source voltage:
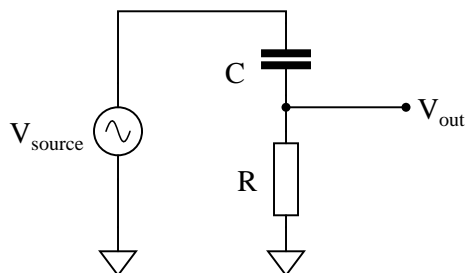
He recognizes this as a series circuit, and therefore realizes that a right triangle would be appropriate for representing component impedances and component voltage drops (because both impedance and voltage are quantities that add in series, and the triangle represents phasor addition):
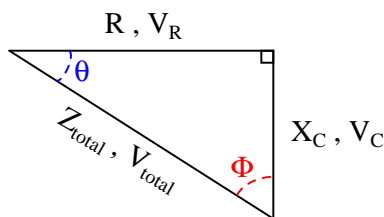
The problem now is, which angle does the student solve for in order to find the phase shift of V_{out}? The triangle contains two angles besides the 90° angle, Θ and Φ. Which one represents the output phase shift, and more importantly, *why*?

file 03748

Answer 84

The proper angle in this circuit is Θ, and it will be a positive (leading) quantity.

Notes 84

Too many students blindly use impedance and voltage triangles without really understand what they are and why they work. These same students will have no idea how to approach a problem like this. Work with them to help them understand!

115

Question 85

Calculate the output voltage of this phase-shifting circuit, expressing it in polar form (magnitude and phase angle relative to the source voltage):
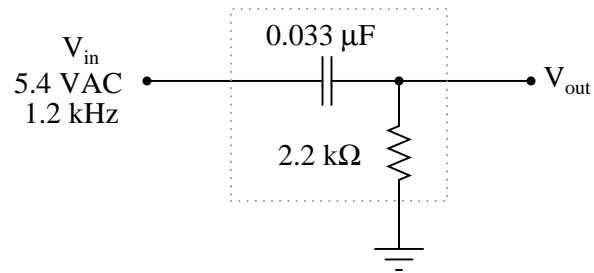
file 02621
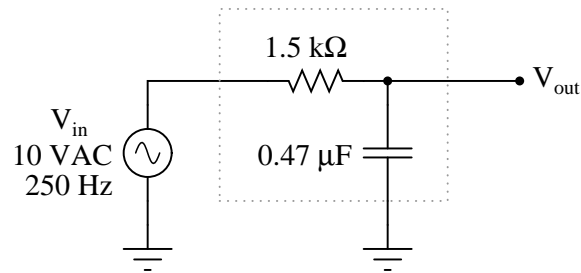
Answer 85

$V_{out} = 2.593 \text{ V} \angle 61.3^o$

Notes 85

This is a very practical application of resistor-capacitor (RC) circuits: to introduce a phase shift to an AC signal. Examples of where a circuit such as this may be used include oscillators (to introduce phase shift into a feedback network for a total phase shift of 360°) and thyristor firing control circuits (phase-shifting the triggering voltage in relation to the source voltage).

Question 86

Calculate the output voltage of this phase-shifting circuit, expressing it in polar form (magnitude and phase angle relative to the source voltage):

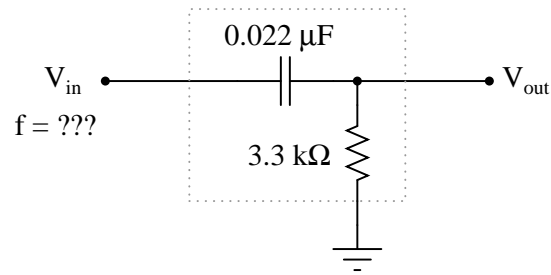
file 02620

Answer 86

$V_{out} = 6.7$ V $\angle$ -47.9^o

Notes 86

This is a very practical application of resistor-capacitor (RC) circuits: to introduce a phase shift to an AC signal. Examples of where a circuit such as this may be used include oscillators (to introduce phase shift into a feedback network for a total phase shift of 360°) and thyristor firing control circuits (phase-shifting the triggering voltage in relation to the source voltage).

Question 87

Determine the input frequency necessary to give the output voltage a phase shift of 70°:

0.022 µF

V_{in}

f = ???

3.3 kΩ

V_{out}

file 02623

Answer 87

$f = 798$ Hz

Notes 87

Phase-shifting circuits are very useful, and important to understand. They are particularly important in some types of oscillator circuits, which rely on RC networks such as this to provide certain phase shifts to sustain oscillation.

Question 88

Determine the input frequency necessary to give the output voltage a phase shift of $40°$:
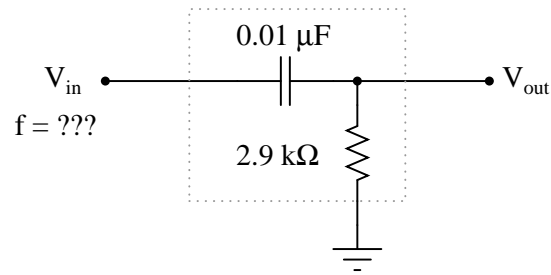

file 02622

Answer 88

$f = 6.54$ kHz

Notes 88

Phase-shifting circuits are very useful, and important to understand. They are particularly important in some types of oscillator circuits, which rely on RC networks such as this to provide certain phase shifts to sustain oscillation.

Question 89

Determine the input frequency necessary to give the output voltage a phase shift of -38º:
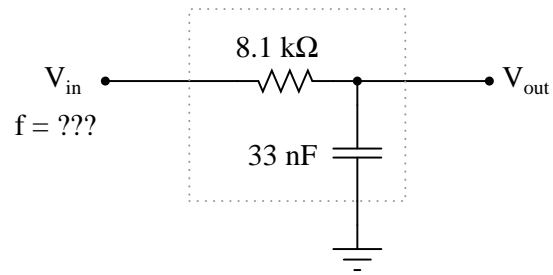

file 02626

Answer 89

$f = 465$ Hz

Notes 89

Phase-shifting circuits are very useful, and important to understand. They are particularly important in some types of oscillator circuits, which rely on RC networks such as this to provide certain phase shifts to sustain oscillation.

Question 90

Determine the input frequency necessary to give the output voltage a phase shift of -25°:

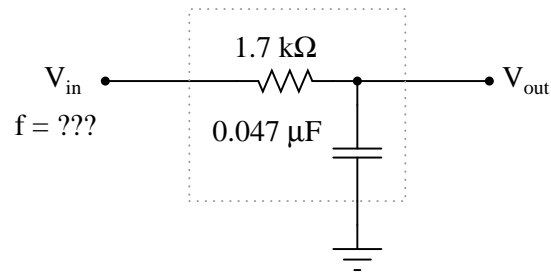file 02625
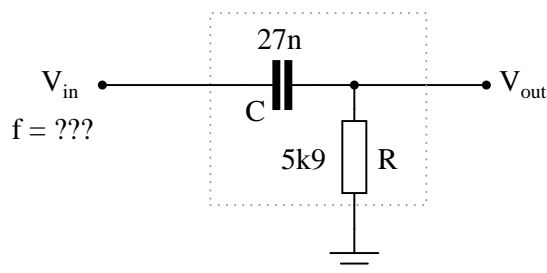
Answer 90

$f = 929$ Hz

Notes 90

Phase-shifting circuits are very useful, and important to understand. They are particularly important in some types of oscillator circuits, which rely on RC networks such as this to provide certain phase shifts to sustain oscillation.

Question 91

Determine the input frequency necessary to give the output voltage a phase shift of 25°:

Also, write an equation that solves for frequency (f), given all the other variables (R, C, and phase angle θ).

file 03284

Answer 91

$f = 2.143$ kHz

$$f = \frac{1}{2\pi RC \tan\theta}$$

Notes 91

Discuss with your students what a good procedure might be for calculating the unknown values in this problem, and also how they might check their work.
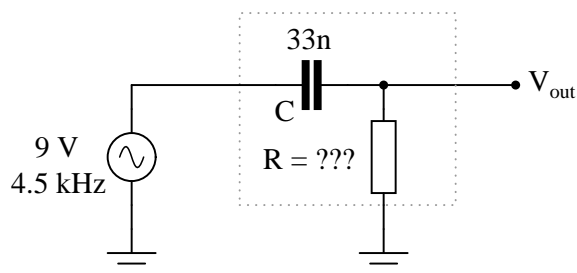
Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 92

Determine the necessary resistor value to give the output voltage a phase shift of 58°:

Also, write an equation that solves for this resistance value (R), given all the other variables (f, C, and phase angle θ).

file 03285

Answer 92

$R = 669.7\ \Omega$

$$R = \frac{1}{2\pi f C \tan \theta}$$

Notes 92

Discuss with your students what a good procedure might be for calculating the unknown values in this problem, and also how they might check their work.
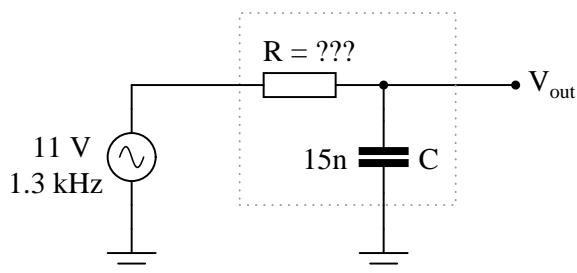
Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 93

Determine the necessary resistor value to give the output voltage a phase shift of -64°:

Also, write an equation that solves for this resistance value (R), given all the other variables (f, C, and phase angle θ).

file 03287

Answer 93

$R = 16.734$ kΩ

$$R = -\frac{\tan\theta}{2\pi f C}$$

Notes 93

Discuss with your students what a good procedure might be for calculating the unknown values in this problem, and also how they might check their work.
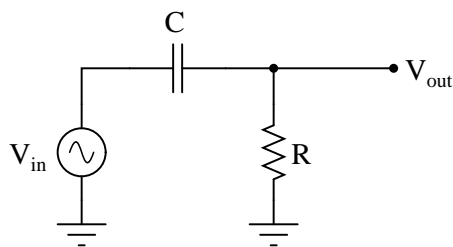
Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 94

Use algebraic substitution to generate an equation expressing the output voltage of the following circuit given the input voltage, the input frequency, the capacitor value, and the resistor value:

$V_{out} =$
file 03818

Answer 94

$$V_{out} = \frac{R \, V_{in}}{\sqrt{\left(\frac{1}{2\pi f C}\right)^2 + R^2}}$$

Notes 94

Discuss with your students what a good procedure might be for calculating the unknown values in this problem, and also how they might check their work.
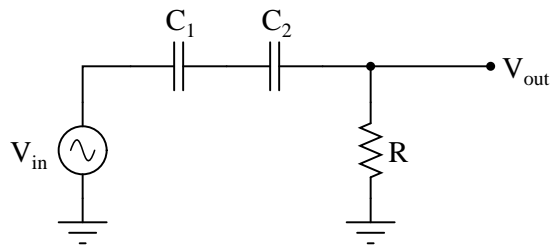
Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 95

Use algebraic substitution to generate an equation expressing the output voltage of the following circuit given the input voltage, the input frequency, the capacitor value, and the resistor value:

$V_{out} =$
file 03819

Answer 95

$$V_{out} = \frac{R\,V_{in}}{\sqrt{\left(\frac{C_1+C_2}{2\pi f C_1 C_2}\right)^2 + R^2}}$$

Notes 95

Discuss with your students what a good procedure might be for calculating the unknown values in this problem, and also how they might check their work.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 96

Complete the table of values for this circuit, representing all quantities in complex-number form (either polar or rectangular, your choice):
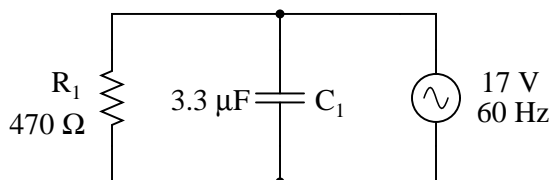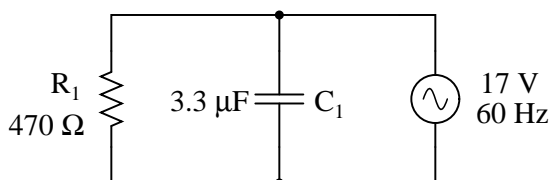

	R_1	C_1	Total
V			$17 \text{ V} \angle 0^o$
I			
Z			

file 03611

Answer 96

|	R_1	C_1	Total
V	$17 \text{ V} \angle 0^o$	$17 \text{ V} \angle 0^o$	$17 \text{ V} \angle 0^o$
I	$36.17 \text{ mA} \angle 0^o$	$21.15 \text{ mA} \angle 90^o$	$41.9 \text{ mA} \angle 30.3^o$
Z	$470 \ \Omega \angle 0^o$	$803.8 \ \Omega \angle -90^o$	$405.7 \ \Omega \angle -30.3^o$

Notes 96

Ask your students to share their problem-solving techniques for this question: how they solved for each parameter and in what order they performed the calculations.

Question 97

This phase-shifting bridge circuit is supposed to provide an output voltage with a variable phase shift from -45° (lagging) to +45° (leading), depending on the position of the potentiometer wiper:
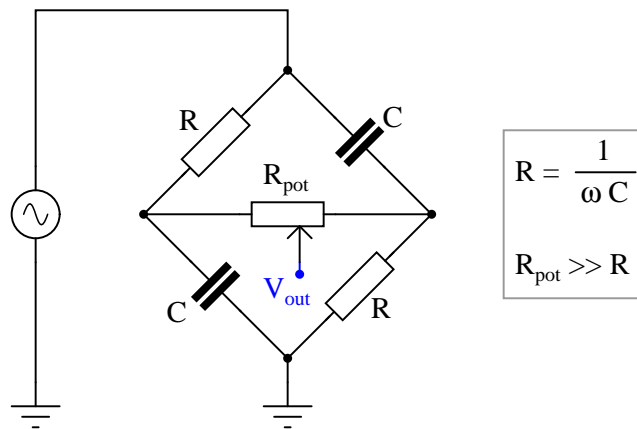

Suppose, though, that the output signal is stuck at +45° leading the source voltage, no matter where the potentiometer is set. Identify a likely failure that could cause this to happen, and explain why this failure could account for the circuit's strange behavior.

file 03464

Answer 97

A broken connection between the left-hand terminal of the potentiometer and the bridge could cause this to happen:
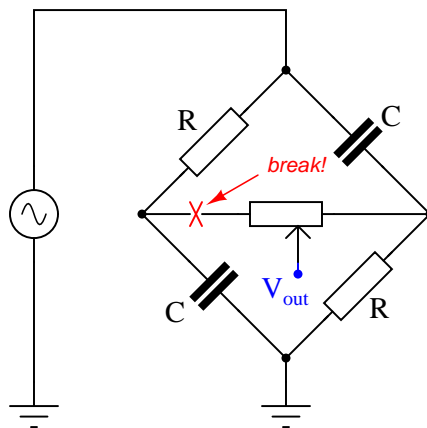
I'll let you figure out why!

Notes 97

It is essential, of course, that students understand the operational principle of this circuit before they may even attempt to diagnose possible faults. You may find it necessary to discuss this circuit in detail with your students before they are ready to troubleshoot it.
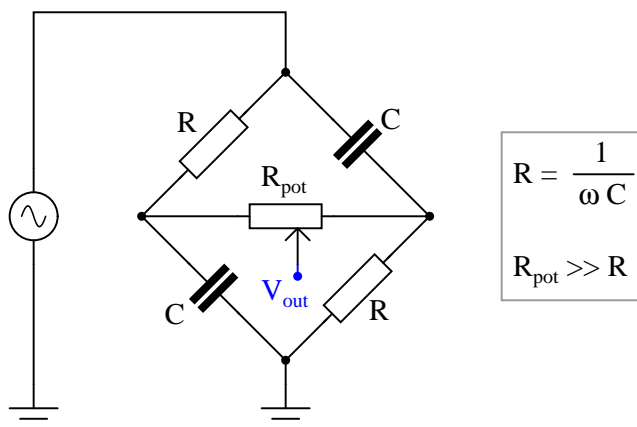
In case anyone asks, the symbolism $R_{pot} >> R$ means "potentiometer resistance is *much* greater than the fixed resistance value."

This phase-shifting bridge circuit is supposed to provide an output voltage with a variable phase shift from -45° (lagging) to +45° (leading), depending on the position of the potentiometer wiper:


$$R = \frac{1}{\omega C}$$

$$R_{pot} \gg R$$

Suppose, though, that the output signal is stuck at -45° lagging the source voltage, no matter where the potentiometer is set. Identify a likely failure that could cause this to happen, and explain why this failure could account for the circuit's strange behavior.

file 03465

Answer 98

A broken connection between the right-hand terminal of the potentiometer and the bridge could cause this to happen:
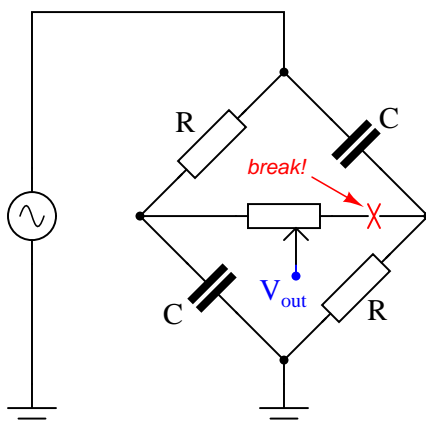

I'll let you figure out why!

Notes 98

It is essential, of course, that students understand the operational principle of this circuit before they may even attempt to diagnose possible faults. You may find it necessary to discuss this circuit in detail with your students before they are ready to troubleshoot it.

In case anyone asks, the symbolism $R_{pot} \gg R$ means "potentiometer resistance is *much* greater than the fixed resistance value."

Question 99

This phase-shifting bridge circuit is supposed to provide an output voltage with a variable phase shift from -45° (lagging) to +45° (leading), depending on the position of the potentiometer wiper:

$$R = \frac{1}{\omega C}$$

$$R_{pot} \gg R$$
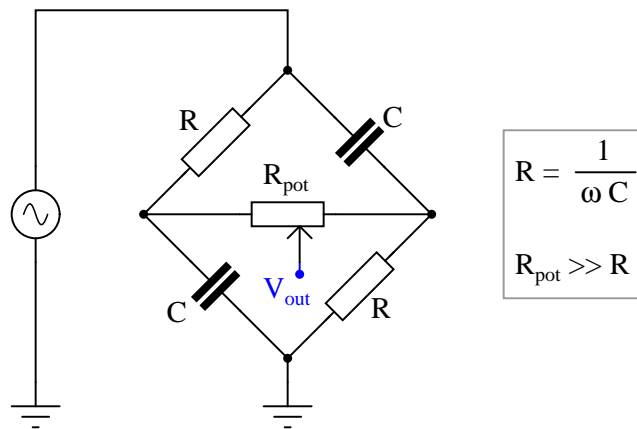
Suppose, though, that the output signal registers as it should with the potentiometer wiper fully to the right, but diminishes greatly in amplitude as the wiper is moved to the left, until there is practically zero output voltage at the full-left position. Identify a likely failure that could cause this to happen, and explain why this failure could account for the circuit's strange behavior.

file 03466

Answer 99

An open failure of the fixed resistor in the upper-left arm of the bridge could cause this to happen:
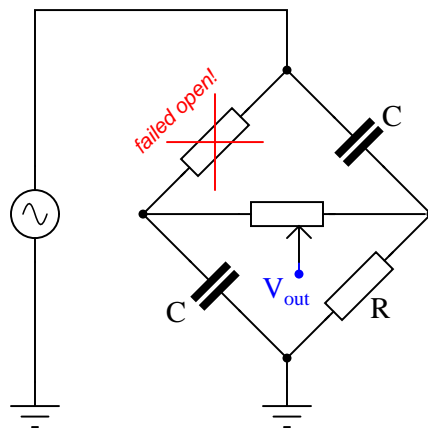
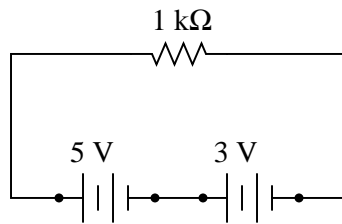Follow-up question: identify another possible component failure that would exhibit the same symptoms.

Notes 99

It is essential, of course, that students understand the operational principle of this circuit before they may even attempt to diagnose possible faults. You may find it necessary to discuss this circuit in detail with your students before they are ready to troubleshoot it.

In case anyone asks, the symbolism $R_{pot} \gg R$ means "potentiometer resistance is *much* greater than the fixed resistance value."
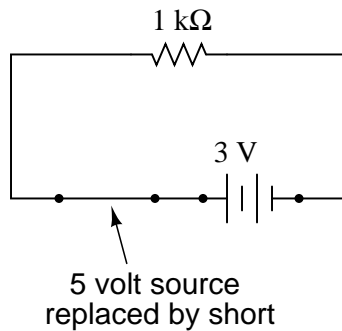
Suppose we have a single resistor powered by two series-connected voltage sources. Each of the voltage sources is "ideal," possessing no internal resistance:
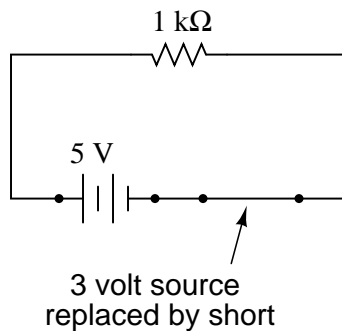

Calculate the resistor's voltage drop and current in this circuit.

Now, suppose we were to remove one voltage source from the circuit, replacing it with its internal resistance (0 Ω). Re-calculate the resistor's voltage drop and current in the resulting circuit:

Now, suppose we were to remove the other voltage source from the circuit, replacing it with its internal resistance (0 Ω). Re-calculate the resistor's voltage drop and current in the resulting circuit:

One last exercise: "superimpose" (add) the resistor voltages and superimpose (add) the resistor currents in the last two circuit examples, and compare these voltage and current figures with the calculated values of the original circuit. What do you notice?

file 00690

Answer 100

Original circuit: $E_R = 8$ volts ; $I_R = 8$ mA

With 3 volt voltage source only: $E_R = 3$ volts ; $I_R = 3$ mA

With 5 volt voltage source only: $E_R = 5$ volts ; $I_R = 5$ mA

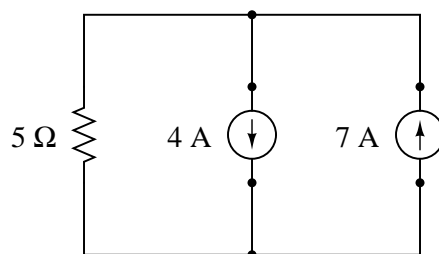5 volts + 3 volts = 8 volts
5 mA + 3 mA = 8 mA

Notes 100

This circuit is so simple, students should not even require the use of a calculator to determine the current figures. The point of it is, to get students to see the concept of *superposition* of voltages and currents.
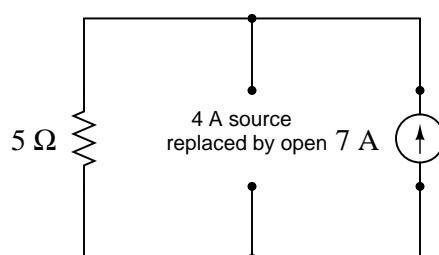
Suppose we have a single resistor powered by two parallel-connected current sources. Each of the current sources is "ideal," possessing infinite internal resistance:
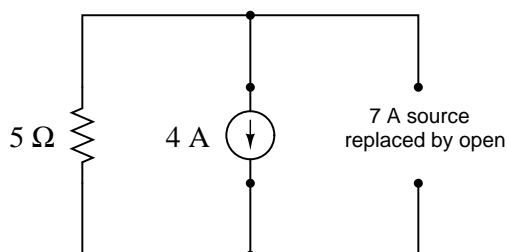

Calculate the resistor's voltage drop and current in this circuit.

Now, suppose we were to remove one current source from the circuit, replacing it with its internal resistance (∞ Ω). Re-calculate the resistor's voltage drop and current in the resulting circuit:

Now, suppose we were to remove the other current source from the circuit, replacing it with its internal resistance (∞ Ω). Re-calculate the resistor's voltage drop and current in the resulting circuit:

One last exercise: "superimpose" (add) the resistor voltages and superimpose (add) the resistor currents in the last two circuit examples, and compare these voltage and current figures with the calculated values of the original circuit. What do you notice?

file 00693

Answer 101

Original circuit: $E_R = 15$ volts ; $I_R = 3$ A

With 7 amp current source only: $E_R = 35$ volts ; $I_R = 7$ A

With 4 amp current source only: $E_R = 20$ volts ; $I_R = 4$ A

35 volts - 20 volts = 15 volts
7 A - 4 A = 3 A

Notes 101

This circuit is so simple, students should not even require the use of a calculator to determine the current figures. If students are not familiar with current sources, this question provides an excellent opportunity to review them. The main point of the question is, however, to get students to see the concept of *superposition* of voltages and currents.

Question 102

Use the Superposition Theorem to calculate the amount of current going through the 55 Ω heater element. Ignore all wire and connection resistances, only considering the resistance of each fuse in addition to the heater element resistance:
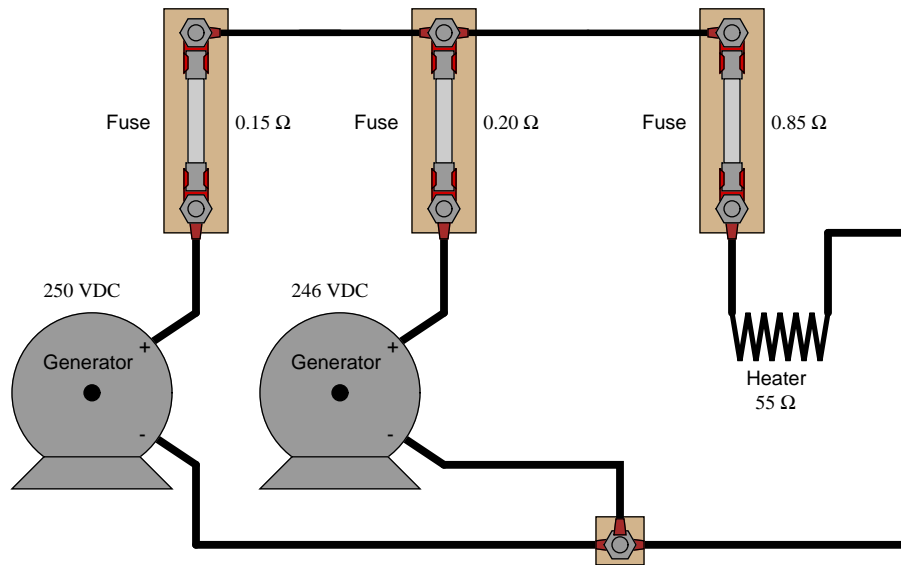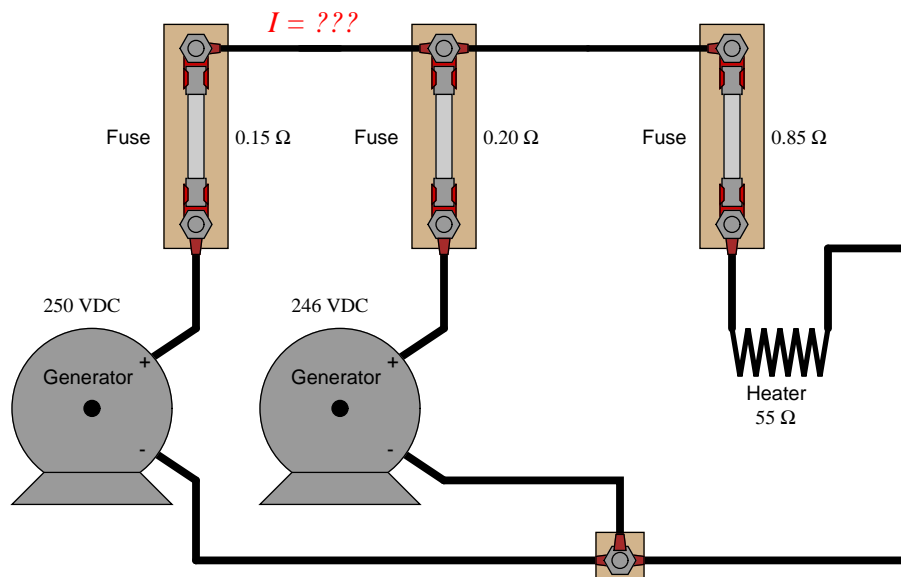

file 03129

Answer 102

$I_{heater} = 4.439$ A

Follow-up question: explain how you could use the Superposition Theorem to calculate current going through the short length of wire connecting the two generators together:
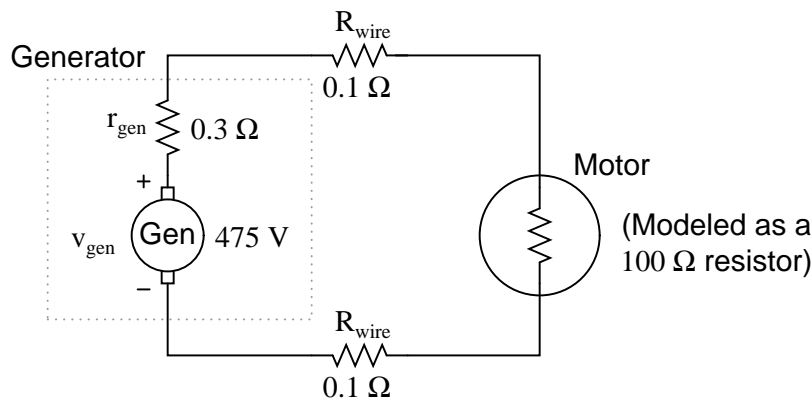
Though there are other methods of analysis for this circuit, it is still a good application of Superposition Theorem.

Question 103

Suppose a DC generator is powering an electric motor, which we model as a 100 Ω resistor:

Calculate the amount of current this generator will supply to the motor and the voltage measured across the motor's terminals, taking into account all the resistances shown (generator internal resistance r_{gen}, wiring resistances R_{wire}, and the motor's equivalent resistance).

Now suppose we connect an identical generator in parallel with the first, using connecting wire so short that we may safely discount its additional resistance:
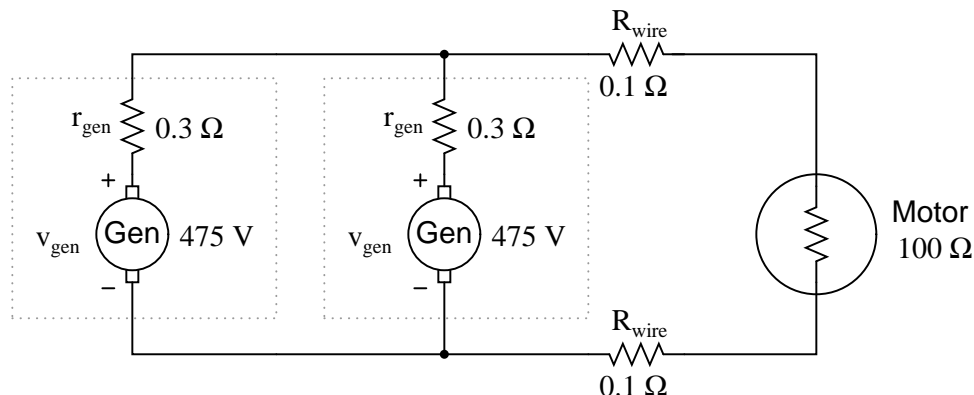
Use the Superposition Theorem to re-calculate the motor current and motor terminal voltage, commenting on how these figures compare with the first calculation (using only one generator).

file 03130

Answer 103

With only one generator connected:

I_{motor} = 4.726 amps V_{motor} = 472.6 volts

With two generators connected:

I_{motor} = 4.733 amps V_{motor} = 473.3 volts

Challenge question: how much current does *each* generator supply to the circuit when there are two generators connected in parallel?

Some students will erroneously leap to the conclusion that another generator will send twice the current through the load (with twice the voltage drop across the motor terminals!). Such a conclusion is easy to reach if one does not fully understand the Superposition Theorem.

Electrical signals are frequently used in industrial control applications to communicate information from one device to another. An example of this is motor speed control, where a computer outputs a speed command signal to a motor "drive" circuit, which then provides metered power to an electric motor:
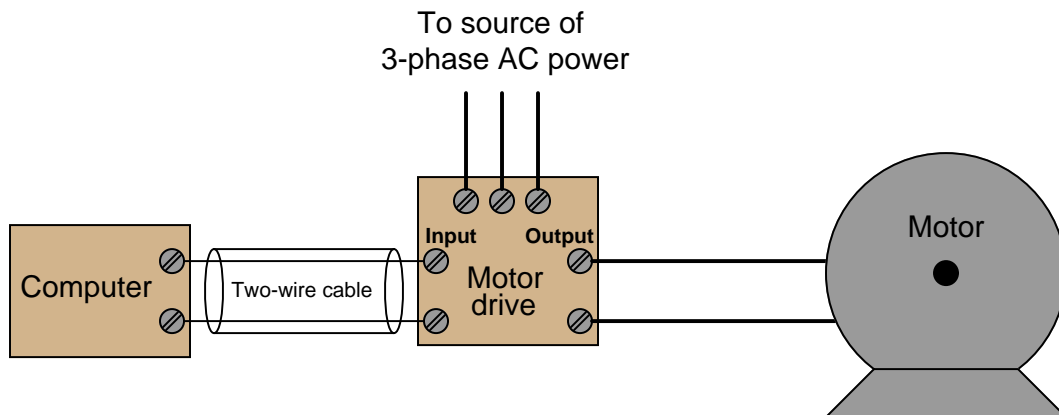
Two common standards for analog control signals are 1-5 volts DC and 4-20 mA DC. In either case, the motor will spin faster when this signal from the computer grows in magnitude (1 volt = motor stopped, 5 volts = motor runs at full speed; or 4 mA = motor stopped, 20 mA = motor runs at full speed).

At first, it would seem as though the choice between 1-5 volts and 4-20 mA as control signal standards is arbitrary. However, one of these standards exhibits much greater immunity to induced noise along the two-wire cable than the other. Shown here are two equivalent schematics for these signal standards, complete with an AC voltage source in series to represent the "noise" voltage picked up along the cable's length:
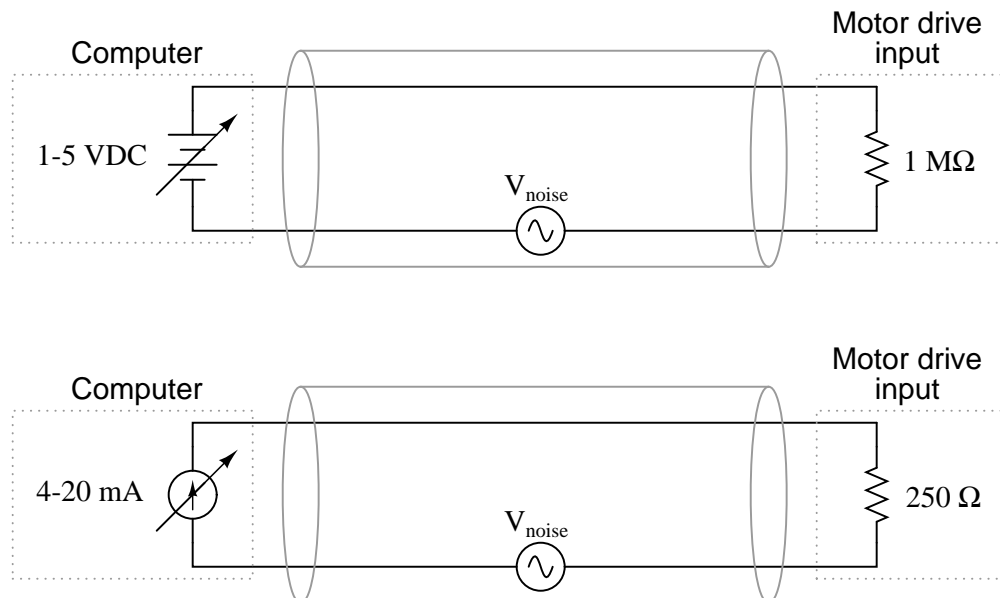
Use the superposition theorem to qualitatively determine which signal standard drops the greatest amount of noise voltage across the motor drive input's resistance, thereby most affecting the motor speed control.

file 03221

Answer 104

The motor drive input in the 1-5 volt signal system "sees" more noise voltage than the motor drive input in the 4-20 mA signal system.

Follow-up question: what bad effects do you think noise superimposed on the DC signal cable would have on motor speed control?

Challenge question: why do you suppose the 1-5 volt signal system requires a much greater input impedance (1 MΩ) than the 4-20 mA signal system? What might happen to the voltage signal received at the motor drive's input terminals if the input resistance were much less?
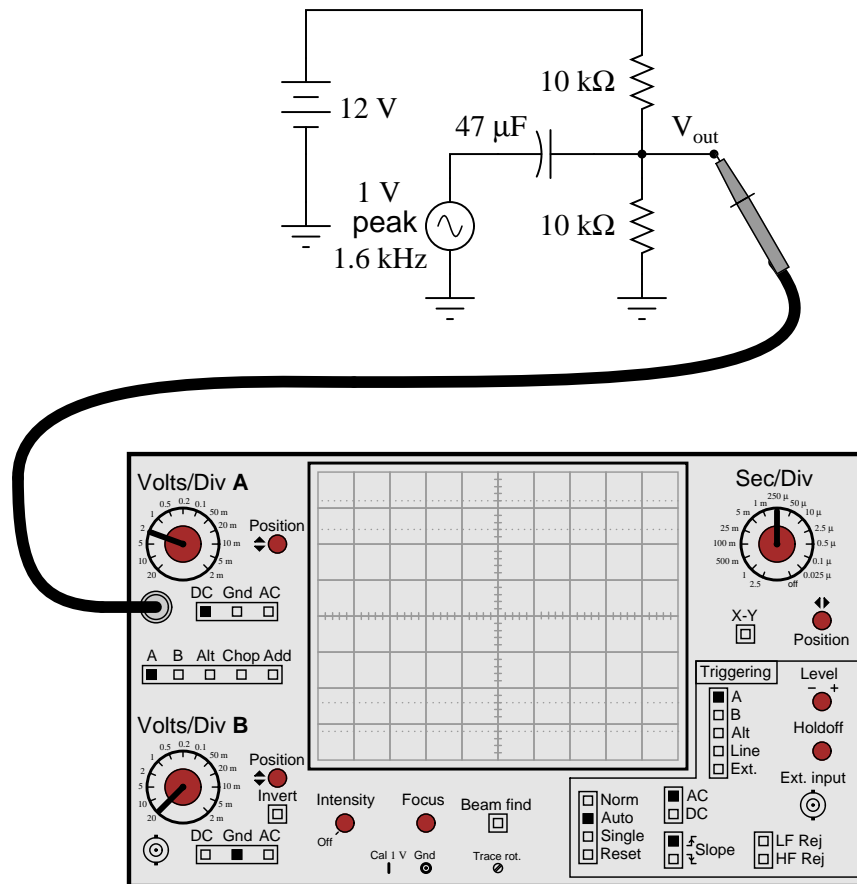
Notes 104

This is s very practical question, as induced noise is no academic matter in real industrial control systems. This is especially true around motor drive circuits, which are well known for their ability to generate *lots* of electrical noise!

Some students may suggest that the distinction between voltage and current signals is moot because shielded-pair cable is suppose to all but eliminate induced noise. In answer to this (good) question, it should be noted that real-life conditions are never ideal, and that induced noise (to some degree) is an unavoidable fact of life, especially in many industrial environments.

The challenge question may seem unanswerable until one considers the unavoidable resistance along the length of the signal cable and calculates the effects of voltage drop along the wire length for a huge input resistance versus a small input resistance.
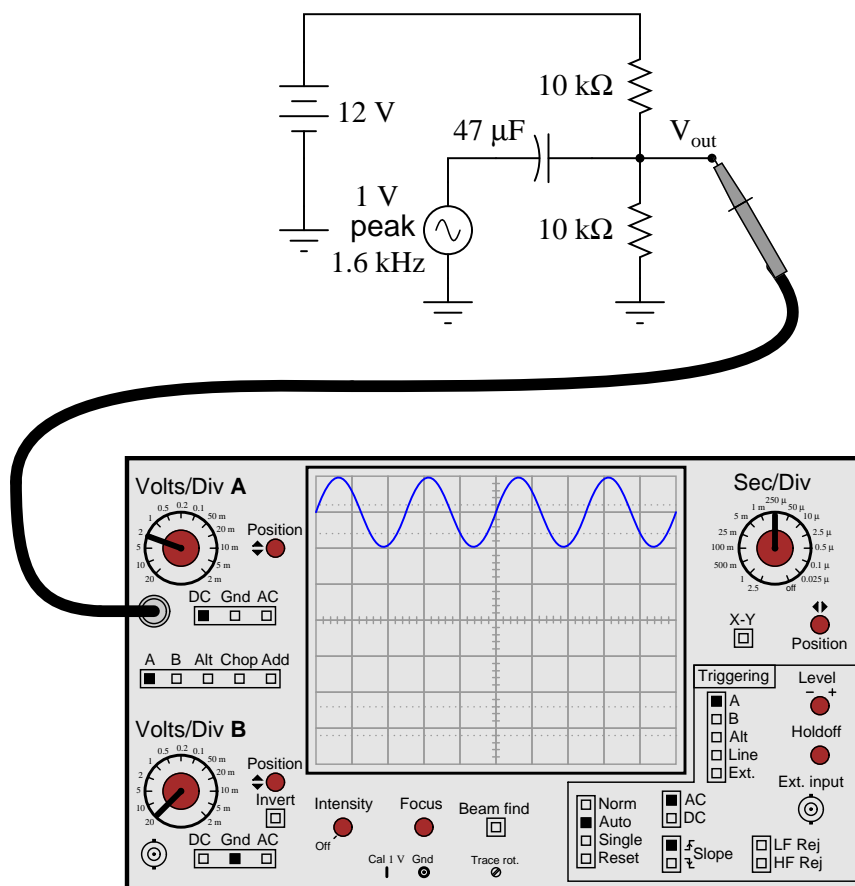
Sketch the approximate waveform of this circuit's output signal (V_{out}) on the screen of the oscilloscope:

Hint: use the Superposition Theorem!

file 03502

Answer 105

Follow-up question: what would the oscilloscope display look like if the coupling switch for channel A had been set to "AC" instead of "DC"?
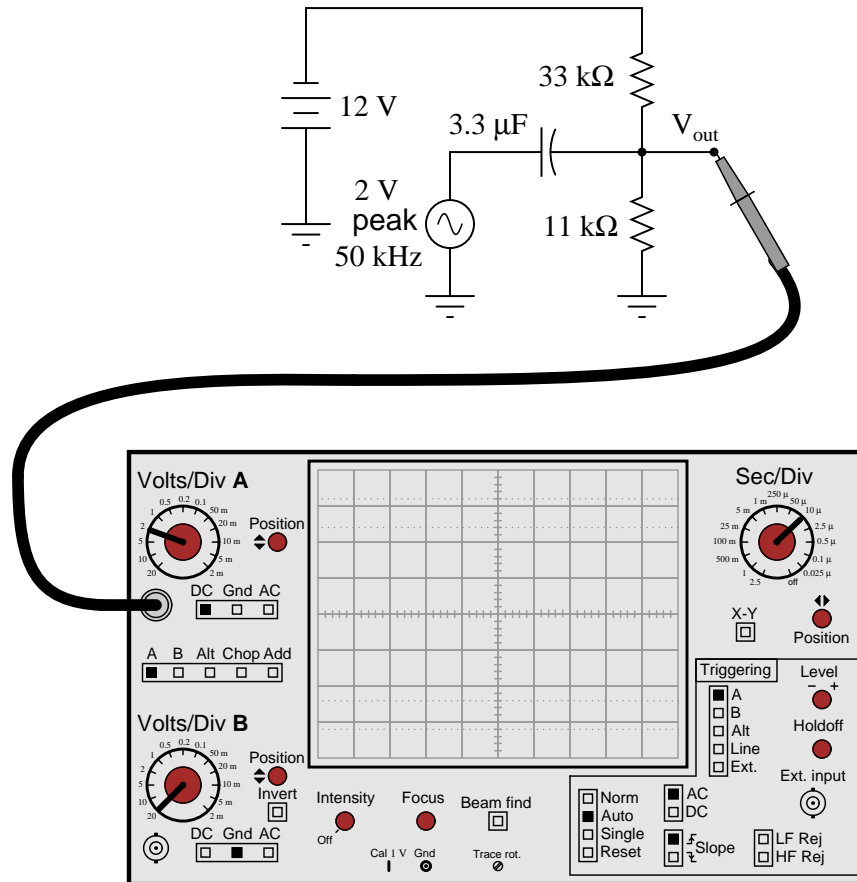

Notes 105

Note that the capacitor size has been chosen for negligible capacitive reactance (X_C) at the specific frequency, such that the 10 kΩ DC bias resistors present negligible loading to the coupled AC signal. This is typical for this type of biasing circuit.

Aside from giving students an excuse to apply the Superposition Theorem, this question previews a circuit topology that is extremely common in transistor amplifiers.
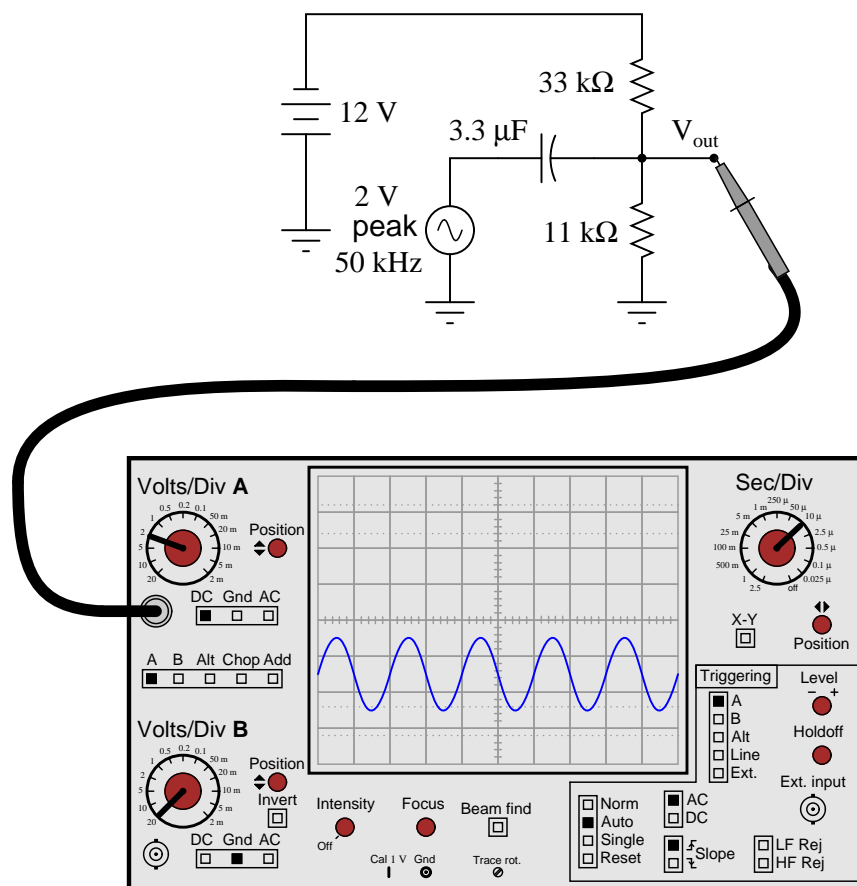
Sketch the approximate waveform of this circuit's output signal (V_{out}) on the screen of the oscilloscope:

Hint: use the Superposition Theorem!

file 03503

Follow-up question: explain why it is acceptable to use a polarized (polarity-sensitive) capacitor in this circuit when it is clearly connected to a source of AC. Why is it not damaged by the AC voltage when used like this?

Notes 106

Note that the capacitor size has been chosen for negligible capacitive reactance (X_C) at the specific frequency, such that the 10 kΩ DC bias resistors present negligible loading to the coupled AC signal. This is typical for this type of biasing circuit.

Aside from giving students an excuse to apply the Superposition Theorem, this question previews a circuit topology that is extremely common in transistor amplifiers.

Question 107

Audio headphones make highly sensitive voltage detectors for AC signals in the audio frequency range. However, the small speakers inside headphones are quite easily damaged by the application of DC voltage.

Explain how a capacitor could be used as a "filtering" device to allow AC signals through to a pair of headphones, yet block any applied DC voltage, so as to help prevent accidental damage of the headphones while using them as an electrical instrument.

The key to understanding how to answer this question is to recognize what a capacitor "appears as" to AC signals versus DC signals.

file 01395

Answer 107

Connect a capacitor in series with the headphone speakers.

Notes 107

I highly recommend to students that they should build a transformer-isolation circuit if they intend to use a pair of audio headphones as a test device (see question file number 00983 for a complete schematic diagram).

145

Question 108

Suppose a friend wanted to install filter networks in the "woofer" section of their stereo system, to prevent high-frequency power from being wasted in speakers incapable of reproducing those frequencies. To this end, your friend installs the following resistor-capacitor networks:
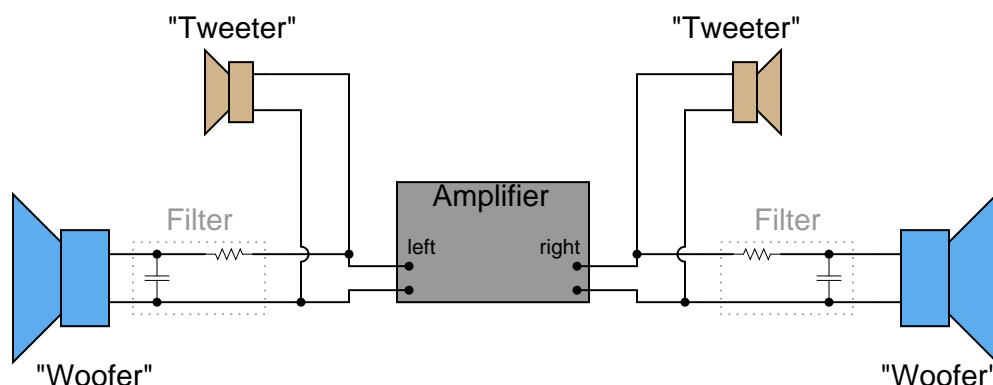
After examining this schematic, you see that your friend has the right idea in mind, but implemented it incorrectly. These filter circuits would indeed block high-frequency signals from getting to the woofers, but they would not actually accomplish the stated goal of minimizing wasted power.

What would you recommend to your friend in lieu of this circuit design?

file 00614

Answer 108

Rather than use a "shunting" form of low-pass filter (resistor and capacitor), a "blocking" form of low-pass filter (inductor) should be used instead.

Notes 108

The reason for this choice in filter designs is very practical. Ask your students to describe how a "shunting" form of filter works, where the reactive component is connected in parallel with the load, receiving power through a series resistor. Contrast this against a "blocking" form of filter circuit, in which a reactive component is connected in series with the load. In one form of filter, a resistor is necessary. In the other form of filter, a resistor is not necessary. What difference does this make in terms of power dissipation within the filter circuit?

Question 109

It is common in audio systems to connect a capacitor in series with each "tweeter" (high-frequency) speaker to act as a simple high-pass filter. The choice of capacitors for this task is important in a high-power audio system.

A friend of mine once had such an arrangement for the tweeter speakers in his car. Unfortunately, though, the capacitors kept blowing up when he operated the stereo at full volume! Tired of replacing these non-polarized electrolytic capacitors, he came to me for advice. I suggested he use mylar or polystyrene capacitors instead of electrolytics. These were a bit more expensive than electrolytic capacitors, but they did not blow up. Explain why.

file 03467

Answer 109

The issue here was not polarity (AC versus DC), because these were *non-polarized* electrolytic capacitors which were blowing up. What *was* an issue was ESR (Equivalent Series Resistance), which electrolytic capacitors are known to have high values of.

Notes 109

Your students may have to do a bit of refreshing (or first-time research!) on the meaning of ESR before they can understand why large ESR values could cause a capacitor to explode under extreme operating conditions.

Question 110

Controlling electrical "noise" in automotive electrical systems can be problematic, as there are many sources of "noise" voltages throughout a car. Spark ignitions and alternators can both generate substantial noise voltages, superimposed on the DC voltage in a car's electrical system. A simple way to electrically model this noise is to draw it as an AC "noise voltage" source in series with the DC source. If this noise enters a radio or audio amplifier, the result will be an irritating sound produced at the speakers:
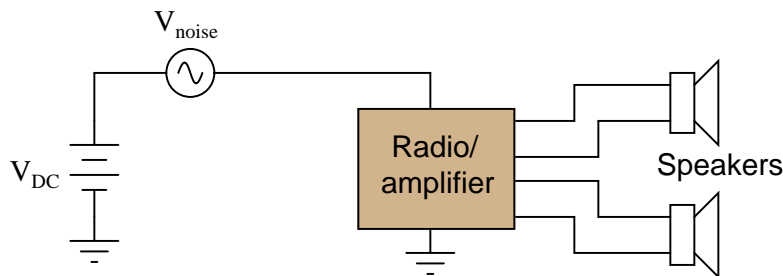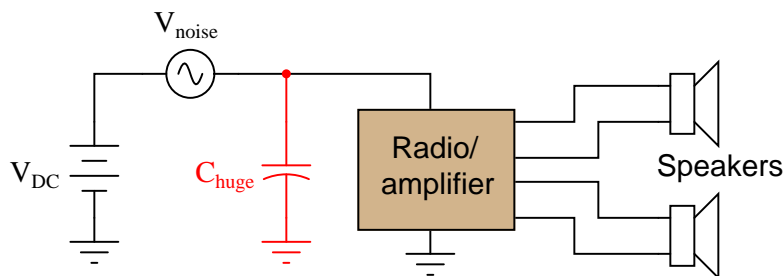

What would you suggest as a "fix" for this problem if a friend asked you to apply your electronics expertise to their noisy car audio system? Be sure to provide at least two practical suggestions.

file 03510

Answer 110

This is perhaps the easiest solution, to install a very large capacitor (C_{huge}) in parallel with the audio load:

Other, more sophisticated solutions exist, however!

Follow-up question: use superposition theorem to show *why* the capacitor mitigates the electrical noise without interfering with the transfer of DC power to the radio/amplifier.
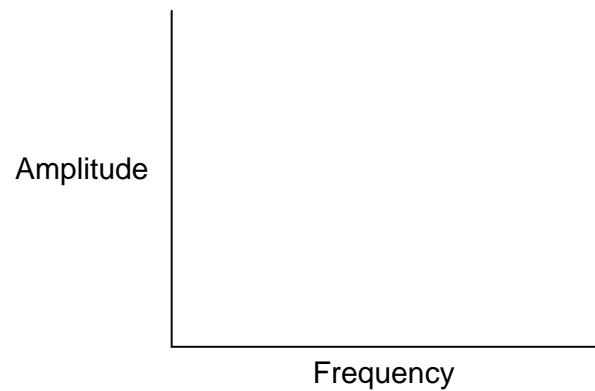
Notes 110

The follow-up question is yet another example of how practical the superposition theorem is when analyzing filter circuits.
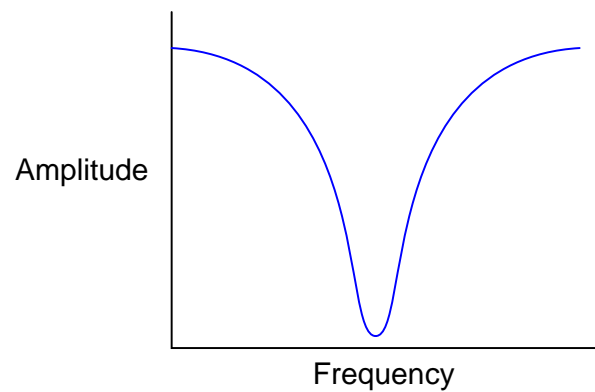
148

Question 111

Plot the typical response of a band-stop filter circuit, showing signal output (amplitude) on the vertical axis and frequency on the horizontal axis:
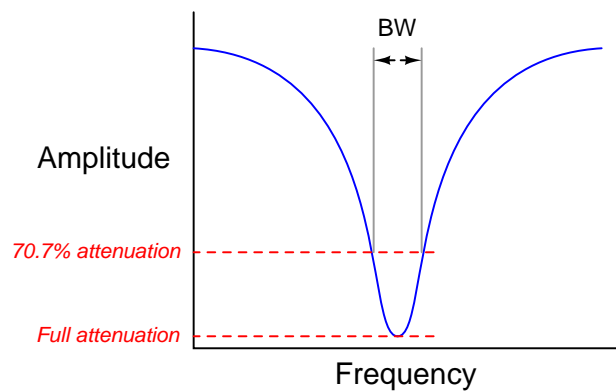

Also, identify and label the *bandwidth* of the circuit on your filter plot.

<u>file 01951</u>

Answer 111

The bandwidth of a band-stop filter circuit is that range of frequencies where the output amplitude is reduced to at least 70.7% of full attenuation:

Bandwidth is an important concept in electronics, for more than just filter circuits. Your students may discover references to bandwidth of amplifiers, transmission lines, and other circuit elements as they do their research. Despite the many and varied applications of this term, the principle is fundamentally the same.
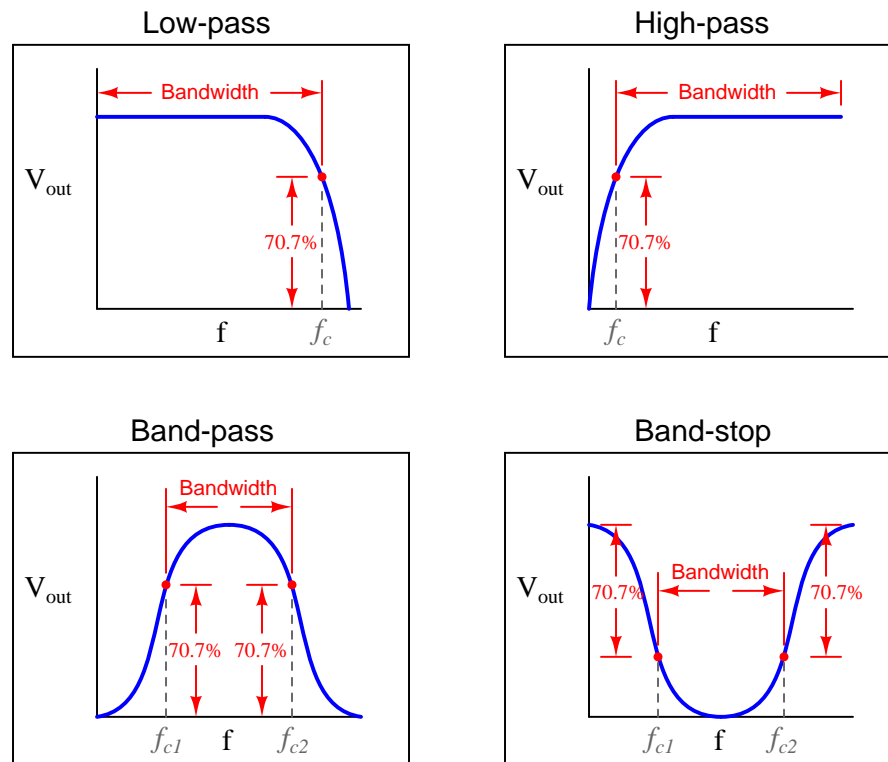
Plot the typical frequency responses of four different filter circuits, showing signal output (amplitude) on the vertical axis and frequency on the horizontal axis:

Low-pass

V_{out}

f

High-pass

V_{out}

f

Band-pass

V_{out}

f

Band-stop

V_{out}

f
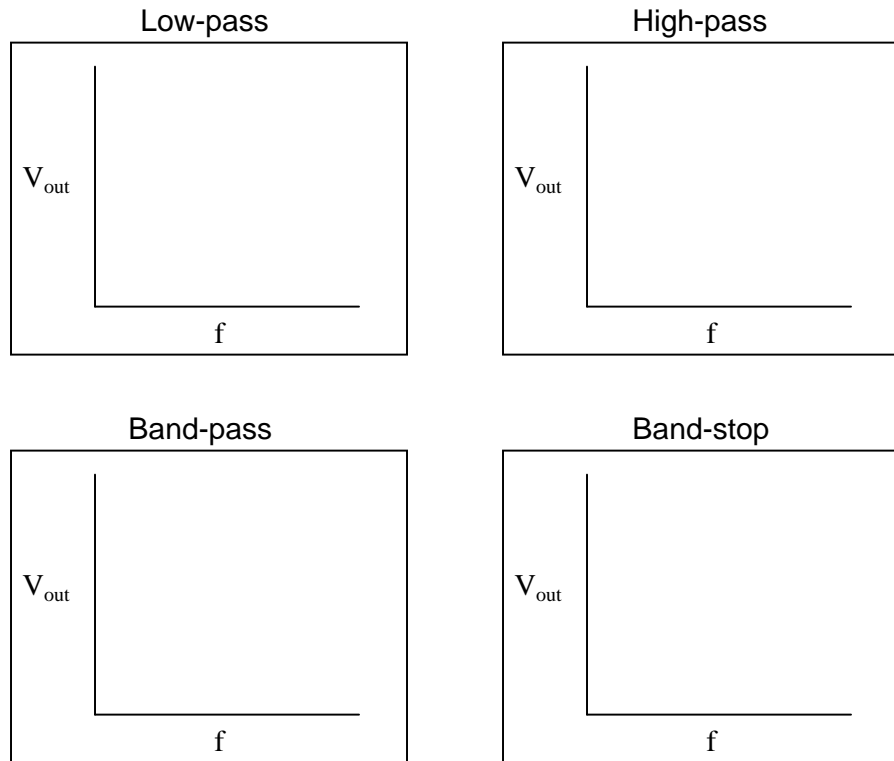
Also, identify and label the *bandwidth* of the filter circuit on each plot.
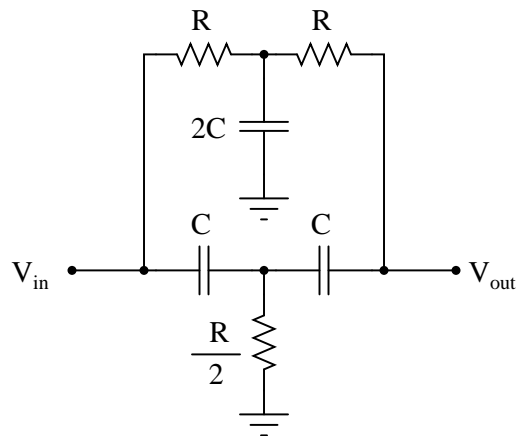<u>file 02571</u>

Although "bandwidth" is usually applied first to band-pass and band-stop filters, students need to realize that it applies to the other filter types as well. This question, in addition to reviewing the definition of bandwidth, also reviews the definition of cutoff frequency. Ask your students to explain where the 70.7% figure comes from. Hint: *half-power* point!

Question 113

The following circuit is called a *twin-tee* filter:

Research the equation predicting this circuit's "notch" frequency, given the component value ratios shown.

$$f_{notch} =$$

<u>file 02579</u>

Answer 113

$$f_{notch} = \frac{1}{2\pi RC}$$

Notes 113

Answering this question is simply a matter of research! There are many references a student could go to for information on twin-tee filters.