

ELTR 115 (AC 2), section 1

Recommended schedule

Day 1

Topics: *Mutual inductance and transformer theory*

Questions: *1 through 15*

Lab Exercise: *Transformer voltage/current ratios (question 61)*

Explain suggested project ideas to students

Give project grading rubric to students, complete with deadlines

Day 2

Topics: *Transformer step ratio*

Questions: *16 through 30*

Lab Exercise: *Auto-transformers (question 62)*

MIT 8.02 video clip: Disk 4, Lecture 24; Transformer w/ loose wire 34:13 to 36:40

MIT 8.02 video clip: Disk 4, Lecture 24; Shorted transformer 40:03 to 41:50

MIT 8.02 video clip: Disk 4, Lecture 24; Ruhmkorff coil demo 47:45 to end

Day 3

Topics: *Maximum power transfer theorem and impedance matching with transformers*

Questions: *31 through 45*

Lab Exercise: *Auto-transformers (question 63)*

Day 4

Topics: *Transformer applications, power ratings, and core effects*

Questions: *46 through 60*

Lab Exercise: *Differential voltage measurement using the oscilloscope (question 64)*

Demo: show a current transformer, and a clamp-on AC ammeter

Day 5

Exam 1: *includes Transformer voltage ratio performance assessment*

Lab Exercise: *work on project*

Project: *Initial project design checked by instructor and components selected (sensitive audio detector circuit recommended)*

Practice and challenge problems

Questions: *66 through the end of the worksheet*

Impending deadlines

Project due at end of ELTR115, Section 3

Question 65: Sample project grading criteria

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Project ideas

AC power supply: (*Strongly Recommended!*) This is basically one-half of an AC/DC power supply circuit, consisting of a line power plug, on/off switch, fuse, indicator lamp, and a step-down transformer. The reason this project idea is strongly recommended is that it may serve as the basis for the recommended power supply project in the next course (ELTR120 – Semiconductors 1). If you build the AC section now, you will not have to re-build an enclosure or any of the line-power circuitry later! Note that the first lab (step-down transformer circuit) may serve as a prototype for this project with just a few additional components.

Sensitive audio detector: A test device used to listen (audibly) to AC signals in the audio-frequency range. Highly recommended, as it provides a great learning experience as well as a very useful piece of test equipment for your personal projects, especially when working on audio amplifiers. May be expensive due to the need for a pair of closed-cup headphones.

LED blinking circuit: Recommended for advanced students only, as it involves semiconductor components which have not been covered yet. May be designed around an astable multivibrator circuit, or a 555 timer chip. Ask instructor for design details.

Signal generator circuit: Recommended for advanced students only, as it involves the use of at least one integrated circuit "chip." There are multiple signal generator chips on the market, all of which are fairly easy to configure and use with no knowledge of their internal operation.

ELTR 115 (AC 2), section 1

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.14** Understand principles and operations of AC circuits using transformers.
- C.15** Demonstrate an understanding of impedance matching theory.
- C.16** Fabricate and demonstrate AC circuits using transformers.
- C.17** Troubleshoot and repair AC circuits using transformers.

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: *Rates of change.*

When studying electromagnetic induction and Lenz's Law, one must think in terms of how fast a variable is changing. The amount of voltage induced in a conductor is proportional to how *quickly* the magnetic field changes, not how strong the field is. This is the first hurdle in calculus: to comprehend what a rate of change is, and it is not obvious.

The best examples I know of to describe rates of change are *velocity* and *acceleration*. Velocity is nothing more than a rate of change of position: how quickly one's position is changing over time. Therefore, if the variable x describes position, then the derivative $\frac{dx}{dt}$ (rate of change of x over time t) must describe velocity. Likewise, acceleration is nothing more than the rate of change of velocity: how quickly velocity changes over time. If the variable v describes velocity, then the derivative $\frac{dv}{dt}$ must describe velocity. Or, since we know that velocity is itself the derivative of position, we could describe acceleration as the *second derivative* of position: $\frac{d^2x}{dt^2}$.

Common mistake: *Reversing transformer ratios.*

Many transformer problems are nothing more than exercises in mathematical ratios. Once students become comfortable manipulating these ratios to solve for voltages, currents, and/or winding turns, it is easy. Unfortunately, it is also very easy to accidentally reverse the ratios (e.g. 3 to 1 instead of 1 to 3). With regard to voltage and current for both sides of a transformer, there is a very simple way to check your work. Like all passive devices, transformers can never output more power than they input. And because they are efficient, their output power is rarely less than 90% of their input power. For many practice problems, 100% efficiency is assumed, so output power must be the same as input power. To check your voltage and current calculations, figure out primary power from primary voltage and primary current, then do the same for the secondary side. The two power calculations should match!

Common mistake: *Failing to respect shock hazard of line-powered circuits.*

For those students who choose to build the line-powered AC power supply, it is good to review the principles of electrical safety. Unlike nearly all the previous labs which harbored little or no shock hazard, this project can shock you. The most important rule you can follow is to simply unplug the circuit from the AC line before reaching toward any part of the circuit with your hand or with a conductive tool. The only things you should touch a live circuit with are test probes for measurement equipment! Another common mistake is to fail to remove conductive jewelry (bracelets, rings, etc.) prior to working with line-powered circuits.

Question 1

If one coil of wire is located very close to another coil of wire, and an electric current is passed through the first coil whose magnitude changes over time, what phenomenon will occur in the second coil of wire?

file 00462

Answer 1

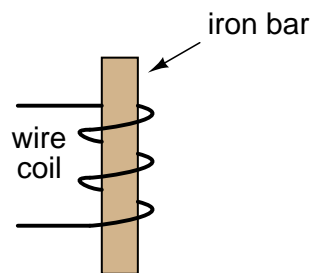
A voltage will be induced in the second coil: *mutual induction*.

Notes 1

Be sure that students understand the answer to this question beyond saying the phrase, "mutual induction." What, exactly, does this phrase mean? Reciting an equation is not a sufficient explanation, either. Ask them what some of the factors are that influence the strength of the mutual inductive effect.

Question 2

Write the equation describing the voltage induced in this coil, solving for (instantaneous) induced voltage (e) in terms of the instantaneous magnetic flux (ϕ) and the number of turns of wire in the coil:



file 00463

Answer 2

$$e = N \frac{d\phi}{dt}$$

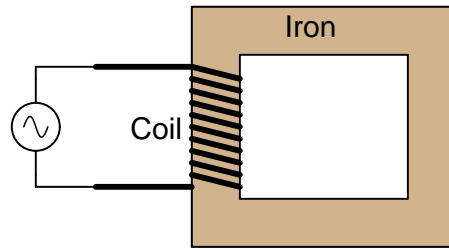
Follow-up question: algebraically manipulate this equation to solve for the number of turns (N) given all the other quantities.

Notes 2

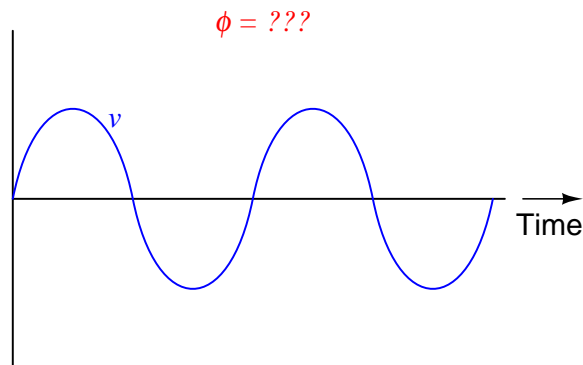
It should be noted that in this particular case, N is equal to three (counting the turns in the illustrated coil).

Question 3

If a coil of insulated wire is wrapped around an iron core, an inductance will be formed. Even if the wire has negligible resistance, the current through the coil from an AC source will be limited by the inductive reactance (X_L) of the coil, as the magnetic flux in the iron core oscillates back and forth to induce a counter-EMF:

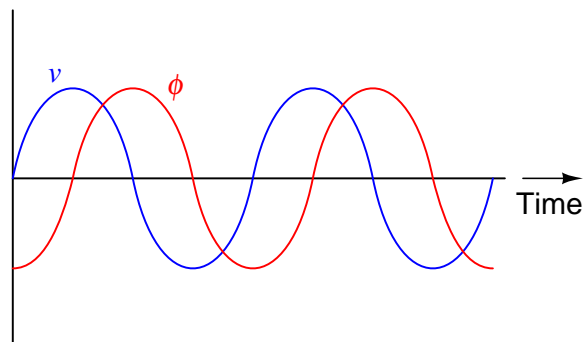


Plot the instantaneous magnetic flux (ϕ) waveform in the iron core corresponding to the instantaneous applied voltage (v) shown in this graph:



file 01875

Answer 3

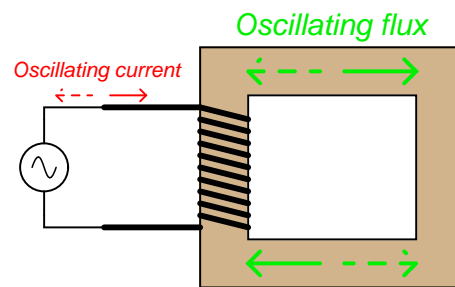


Notes 3

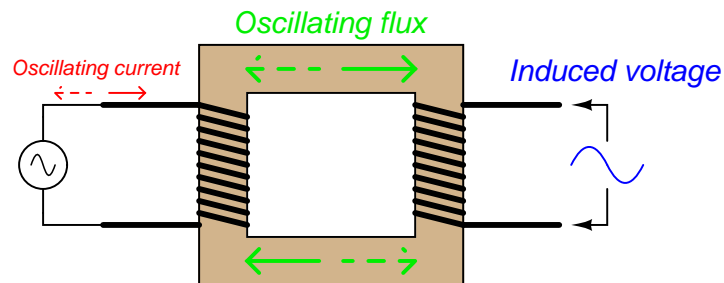
There is a simple formula (albeit containing a derivative term) describing the relationship between instantaneous flux (ϕ) and instantaneous induced voltage (v). Your students ought to know what it is, and that it should be applied to this question!

Question 4

If we energize an inductor's coil with an oscillating (AC) voltage, we will generate an oscillating magnetic flux in the inductor core:

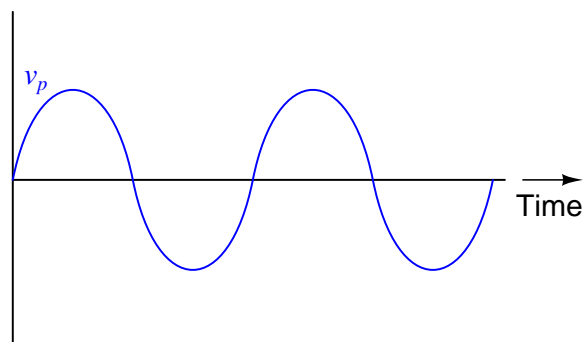


If we wrap a second coil of wire around the same magnetic core as the first (inductor) coil, we set up a situation where mutual inductance exists: a change of current through one coil induces a voltage in the other, and visa-versa. This, obviously, will result in an AC voltage being induced in the second wire coil:



What name is given to such a device, with two coils of wire sharing a common magnetic flux? Also, plot both the magnetic flux waveform and the secondary (induced) voltage waveform on the same graph as the primary (applied) voltage waveform:

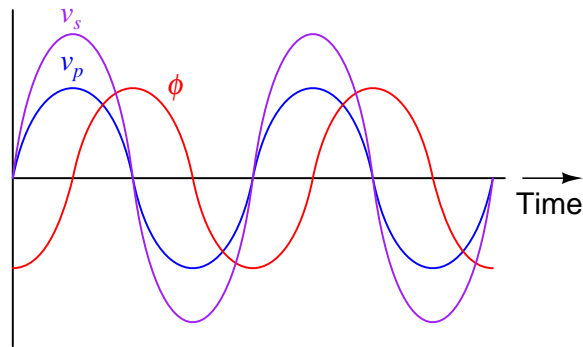
$$v_s = ???$$
$$\phi = ???$$



file 01876

Answer 4

This device is called a *transformer*.



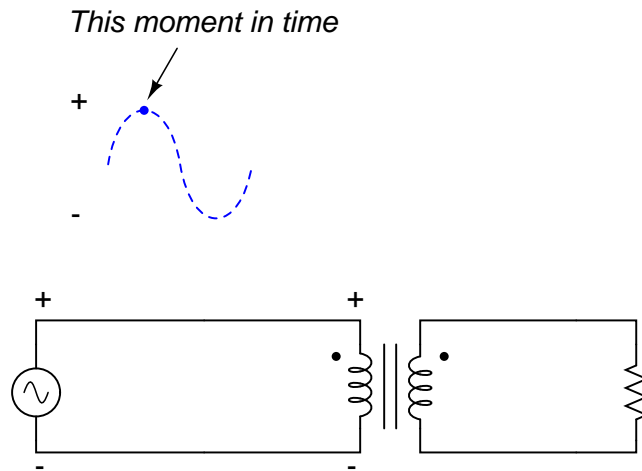
Note: the relative amplitudes of v_p and v_s are arbitrary. I drew them at different amplitudes for the benefit of the reader: so the two waveforms would not perfectly overlap and become indistinguishable from one another.

Notes 4

Ask your students how the secondary coil would have to be made in order to truly generate a voltage greater than the applied (primary) coil voltage. How about generating a secondary voltage less than the primary?

Question 5

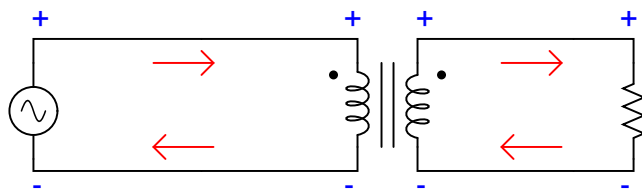
Shown here is a schematic diagram of a transformer powering a resistive load, at the exact moment in time where the primary winding's voltage is at its positive (+) peak:



Identify the polarity of voltage across the load resistor at this exact moment in time, as well as the direction of current in each of the windings.

file 00490

Answer 5



Note: *The direction of current shown assumes "conventional flow" notation, not "electron flow" notation!*

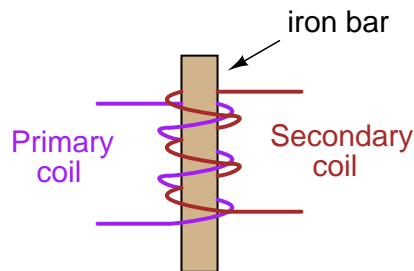
Follow-up question: note the relationship between direction of current and polarity of voltage for each of the transformer windings. What do these different relationships suggest, in regard to the "flow" of power in the circuit?

Notes 5

One perspective that may help students understand the directions of current through each winding of the transformer, in relation to the voltage polarities, is to think of each winding as either being a *source* of electrical power or a *load*. Ask your students, "which winding acts as a *source* in this circuit, and which one acts as a *load*?" Imagine these sources and loads are DC (so we may maintain the same polarity of voltage, for the sake of analysis). Which way would you draw the currents for a DC source and for a DC load?

Question 6

There are two wire windings wrapped around a common iron bar in this illustration, such that whatever magnetic flux may be produced by one winding is fully shared by the other winding:



Write two equations describing the induced voltage at each winding ($e_p = \dots$ and $e_s = \dots$), in each case expressing the induced voltage in terms of the instantaneous magnetic flux (ϕ) and the number of turns of wire in that winding (N_p and N_s , respectively).

Then, combine these two equations, based on the fact that the magnetic flux is equal for each winding.
[file 00464](#)

Answer 6

$$e_p = N_p \frac{d\phi}{dt}$$

$$e_s = N_s \frac{d\phi}{dt}$$

Then, combining the two equations:

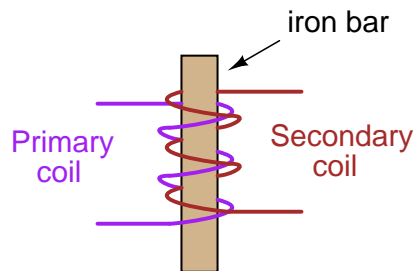
$$\frac{e_p}{N_p} = \frac{e_s}{N_s}$$

Notes 6

Obtaining the last equation is an application of the mathematical truth that quantities equal to the same thing are equal to each other (if $a = c$ and $b = c$, then $a = b$).

Question 7

There are two wire windings wrapped around a common iron bar in this illustration, such that whatever magnetic flux may be produced by one winding is fully shared by the other winding:



Write two equations describing the induced voltage at each winding ($e_p = \dots$ and $e_s = \dots$), in each case expressing the induced voltage in terms of the instantaneous current through that winding (i_p and i_s , respectively) and the inductance of each winding (L_p and L_s , respectively).

We know that the induced voltages in the two windings are related to each other by this equation, if there is perfect "coupling" of magnetic flux between the two windings:

$$\frac{e_p}{N_p} = \frac{e_s}{N_s}$$

Knowing this, write two more equations describing induced voltage, this time expressing the induced voltage in each winding in terms of the instantaneous current in the *other* winding. In other words,

$$e_p = \dots i_s$$

$$e_s = \dots i_p$$

file 00465

Answer 7

Equations describing self-inductance:

$$e_p = L_p \frac{di_p}{dt}$$

$$e_s = L_s \frac{di_s}{dt}$$

Equations describing inductance from one winding to the other:

$$e_p = L_s \frac{N_p}{N_s} \frac{di_s}{dt}$$

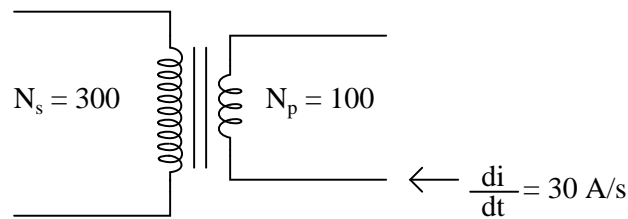
$$e_s = L_p \frac{N_s}{N_p} \frac{di_p}{dt}$$

Notes 7

The first two equations are mere review. The second two equations require algebraic manipulation and substitution between equations.

Question 8

Suppose two wire coils are wound around a common iron core, the "primary" coil with 100 turns of wire and the "secondary" coil with 300 turns of wire:



If the inductance of the primary coil is 2 H, what is the inductance of the secondary coil, assuming that it "sees" the exact same magnetic circuit as the first coil (same permeability, same cross-sectional area, same length)?

If an electric current changing at a rate of 30 amps per second passes through the primary coil, how much voltage will be induced in *each* coil?

If only half the lines of magnetic flux from the primary coil "coupled" with the secondary coil, how much voltage would be induced in the secondary coil, given a primary current rate-of-change of 30 amps per second?

file 00466

Answer 8

$$L_s = 18 \text{ H}$$

$$e_p = 60 \text{ volts}$$

$$e_s = 180 \text{ volts}$$

If only half the lines of flux coupled the two coils ($k = 0.5$), then $e_s = 90$ volts.

Follow-up question: what do you notice about the ratio of primary and secondary *inductances* compared with primary and secondary *winding turns*? Can you generalize this in the form of an equation?

Notes 8

The key to this question is determining the ratio of inductances, based on the ratio of turns in the windings. As the answer reveals, it is a nonlinear proportionality. The sentence where I specify the "same permeability, same cross-sectional area, same length" is a hint to students for what equation they need to find in order to identify the relationship between wire turns and inductance.

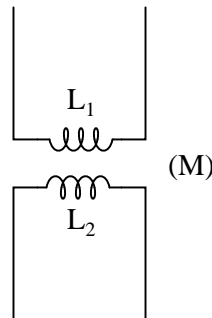
Question 9

Mutual inductance is the term given to the phenomenon where a change in current through one inductor causes a voltage to be induced in another. When two inductors (L_1 and L_2) are magnetically "coupled," the mutual inductance (M) relates their voltages and currents as such:

$$e_1 = M \frac{di_2}{dt} \quad \text{Voltage induced in coil 1 by change of current in coil 2}$$

$$e_2 = M \frac{di_1}{dt} \quad \text{Voltage induced in coil 2 by change of current in coil 1}$$

Mutually coupled inductances



When the magnetic coupling between the two inductors is perfect ($k = 1$), how does M relate to L_1 and L_2 ? In other words, write an equation defining M in terms of L_1 and L_2 , given perfect coupling.

Hint:

$$e_1 = L_2 \frac{N_1}{N_2} \frac{di_2}{dt}$$

$$e_2 = L_1 \frac{N_2}{N_1} \frac{di_1}{dt}$$

$$\frac{L_1}{L_2} = \left(\frac{N_1}{N_2} \right)^2$$

file 00468

Answer 9

$$M = \sqrt{L_1 L_2}$$

Challenge question: is mutual inductance expressed in the same unit of measurement that self-inductance is? Why or why not?

Notes 9

The solution to this question involves quite a bit of algebraic manipulation and substitution. Of course, it may also be found in many basic electronics textbooks, but the point of this question is for students to see how it may be derived from the equations they already know.

Question 10

The coefficient of magnetic coupling between two coils affects the amount of mutual inductance between those two coils. This fact should be obvious, as coils not sharing any magnetic flux ($k = 0$) cannot have any mutual inductance between them.

Write an equation defining M in terms of L_1 and L_2 , when k is something less than 1.

file 01874

Answer 10

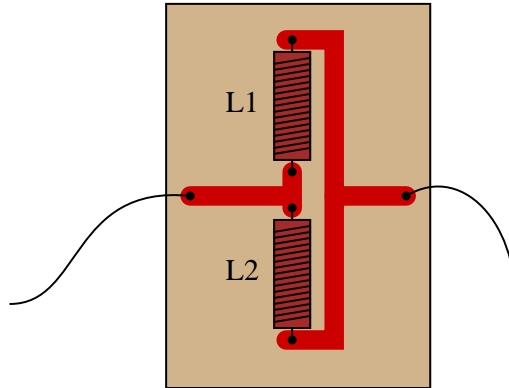
$$M = k\sqrt{L_1 L_2}$$

Notes 10

Ask your students *how* they obtained their answer. Of course this equation may be found in many basic electronics textbooks, but the point of this question is for students to see how it may be *derived* from the equations they already know.

Question 11

Suppose a technician needs 167 mH of inductance in a circuit, but only has 500 mH and 250 mH inductors on hand. He decides he should be able to achieve approximately 167 mH of inductance easily enough by connecting these two inductors in parallel with one another on a printed circuit board:



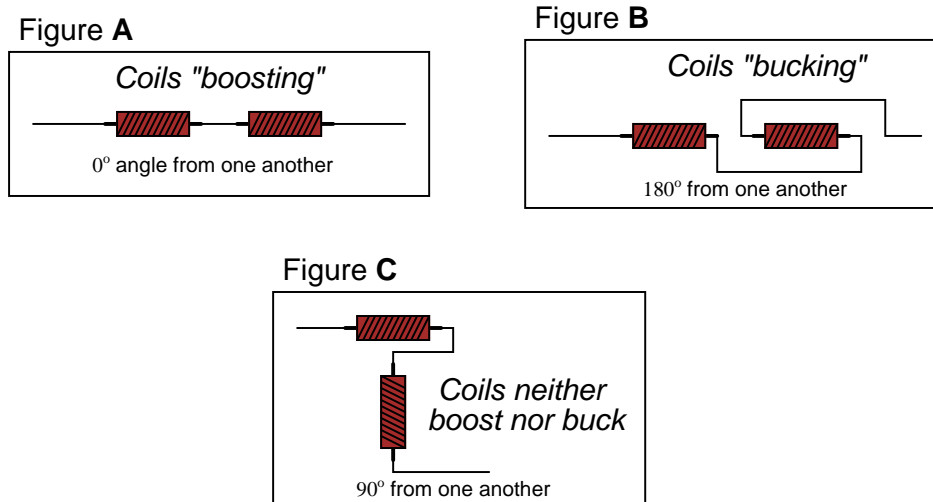
However, upon testing this parallel inductor arrangement, the technician finds the total inductance to be significantly *less* than the 167 mH predicted. Puzzled, he asks a fellow technician for help. The other technician inspects the board, and immediately suggests that the two inductors be re-located with their axes perpendicular to one another. The first technician doesn't understand why the physical location of the inductors should matter. After all, it never mattered how he located resistors and capacitors with respect to one another, so long as their connecting wires (or board traces) went to the right places. Can you explain to him why inductors might be sensitive to physical orientation?

[file 01285](#)

Answer 11

Presently, the respective magnetic fields from the two inductors are linking with each other in an opposing manner!

Follow-up question: coils placed in linear proximity to one another will magnetically "link" in such a way as to either "boost" (Figure A) or "buck" (Figure B) one another. If placed perpendicular (90°) to one another, the magnetic linking is nonexistent and the two inductors act as independent entities:



What trigonometric function (sine, cosine, tangent, cotangent, secant, cosecant) follows this same pattern: full positive at 0° , full negative at 180° , and zero at 90° ?

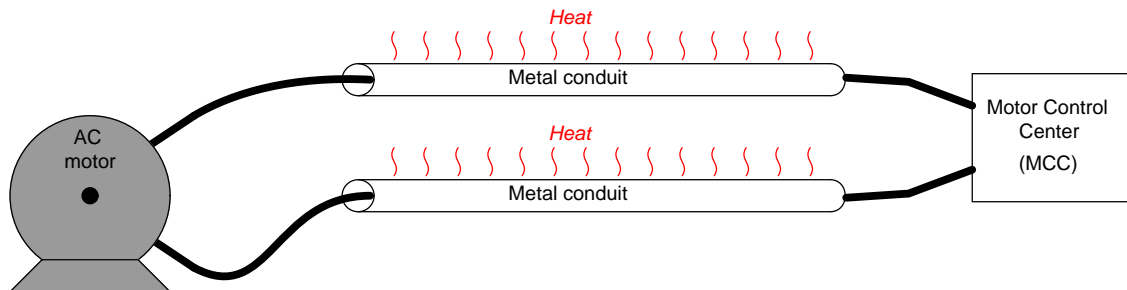
Notes 11

A potential point of confusion here is that some students may think the orientation being spoken of is absolute: with reference to the earth's magnetic field. What I'm trying to get them to see, however, is the relationship between the two coils' magnetic fields, which is an entirely different matter. To expose this misunderstanding, ask your students whether or not the position of the printed circuit board with respect to compass directions (north, south, east, or west) would have any effect on these two inductors' combined inductance. For those who mistakenly answer "yes" to this question, review Faraday's Law of electromagnetic induction: that induced voltage only occurs when there is a *change* of magnetic flux over time, and that the earth's magnetic field is constant (for all practical purposes).

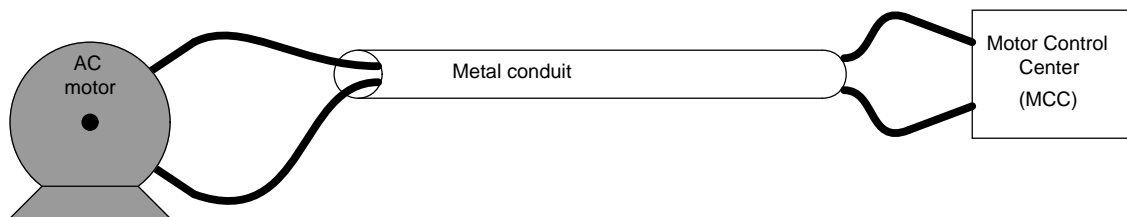
The follow-up question gets students thinking in terms of the mutual inductance as a function of the physical angle between the two inductors, and relating a pattern (analyzed at three points) to common trig functions. This form of reasoning is very useful in problem-solving, because the ability to see patterns as a function of a certain variable (such as an angle) is the first step in mathematically modeling a system.

Question 12

Mutual inductance can exist even in places where we would rather it not. Take for instance the situation of a "heavy" (high-current) AC electric load, where each conductor is routed through its own metal conduit. The oscillating magnetic field around each conductor induces currents in the metal conduits, causing them to resistively heat (Joule's Law, $P = I^2 R$):

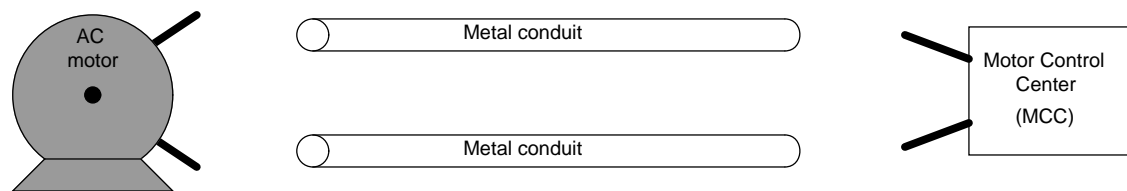


It is standard industry practice to avoid running the conductors of a large AC load in separate metal conduits. Rather, the conductors should be run in the same conduit to avoid inductive heating:



Explain why this wiring technique eliminates inductive heating of the conduit.

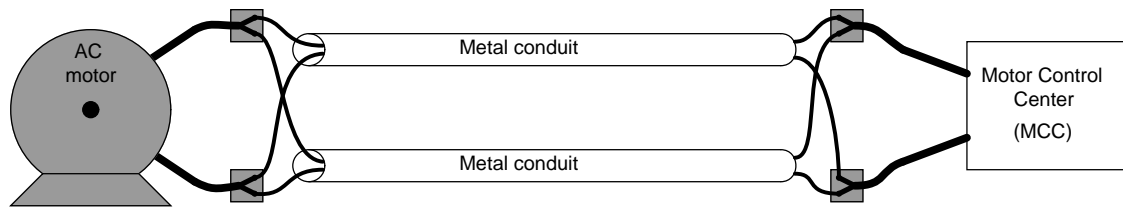
Now, suppose two empty metal conduits stretch between the location of a large electric motor, and the motor control center (MCC) where the circuit breaker and on/off "contactor" equipment is located. Each conduit is too small to hold both motor conductors, but we know we're not supposed to run each conductor in its own conduit, lest the conduits heat up from induction. What do we do, then?



file 00459

Answer 12

Use terminal blocks to "split up" the conductors from one pair into two pairs:

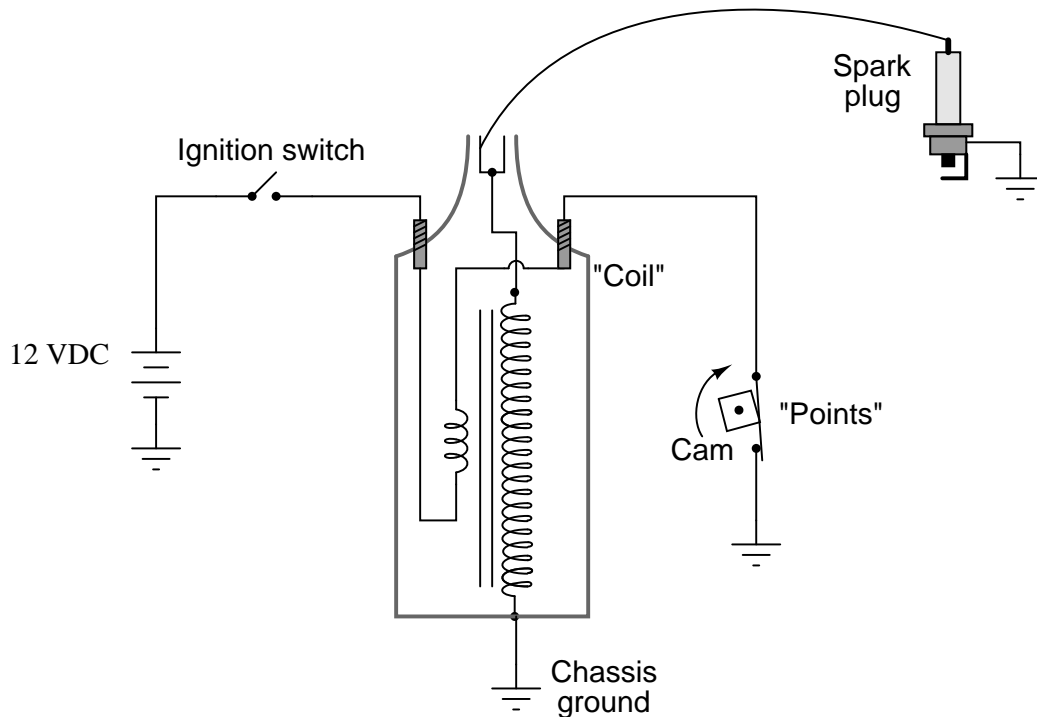


Notes 12

This wiring technique is very commonly used in industry, where conductor gauges for high-horsepower electric motors can be quite large, and conduits never quite large enough.

Question 13

The *ignition coil* of a gasoline-powered internal combustion automobile engine is an example of a transformer, although it is not powered by alternating current. Explain how a transformer may be operated on electricity that is *not* AC:



file 00251

Answer 13

In order for a transformer to function, the primary winding current must change rapidly with regard to time. Whether this is a current that truly alternates, or just one that *pulses* in the same direction, is irrelevant.

Challenge question: is the wave-shape of the secondary voltage sinusoidal? Why or why not?

Notes 13

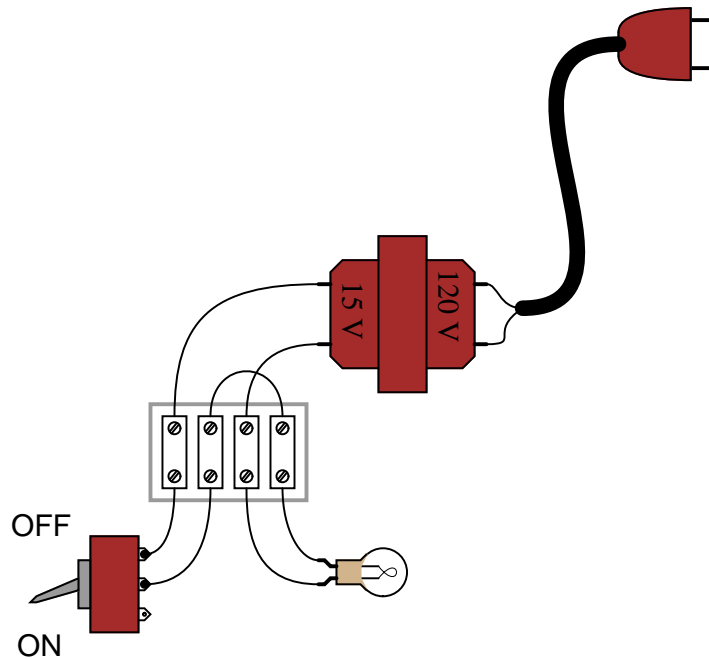
This is a very common application of transformer technology: the ignition "coil" used to ignite the air-fuel mixture inside a gasoline engine's combustion chamber. This question also addresses an issue sometimes misunderstood by students, that transformers are fundamentally AC devices, not DC.

It might be a good idea to have an automotive ignition coil available for classroom demonstration. In lieu of a spark plug, a neon lamp may be used to indicate the presence of high voltage.

As for answering the challenge question, an oscilloscope will quickly prove the nature of the waveshape, for any transformer energized with pulsating DC.

Question 14

Something has failed in this circuit, because the light bulb does not light up when the switch is closed:



What type(s) of transformer fault(s) would cause a problem like this, and how might you verify using a multimeter?

file 00249

Answer 14

The most common type of transformer fault causing a problem like this is an *open* winding. This is very easy to check using a multimeter (I'll let you answer this part of the question!).

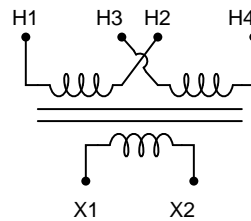
Notes 14

Of course, faults in this circuit having nothing to do with the transformer could also prevent the light bulb from lighting. If time permits, it would be good to analyze a few failure scenarios with your students, challenging them to locate the source of the trouble as efficiently as possible.

Question 15

Industrial *control power transformers* are used to step down 480 or 240 volts to a level more acceptable for relay control circuitry: usually 120 volts. Some control power transformers are built with multiple primary windings, to facilitate connection to either a 480 volt or 240 volt AC power source:

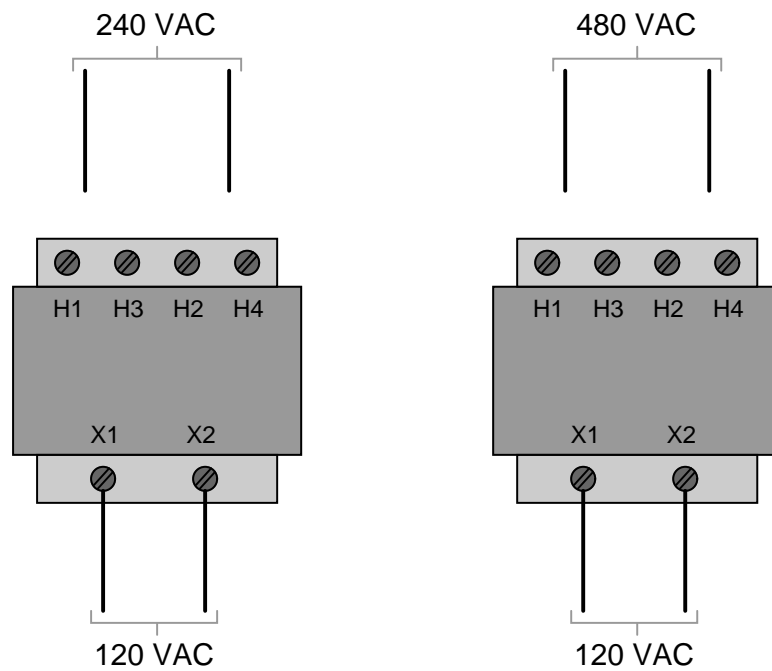
240 × 480 primary



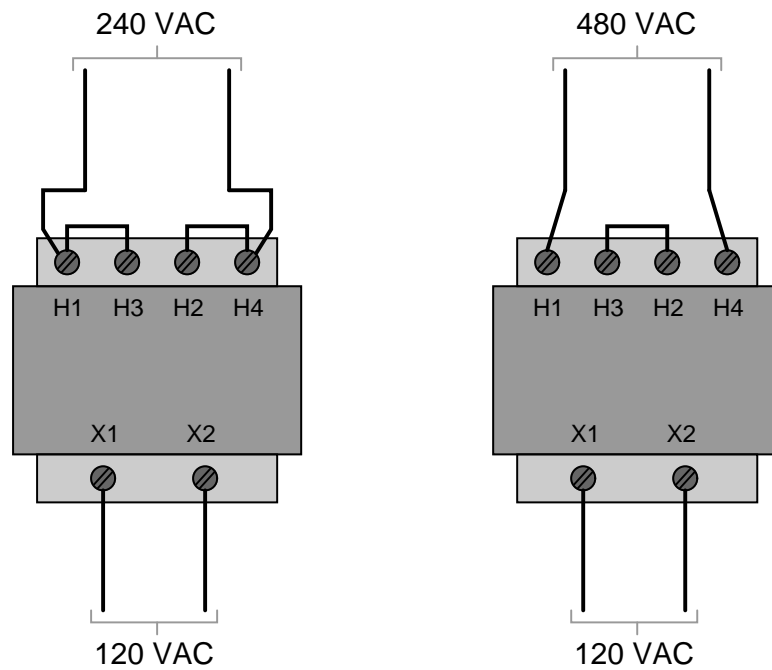
120 secondary

Such transformers are usually advertised as having "240 × 480" primary windings, the "×" symbol representing two independent windings with four connection points (H1 through H4).

Show the connections on the four "H" terminals necessary for 240 volt operation, and also for 480 volt operation, on the following illustrations:



file 01569



This type of transformer is *very* common in industrial control systems. Discuss with your students why the primary winding terminals are arranged as they are (H1-H3-H2-H4), to facilitate near-terminal jumpering with metal clips.

Question 16

Suppose 1200 turns of copper wire are wrapped around one portion of an iron hoop, and 3000 turns of wire are wrapped around another portion of that same hoop. If the 1200-turn coil is energized with 15 volts AC (RMS), how much voltage will appear between the ends of the 3000-turn coil?

file 00246

Answer 16

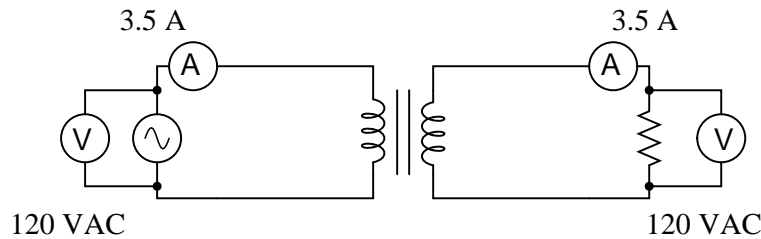
37.5 volts AC, RMS.

Notes 16

Transformer winding calculations are simply an exercise in mathematical ratios. If your students are not strong in their ratio skills, this question provides an application to sharpen them!

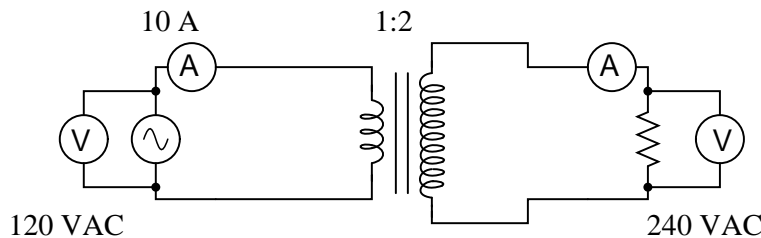
Question 17

If an *isolation transformer* (a transformer with the same number of "turns" in the primary and secondary coils) is connected between an AC source and an AC load, we will measure the same voltage and the same current at both source and load terminals:



If we calculate power output by the source and power dissipated by the load, the value is the same: 420 Watts ($P = IV$).

Now suppose we analyze a circuit containing a *step-up* transformer (one with more turns of wire in the secondary coil than in the primary coil). With a step-up transformer, the load voltage will be greater than the supply voltage. In this example, I show a step-up transformer with a 1:2 step ratio:



Assuming the load resistance is completely different from the first (isolation transformer) circuit, what can you deduce about the load current and the power (both source and load) in this circuit? Is the load current less than the source current? Is the load current greater than the source current? Is the load power greater than the source power? Explain your answers.

[file 01877](#)

Answer 17

The basic physical law known as *The Law of Conservation of Energy* tells you all you need to know about source power and load power! And from that, you should not only be able to qualitatively determine the load current in this circuit, but also calculate it with a fair degree of precision.

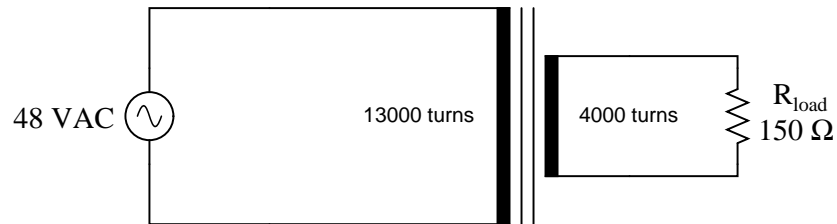
Notes 17

The only reason I hesitate to tell students they can calculate load current *precisely* is because it was not stated whether or not the transformer is "lossy" at all. No real transformer is 100% lossless, of course, and this is something that we must take into consideration in "real life."

I have found that the Conservation of Energy approach not only makes sense to students as they learn to calculate transformer behavior, but it is an excellent reinforcement of a basic physical law, a good understanding of which will serve them well throughout their careers.

Question 18

Calculate all listed values for this transformer circuit:



- $V_{primary} =$
- $V_{secondary} =$
- $I_{primary} =$
- $I_{secondary} =$

Explain whether this is a *step-up*, *step-down*, or *isolation* transformer, and also explain what distinguishes the "primary" winding from the "secondary" winding in any transformer.

file 01878

Answer 18

- $V_{primary} = 48$ volts
- $V_{secondary} = 14.77$ volts
- $I_{primary} = 30.3$ mA
- $I_{secondary} = 98.5$ mA

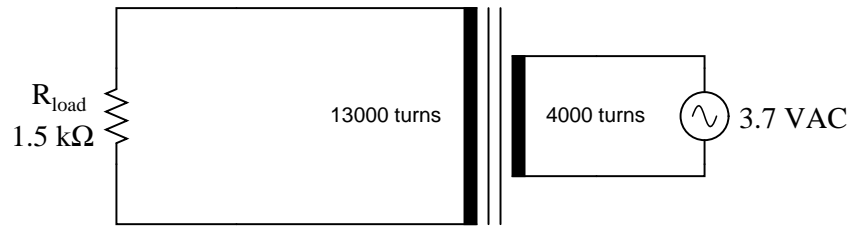
This is a *step-down* transformer.

Notes 18

Most transformer problems are nothing more than ratios, but some students find ratios difficult to handle. Questions such as this are great for having students come up to the board in the front of the classroom and demonstrating how they obtained the results.

Question 19

Calculate all listed values for this transformer circuit:



- $V_{primary} =$
- $V_{secondary} =$
- $I_{primary} =$
- $I_{secondary} =$

Explain whether this is a *step-up*, *step-down*, or *isolation* transformer, and also explain what distinguishes the "primary" winding from the "secondary" winding in any transformer.

file 01879

Answer 19

- $V_{primary} = 3.7\text{ volts}$
- $V_{secondary} = 12.0\text{ volts}$
- $I_{primary} = 26.1\text{ mA}$
- $I_{secondary} = 8.02\text{ mA}$

This is a *step-up* transformer.

Notes 19

Most transformer problems are nothing more than ratios, but some students find ratios difficult to handle. Questions such as this are great for having students come up to the board in the front of the classroom and demonstrating how they obtained the results.

Note to your students how the distinction between a step-up and a step-down transformer is simply a matter of usage. It is possible to use a transformer either way!

Question 20

In a typical step-up or step-down transformer, the higher-voltage winding usually uses finer gauge wire than the lower-voltage winding. Explain why this is.

file 00248

Answer 20

The higher-voltage winding handles less current than the lower-voltage winding.

Notes 20

If you happen to have a transformer that has been cut in half (right through the core), it will make an excellent demonstration piece for discussion. The difference between windings will be immediately apparent to the students when they see one.

Question 21

A mechanic goes to school and takes a course in AC electric circuits. Upon learning about step-up and step-down transformers, he makes the remark that "Transformers act like electrical versions of gears, with different ratios."

What does the mechanic mean by this statement? What exactly is a "gear ratio," and is this an accurate analogy for a transformer?

file 00253

Answer 21

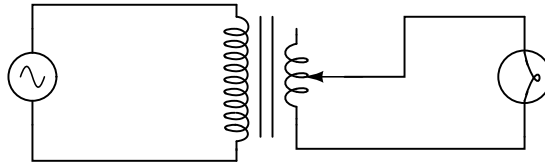
Just as meshing gears with different tooth counts transform mechanical power between different levels of speed and torque, electrical transformers transform power between different levels of voltage and current.

Notes 21

Not only is this a sound analogy, but one that many mechanically-minded people relate with easily! If you happen to have some mechanics in your classroom, provide them with the opportunity to explain the concept of gear ratios to those students who are unaware of gear system mathematics.

Question 22

Explain how this special transformer is able to control power to the light bulb:



What advantages might there be to using a transformer to control AC power, as opposed to a variable resistor?

Note: a similar type of device is called a *Variac*, and it enjoys the same advantages of AC power control as the variable transformer shown in the question.

[file 00252](#)

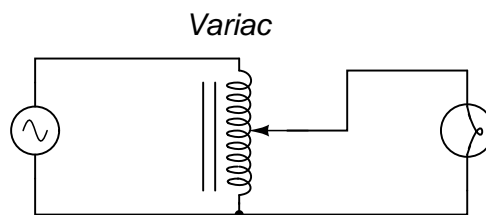
Answer 22

This transformer controls power to the light bulb by providing a variable voltage ratio between source and load.

Notes 22

It may help to give some numerical examples of voltage step-down ratio for the transformer in this circuit, for students to better understand how this device controls light bulb power. Remind your students that modern transformers are very efficient devices, with full-load efficiency ratings typically in excess of 95%.

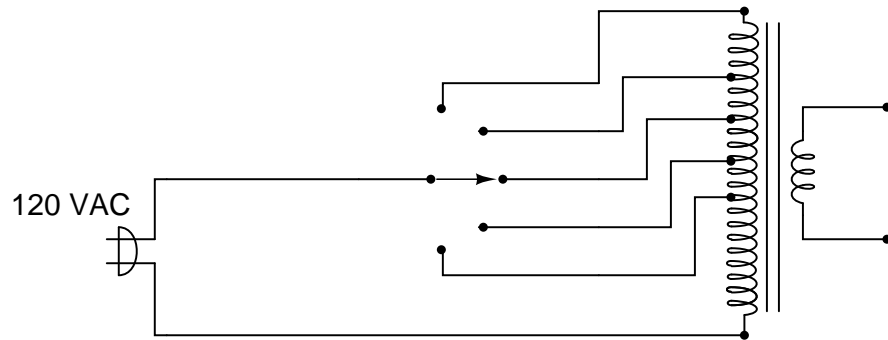
If students ask about the Variac, you may want to show them this diagram:



Of course, the Variac is a type of *autotransformer*, and as such does not provide the electrical isolation of a regular transformer. In some instances, this may be important!

Question 23

In this variable-voltage transformer circuit, the input voltage (120 VAC) is switched to different "taps" on the transformer's primary winding to create different step-down ratios.



While it is possible to "tap" the secondary winding of the transformer to achieve different output voltages instead of the primary, there is a good reason for locating the switch in the primary side of the circuit. Identify this practical reason.

file 00050

Answer 23

To minimize the amount of current the switch contacts have to handle.

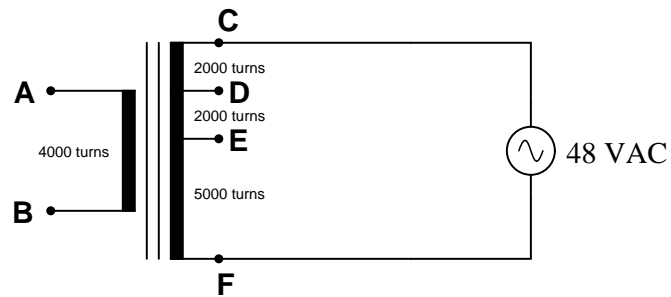
Notes 23

It is important to always keep in mind practical limitations of components such as switch contacts when designing circuits. Sure, there may be many alternative ways of building a working circuit, but some ways will be more practical than others.

In some cases, it might be better to locate the switch (and winding taps) on the secondary side of a step-down transformer rather than the primary. Imagine if the primary winding voltage was 100 kVAC instead of 120 VAC. Pose this scenario to your students and ask them what practical switch limitations might force re-location to the secondary winding of the transformer.

Question 24

How much voltage is there between the following pairs of points in this circuit?



- Between **C** and **F**: $V_{CF} =$
- Between **A** and **B**: $V_{AB} =$
- Between **D** and **E**: $V_{DE} =$
- Between **D** and **F**: $V_{DF} =$

file 00667

Answer 24

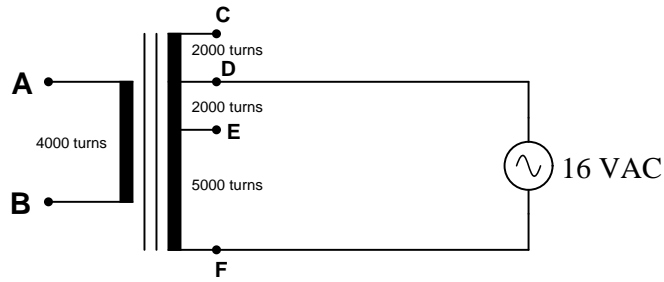
- Between **C** and **F**: $V_{CF} = 48 \text{ V}$
- Between **A** and **B**: $V_{AB} = 21.33 \text{ V}$
- Between **D** and **E**: $V_{DE} = 10.67 \text{ V}$
- Between **D** and **F**: $V_{DF} = 37.33 \text{ V}$

Notes 24

This question checks students' ability to relate the winding ratios of a transformer to voltages in the circuit. The symbolism here is common in Europe, but not so common in the United States.

Question 25

How much voltage is there between the following pairs of points in this circuit?



- Between **D** and **F**: $V_{DF} =$
- Between **A** and **B**: $V_{AB} =$
- Between **D** and **E**: $V_{DE} =$
- Between **C** and **F**: $V_{CF} =$

file 00668

Answer 25

- Between **D** and **F**: $V_{DF} = 16 \text{ V}$
- Between **A** and **B**: $V_{AB} = 9.14 \text{ V}$
- Between **D** and **E**: $V_{DE} = 4.57 \text{ V}$
- Between **C** and **F**: $V_{CF} = 20.57 \text{ V}$

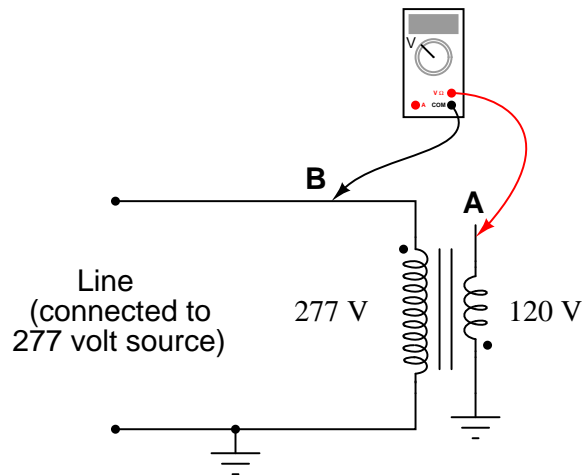
Notes 25

This question checks students' ability to relate the winding ratios of a transformer to voltages in the circuit. Note that one of the voltages actually exceeds the source voltage of 16 volts, even though this is technically a "step-down" transformer. The fact that the source voltage is not impressed upon the entire primary winding is key here.

The symbolism for this transformer is common in Europe, but not so common in the United States.

Question 26

How much AC voltage is there between points **A** and **B** in this circuit?



file 00666

Answer 26

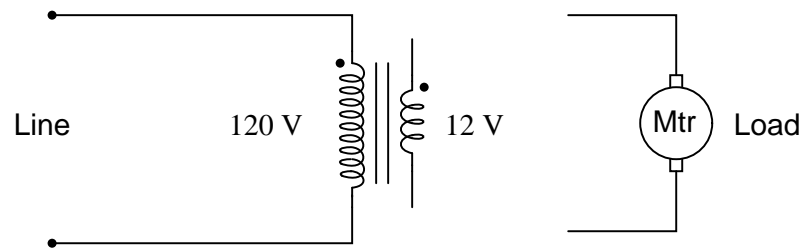
$$V_{AB} = 397 \text{ VAC}$$

Notes 26

In reality, this is nothing more than an exercise in Kirchhoff's Voltage Law (KVL): determining the voltage between two points in a loop, knowing the voltages between other points in that same loop. Two principal challenges present themselves in this exercise: identifying the loop, and relating the dot convention to polarity markings. Different students will likely have different approaches to this problem, so it should make for an interesting discussion!

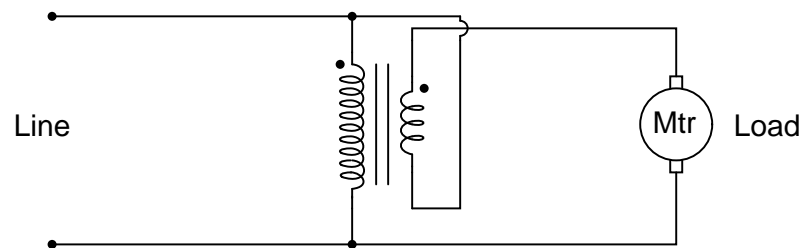
Question 27

Connect the windings of this step-down transformer so that it "boosts" the voltage going to the load by 12 volts:



file 00242

Answer 27

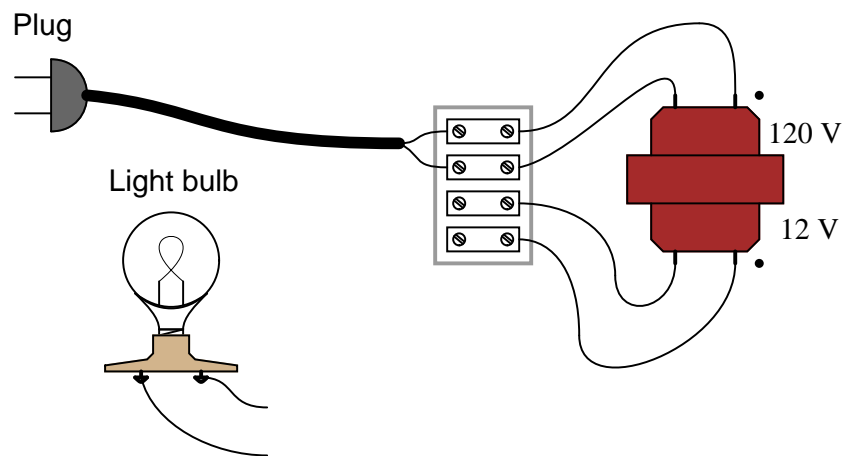


Notes 27

Phase markings (the dots near the end of each winding) are very important when deciding which way to connect transformer windings! Some students may find it helpful to use DC polarity markings (+ and -) in addition to dots, to determine whether voltages will be in-phase (boosting) or out-of-phase (bucking).

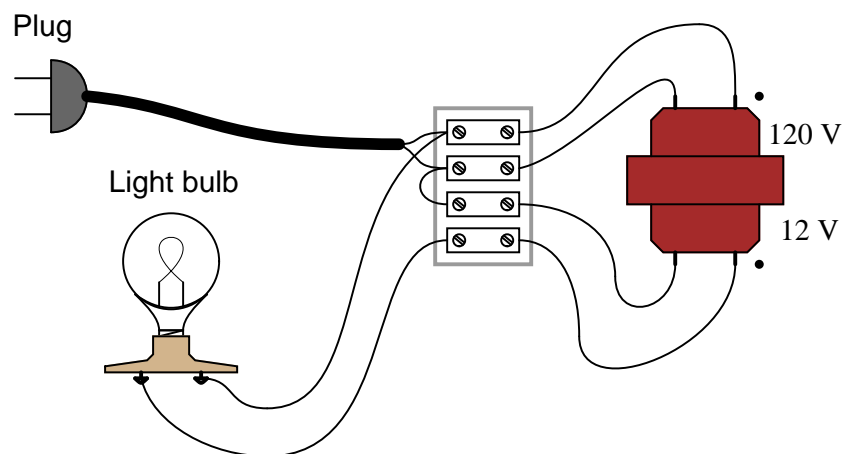
Question 28

Connect the windings of this step-down transformer so that it "bucks" the voltage going to the light bulb by 12 volts:



[file 00243](#)

Answer 28

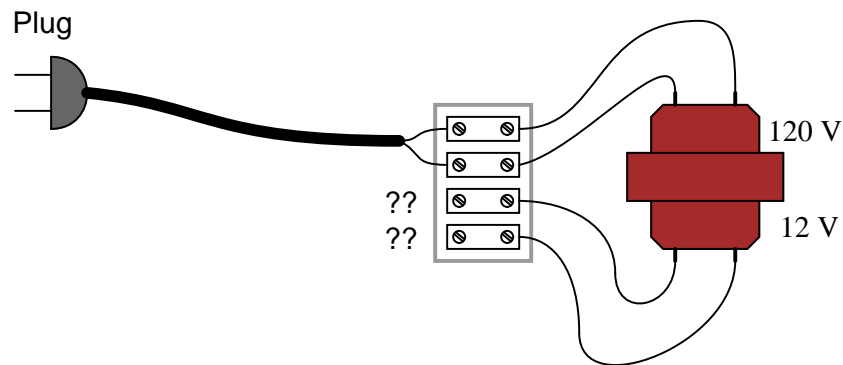


Notes 28

Phase markings (the dots near the end of each winding) are very important when deciding which way to connect transformer windings! Some students may find it helpful to use DC polarity markings (+ and -) in addition to dots, to determine whether voltages will be in-phase (boosting) or out-of-phase (bucking).

Question 29

How could we possibly determine the phasing of the windings in this step-down transformer (120 VAC, 60 Hz primary) so we would know how to connect them for either boosting or bucking service?



file 00244

Answer 29

Connect one of the secondary wires to one of the primary wires. Then, measure voltage with a voltmeter between the other two secondary and primary winding wires (the two that are not electrically common). The voltage reading obtained by this test will indicate the phasing.

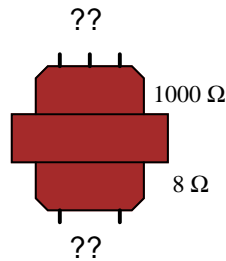
Notes 29

Note that the answer given to this question leaves the particular details of how to interpret the voltmeter readings unanswered. Challenge your students to figure this out on their own.

Given that autotransformer connections are so practical, it is important for students to know how to test a transformer to see how its (unmarked) windings are phased.

Question 30

Suppose you had an audio impedance-matching transformer ($1000\ \Omega$ to $8\ \Omega$), and you wished to know the phase relationships of the windings. Unfortunately, the only test equipment you have is an analog DC voltmeter and a 9-volt battery. Explain how you would use these two devices to test winding "polarity."



Note: you may disregard the center-tap of the $1000\ \Omega$ primary winding.
[file 01562](#)

Answer 30

I won't give you the answer directly here, but I will give you a hint: although transformers cannot function on continuous DC, they will respond to *pulses* of current in a given direction! In other words, you can use intermittent DC from the 9-volt battery to test the windings.

Challenge question: calculate the turns ratio of this transformer, based on the ratio of impedances.

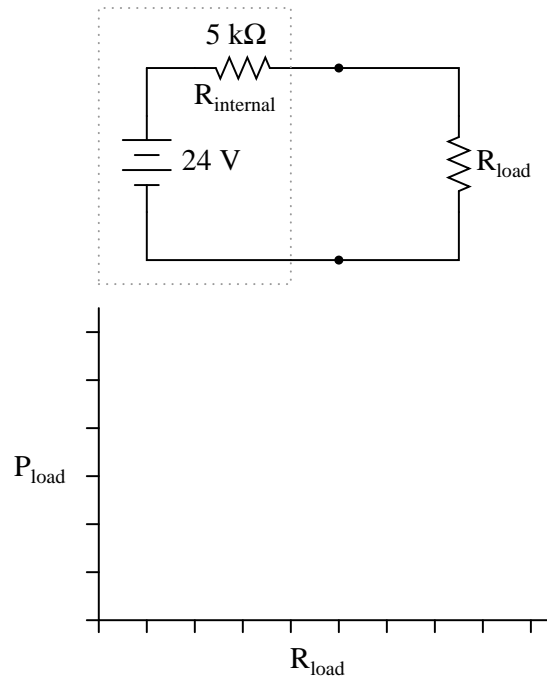
Notes 30

Note that the answer given to this question leaves the particular details of how to interpret the voltmeter readings unanswered. Challenge your students to figure this out on their own.

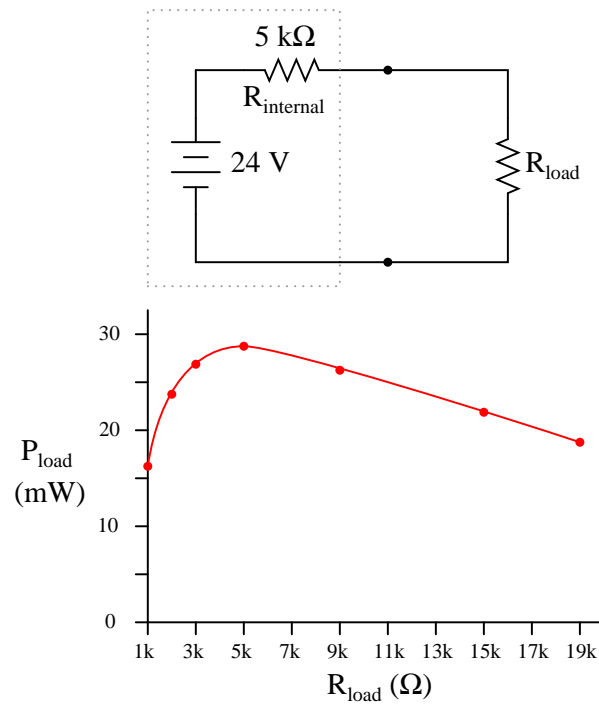
Audio matching transformers are easy to obtain, so I encourage you have your students try this as a lab exercise.

Question 31

Plot the power dissipation of the load resistance, for several values between 1 k Ω and 20 k Ω :



At what load resistance value is the load's power dissipation maximized?
file 00391



Notes 31

What practical application can you think of for this principle of power maximization? In what applications might we be interested in delivering the maximum amount of power possible to a load?

Question 32

Explain what the *Maximum Power Transfer Theorem* is, in your own words.
file 01881

Answer 32

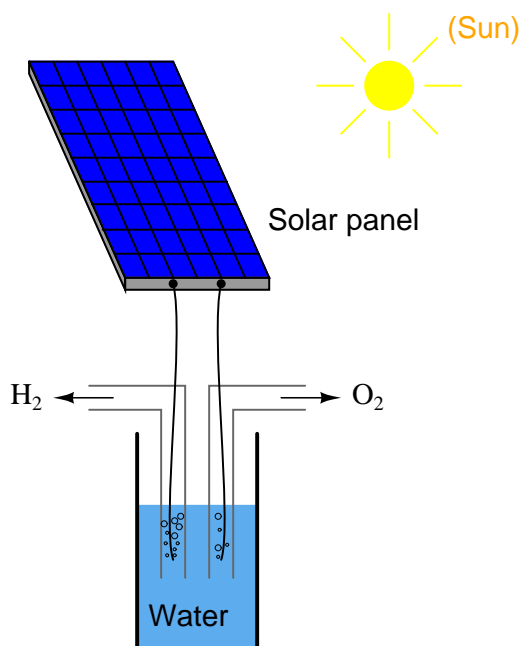
This I leave to you to research!

Notes 32

This theorem is very easy to research, being described in just about every introductory electronics textbook. While it may not be intuitive, at least it is useful and easy to remember!

Question 33

Suppose we were planning to use a photovoltaic panel to generate electricity and electrolyze water into hydrogen and oxygen gas:



Our goal is to electrolyze as much water as possible, and this means we must maximize the electrolysis cell's power dissipation. Explain how we could experimentally determine the optimum internal resistance of the electrolysis cell, prior to actually building it, using nothing but the solar panel, a rheostat, and a DMM (digital multimeter).

file 00392

Answer 33

Experimentally determine what amount load resistance drops exactly one-half of the panel's open-circuit voltage.

Follow-up question: assuming that the open-circuit voltage of this solar panel were high enough to pose a shock hazard, describe a procedure you might use to safely connect a "test load" to the panel.

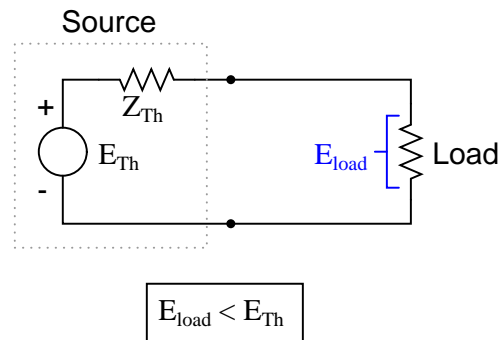
Notes 33

Students should at this point understand the maximum power transfer theorem, and also the concept of a voltage source having a certain amount of internal resistance. The "trick" of this question is, of course, how to determine the panel's internal resistance. Do not be surprised if a student suggests using the meter to measure the panel's resistance directly (though this will not work with a real photovoltaic panel).

Regarding the safety-oriented follow-up question, you might want to ask your students what the commonly accepted "shock hazard" voltage level is (30 volts).

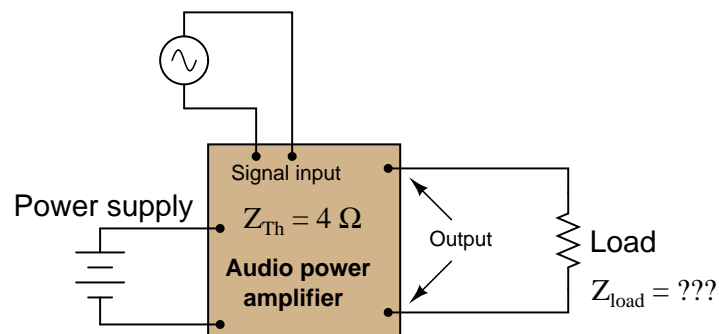
Question 34

All electrical sources contain some internal impedance. This explains why voltage sources "sag" when placed under load:



In this diagram, the source's internal impedance has been "lumped" into a single component, labeled Z_{Th} , the Thévenin impedance. This intrinsic impedance naturally limits the amount of power any source can deliver to a load. It also creates a condition where load power is optimized at a particular load impedance.

Determine the load impedance value necessary for maximum power dissipation, if powered by an audio amplifier circuit with an internal (Thévenin) impedance of $4\ \Omega$.



file 00662

Answer 34

$$Z_{load} \text{ (ideal)} = 4\ \Omega$$

Notes 34

Discuss with your students the "Maximum Power Transfer Theorem" as it relates to this question.

Question 35

Suppose you were to take a 3 kW electric heater rated for 240 VAC and connect it to a 120 VAC power source. How much power would it dissipate when connected to a voltage source equal to *half* its rating?

file 00657

Answer 35

$$P = 750 \text{ W}$$

Notes 35

A common mistake students make is to think that applying half the normal amount of voltage to a resistor results in half the power dissipation. This is not correct. There are many ways to disprove the assertion mathematically, and I won't bother to list my favorite here. Discuss this with your students, and see what *their* reasoning is.

Question 36

How much resistance must a heating element possess in order to dissipate 3 kW of power at 240 VAC?
How much resistance must a heating element possess in order to dissipate the same amount of power (3 kW) at half the voltage (120 VAC)?

file 00658

Answer 36

$$R_{240V} = 19.2 \, \Omega$$

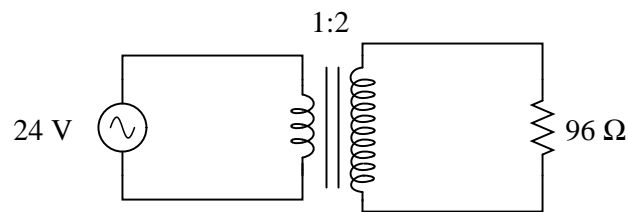
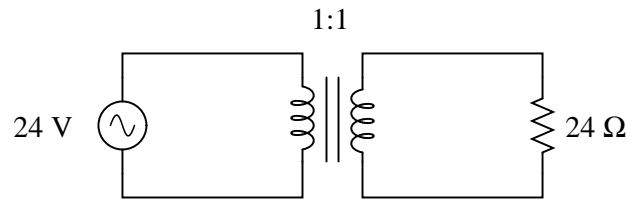
$$R_{120V} = 4.8 \, \Omega$$

Notes 36

This question is an exercise in algebraic manipulation. Sure, students will be able to find an equation solving for resistance in terms of power and voltage, but for the sake of algebra practice they should be asked to derive the equation from a more common power equation, such as $P = \frac{E^2}{R}$.

Question 37

Calculate the amount of power supplied by the source in each of these circuits:



What do you notice about these two circuits that is interesting? How much impedance does each source "think" it is supplying power to, based on the following formula?

$$Z = \frac{V_{source}}{I_{source}}$$

file 01880

Answer 37

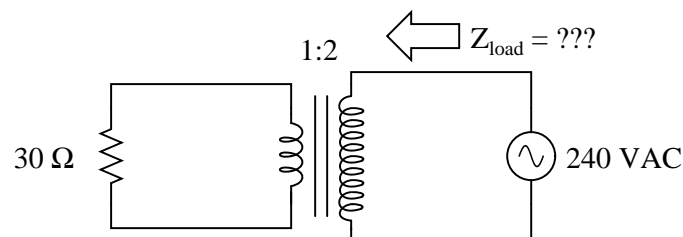
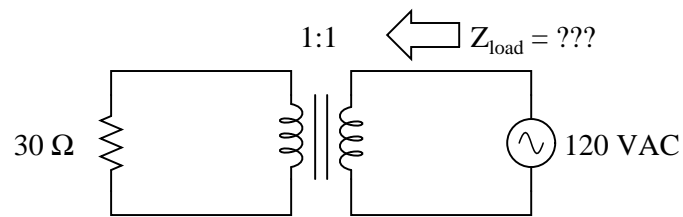
In each case, the source outputs the same amount of current, which means it "sees" the same impedance.

Notes 37

I like using specific numerical examples to introduce the concept of impedance transformation, because I find abstract mathematical presentations tend to "lose" a lot of students.

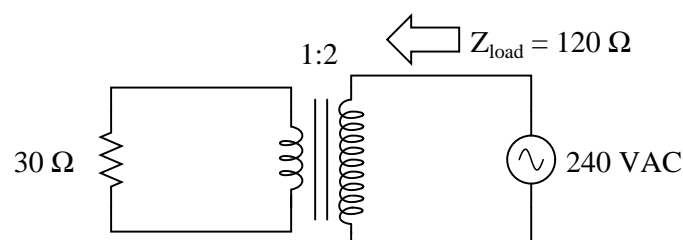
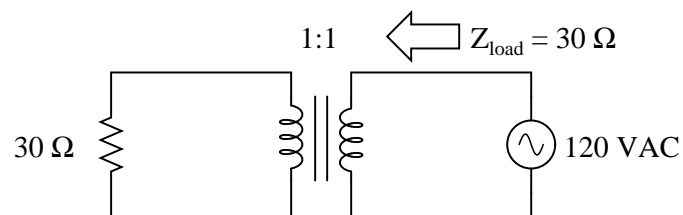
Question 38

In each of these circuits, calculate the amount of load impedance "seen" by the voltage sources given the turns ratio of each transformer:



Hint: "impedance" (Z) is defined mathematically as the ratio of voltage (E) to current (I).
[file 00659](#)

Answer 38



The setup of this problem may confuse some students, with reference to the amount of impedance that a source "sees". Hopefully, the anthropomorphic language will not be a barrier to understanding. The point is, for students to realize that just as a load can have a voltage or a current "impressed" upon it, a source can have a load "impressed" upon it as well. In this particular question, the issue is how the 1:2 step-down transformer ratio affects the amount of loading impressed upon the 240 VAC source by the 30 ohm resistor. That the resistor "sees" the same source voltage should be obvious. That the sources see very different impedance loadings (due to the transformer) is the purpose of this question.

Question 39

If a step-up transformer has a turns ratio of 3:1, calculate the following:

- The voltage ratio (secondary:primary)
- The current ratio (secondary:primary)
- The winding inductance ratio (secondary:primary)
- The load impedance ratio (secondary:primary)

What mathematical pattern(s) do you see between the turns ratio and these four ratios?

file 00661

Answer 39

- The voltage ratio (secondary:primary) = 3:1
 - The current ratio (secondary:primary) = 1:3
 - The winding inductance ratio (secondary:primary) = 9:1
 - The load impedance ratio (secondary:primary) = 9:1
-

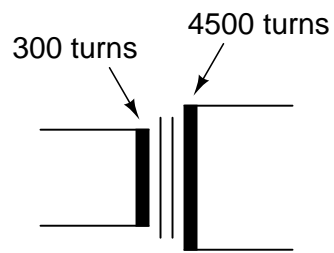
Notes 39

Determining the voltage and current ratios should be trivial. Calculating the impedance ratio will likely require the set-up of an example problem, based on known values of voltage and current.

The most important part of this question is the identification of mathematical patterns and trends relating the turns ratio to the requested ratios. Of particular note are the inductance and impedance ratios. Why are they 9:1 and not 3:1? Ask your students what mathematical operation relates the number 3 to the number 9? If necessary, have them work through another example problem (with a different turns ratio) to see the impedance transformation ratio there, and the resulting relationship between that ratio and the turns ratio.

Question 40

What would happen to the impedance transformation ratio if a short-circuit developed between some of the turns in the 300-turn winding of this transformer? Explain your answer.



file 00665

Answer 40

The impedance ratio would increase.

Notes 40

This is somewhat of a "trick" question, because students are accustomed to equating a "short" with a decrease in impedance. While this is generally true, what we're talking about here is an impedance *ratio*, rather than any one impedance in particular.

Question 41

An audio power amplifier with an internal impedance of $8\ \Omega$ needs to power a set of speakers with a combined total impedance of $1\ \Omega$. We know that connecting this speaker array directly to the amplifier's output will not result in optimum power transfer, because of the impedance mismatch.

Someone suggests using a transformer to match the two disparate impedances, but what turns ratio does this transformer need to have? Should it be used in a step-up configuration, or a step-down configuration? Explain your answers.

file 00663

Answer 41

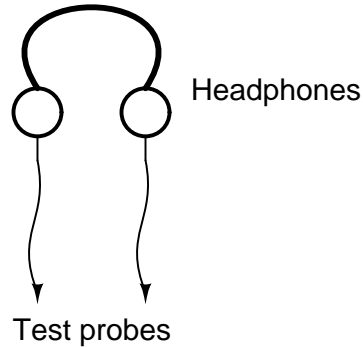
2.83:1 winding ratio, step-down.

Notes 41

Students should know at this point how to calculate the impedance transformation ratio from a transformer's winding ratio. In this question, they are challenged to calculate "backwards" to find the winding ratio from the impedance ratio.

Question 42

A simple pair of audio headphones makes a remarkably sensitive and useful piece of test equipment for detecting signals in a wide variety of circuits. Even very small DC voltages may be detected with a pair of headphones, if you listen for a "click" sound when contact is made or broken between a voltage source and the headphone's test probes.



Yet, a plain pair of headphones is unsuitable for many test applications for two reasons:

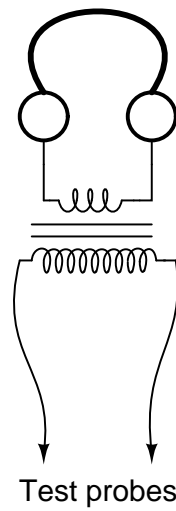
- Electrical safety
- Low impedance

It is generally *not* a good idea to place your body in a position where it may come into direct contact with a live circuit, especially if that circuit harbors substantial voltages. Being that headphones are worn on a person's head, with the potential for electrical contact between one of the speaker elements and the wearer's head, this is quite possibly unsafe.

Secondly, the impedance of a high-quality headphone set is generally 8 ohms. While being a common audio speaker impedance, this low value would place far too great of a "burden" on many types of electronic circuits if directly connected. What is desired for a piece of test equipment is 1000 Ω or more.

Explain how a transformer may be inserted into the headphone test circuit in such a way as to address both these problems.

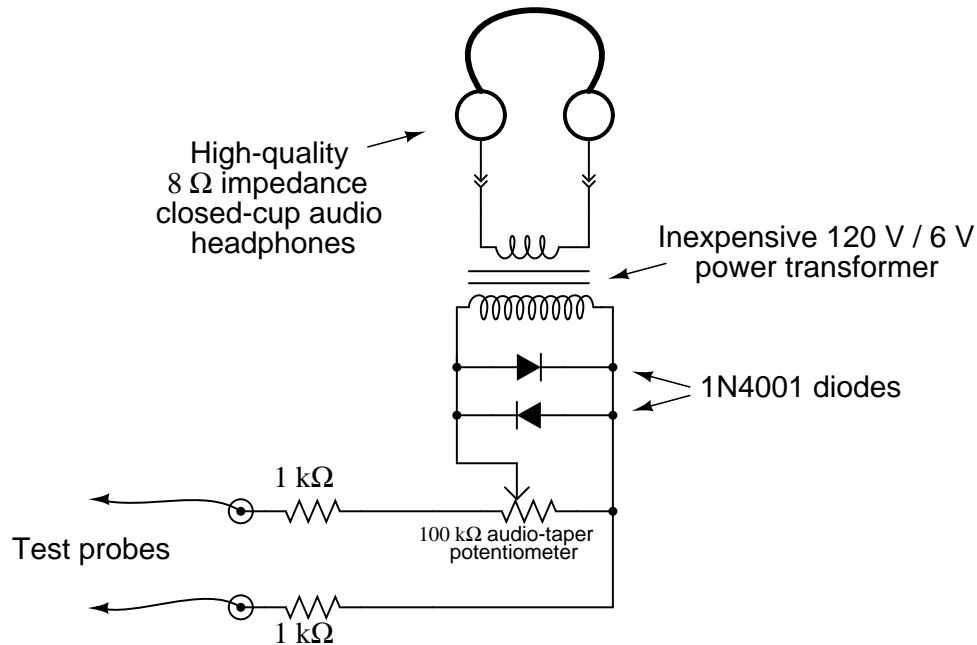
file 00664



Follow-up question: even though a pair of headphones used in this manner cannot provide *quantitative* measurements of signals, there are some *qualitative* features which a skilled user may discern from the sounds produced. Describe what features of an AC signal may be detected with headphones, and how this compares to the information obtained from an oscilloscope.

This question reviews both the principles of impedance matching and electrical isolation, in addition to exposing students to a novel and inexpensive piece of test equipment they can build on their own. I highly recommend making the construction and use of one of these devices a lab project in your curriculum. I use a headphone test set regularly in my own experimentation, and I have found it very useful in understanding AC phenomenon (especially if you do not have your own oscilloscope).

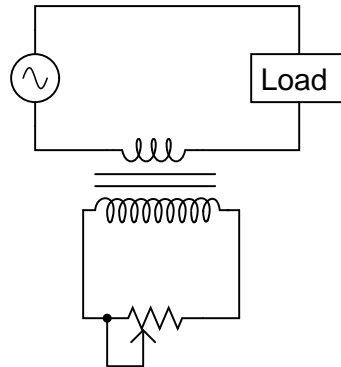
The circuit I recommend for students to build is this:



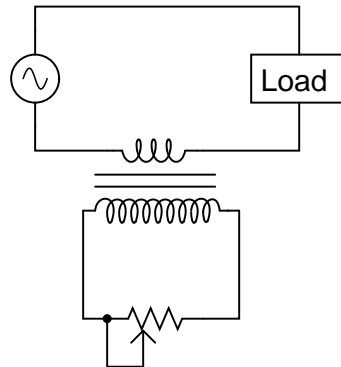
The 1 kΩ resistors and 1N4001 rectifying diodes provide protection against hearing damage, by limiting the voltage which may be applied to the primary winding of the transformer. The potentiometer, of course, provides volume control, while the transformer steps up the headphones' impedance and provides electrical isolation. I recommend a 120 volt power transformer for the task because it is rated for line voltage, and will surely provide the necessary isolation between circuit and headphones necessary for safety. A regular 8:1000 ohm "audio transformer" is not necessarily rated for the same (high) levels of voltage, and therefore would not provide the same margin of safety. For best performance, use a pair of headphones with the greatest "sensitivity" rating (measured in dB) possible.

Question 43

This is an interesting application of a transformer:



With this circuit, power to the AC load may be controlled by the variable resistor's setting:



Calculate the amount of series impedance the transformer places in the load current's path, if the variable resistor is set to a resistance of 15 ohms, and the winding ratio is 20:1.

file 00754

Answer 43

0.0375 Ω

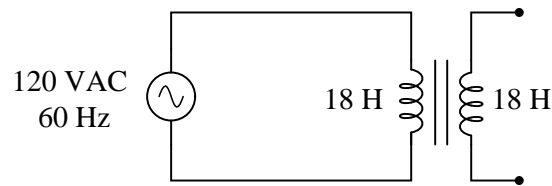
Follow-up question identify any potential safety hazards associated with using a transformer in this capacity.

Notes 43

Ask your students to think of a practical application for a circuit like this. Also, challenge them with this question: if the resistor were to open fully (∞ ohms), would current to the load completely stop? Why or why not?

Question 44

Calculate the primary winding current (magnitude and phase angle) for this unloaded isolation transformer, with primary and secondary inductances of 18 Henrys each:



Assume the winding inductances are "pure" (no resistive components).
file 01882

Answer 44

$$I_{primary} = 17.68 \text{ mA} \angle -90^\circ$$

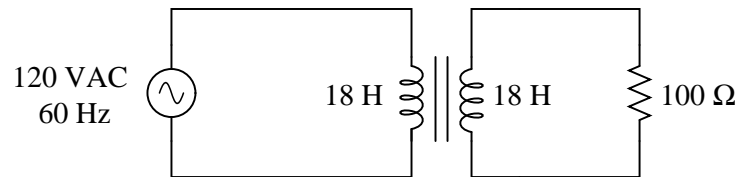
Challenge question: what changes, if any, would result in the primary current value if this were not an isolation transformer, but rather a transformer where the secondary inductance was something other than 18 H?

Notes 44

Students should realize from the answer that an unloaded transformer simply appears as an inductor to the source.

Question 45

Calculate the primary winding current (magnitude and phase angle) for this resistively loaded isolation transformer, with primary and secondary inductances of 18 Henrys each:



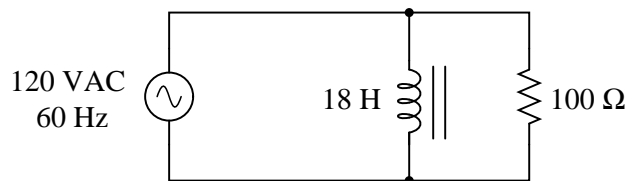
Also, draw an equivalent schematic diagram (with no transformer in it) illustrating the impedance "seen" by the AC power source. Assume no winding resistance in either transformer winding, and a magnetic coupling coefficient between the two windings of exactly 1.

file 01883

Answer 45

$$I_{primary} = 1.2001 \text{ A } \angle -0.84^\circ$$

Equivalent (transformerless) circuit



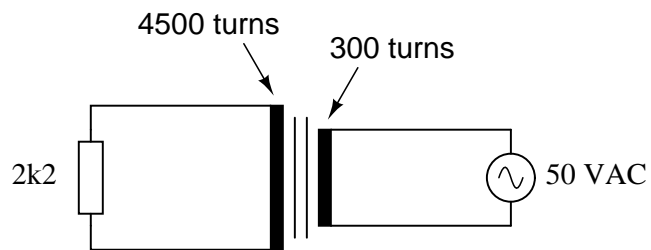
Follow-up question: what kind of impedance (predominantly resistive, inductive, or capacitive) does the AC source "see" in this circuit? Contrast this against a situation with no load connected to the transformer at all.

Notes 45

This question illustrates how reflected load impedance is "seen" by the source, and how it interacts with the transformer's intrinsic winding impedance.

Question 46

Calculate all voltages and all currents in this circuit, given the component values and the number of turns in each of the transformer's windings:



file 00660

Answer 46

$$E_R = 750 \text{ V}$$

$$I_R = 340.9 \text{ mA}$$

$$E_{source} = 50 \text{ V}$$

$$I_{source} = 5.114 \text{ A}$$

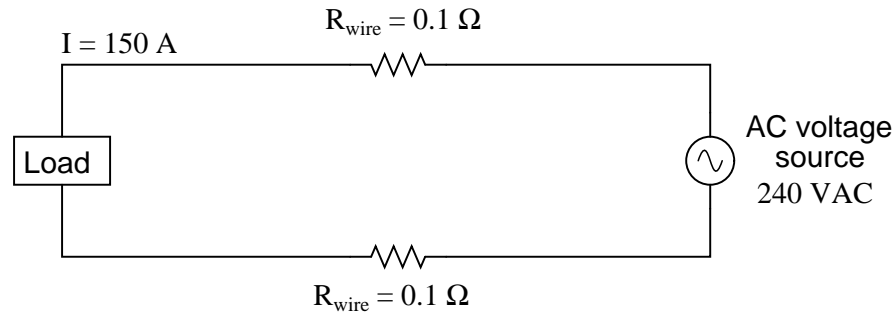
Follow-up question: given the voltage and current figures of the power source, how much impedance does it "think" it is driving?

Notes 46

This question checks students' ability to relate the winding ratio to voltage and current ratios in a transformer circuit. The symbolism here is common in Europe, but not so common in the United States.

Question 47

Suppose a power system were delivering AC power to a resistive load drawing 150 amps:



Calculate the load voltage, load power dissipation, the power dissipated by the wire resistance (R_{wire}), and the overall power efficiency ($\eta = \frac{P_{\text{load}}}{P_{\text{source}}}$).

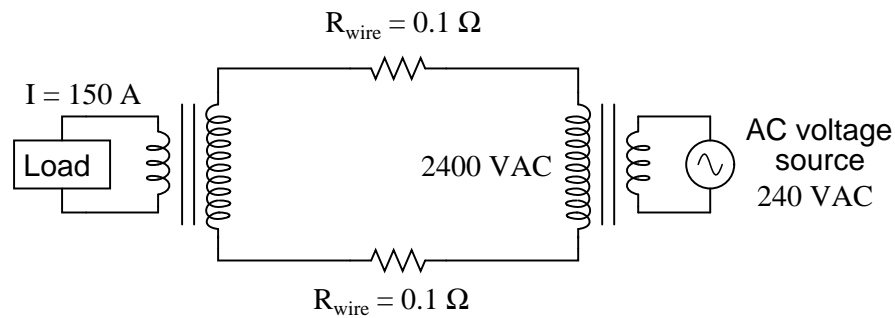
$$E_{\text{load}} =$$

$$P_{\text{load}} =$$

$$P_{\text{lines}} =$$

$$\eta =$$

Now, suppose we were to use a pair of perfectly efficient 10:1 transformers to step the voltage up for transmission, and back down again for use at the load. Re-calculate the load voltage, load power, wasted power, and overall efficiency of this system:



$$E_{\text{load}} =$$

$$P_{\text{load}} =$$

$$P_{\text{lines}} =$$

$$\eta =$$

file 00247

Answer 47

Simple system (no transformers):

$$E_{load} = 210 \text{ volts}$$

$$P_{load} = 31.5 \text{ kW}$$

$$P_{lines} = 4.5 \text{ kW}$$

$$\eta = 87.5\%$$

Complex system (with transformers):

$$E_{load} = 239.7 \text{ volts}$$

$$P_{load} = 35.96 \text{ kW}$$

$$P_{lines} = 45 \text{ W}$$

$$\eta = 99.88\%$$

Follow-up question: can you think of any disadvantages of the circuit using 10:1 transformers compared to the original (transformerless) power system?

Notes 47

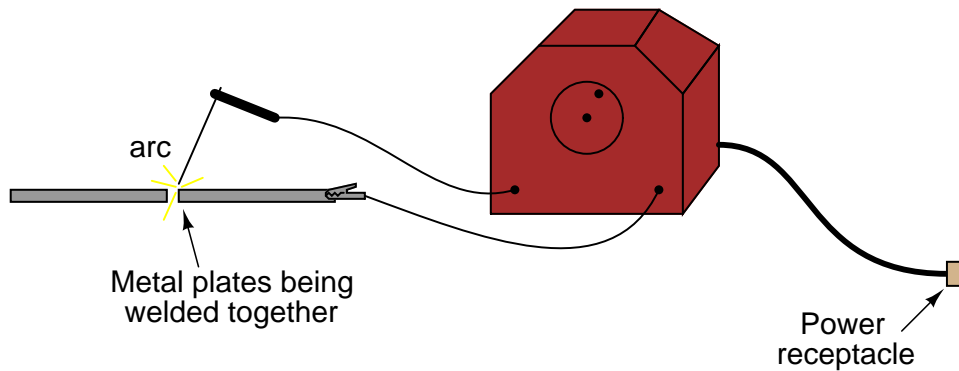
An example like this usually clarifies the benefits of using AC instead of DC for transmission of large amounts of electrical power over substantial distances, better than simply telling students why transformers are used in power systems. Even with modest power losses in the transformers (say, 3% loss in each), the overall efficiency is still much greater in this system than without using transformers at all.

In discussing the follow-up question, be sure to bring up safety as a consideration if none of your students do.

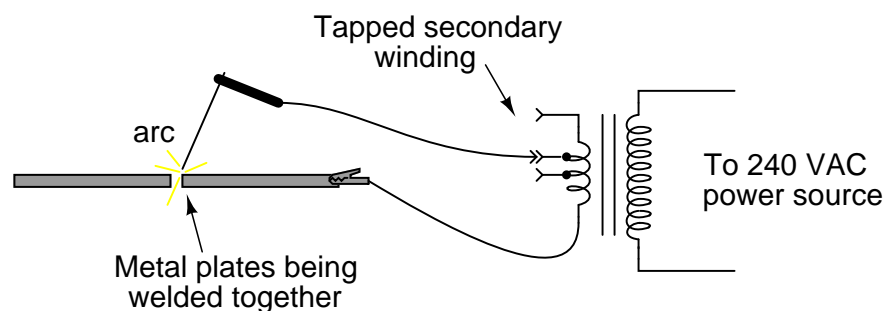
Question 48

An electric *arc welder* is a power conversion device, used to step utility power voltage (usually 240 or 480 volts AC) down to a low voltage, and conversely step up the current (to 100 amps or more), to generate a very hot arc used to weld metal pieces together:

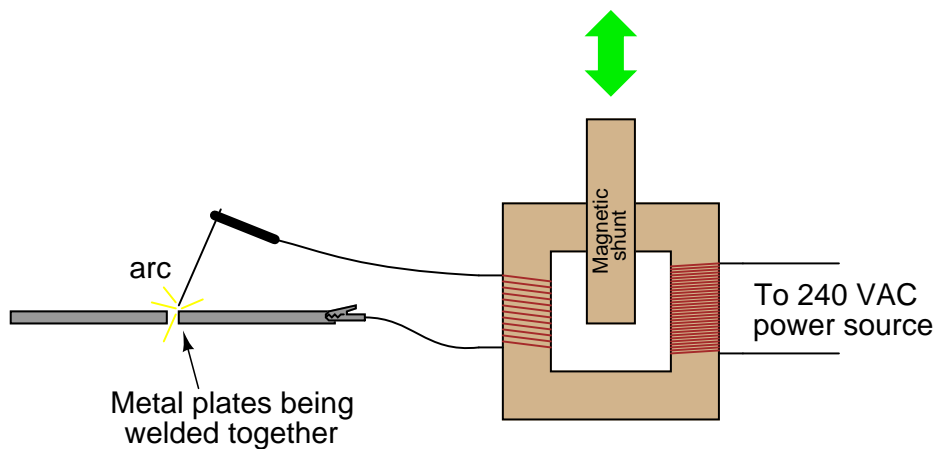
Electric "arc" welding



The simplest designs of arc welder are nothing more than a large step-down transformer. To achieve different power intensities for welding different thicknesses of metal, some of these arc welders are equipped with taps on the secondary winding:



Some arc welder designs achieve continuous variability by moving a magnetic "shunt" in and out of the transformer core structure:



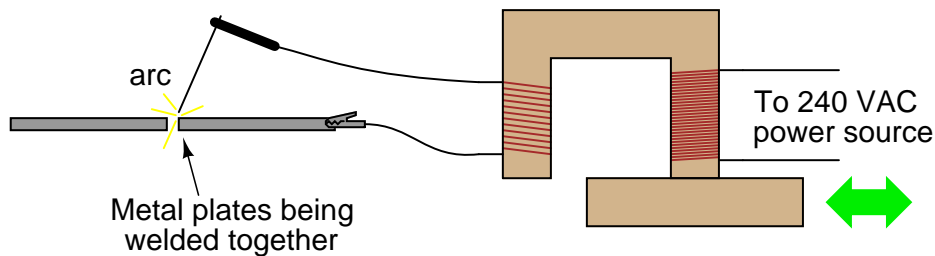
Explain how this shunt works. Which way does it need to be moved in order to increase the intensity of the welding arc? What advantages does this method of arc power control have over a "tapped" secondary winding?

file 00489

Answer 48

As the shunt is pulled further away from the core (up, in the illustration), the welding arc intensity increases.

Challenge question: why would it not be a good idea to achieve the same continuously-variable arc control by varying the reluctance (\mathcal{R}) of the transformer's magnetic circuit, like this?



Notes 48

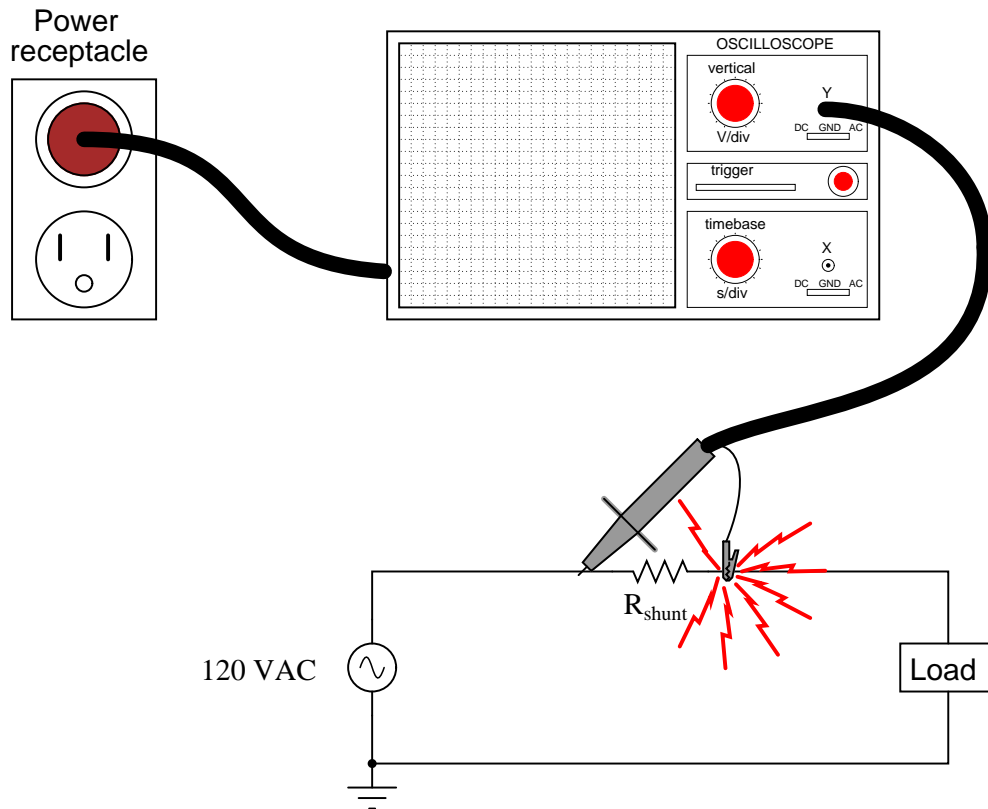
This question illustrates an application of the coupling (k) factor between mutual inductors. There are a few advantages of controlling the arc welder's output in this manner, as compared to using winding taps, so be sure to discuss this with your students.

As to the challenge question, controlling the transformer output in this manner would also affect the magnetizing inductance of the primary winding, which would have detrimental effects at low settings (what would happen to the "excitation" current of the primary winding as its inductance decreases?).

Question 49

Shunt resistors are commonly used to measure current in power circuits, by producing a small voltage drop in direct proportion to the circuit current. They are especially useful for measuring complex current waveforms in AC circuits, since they do not distort the waveform at all.

Suppose you wished to measure the current waveform in this power circuit by using an oscilloscope to measure voltage dropped across the shunt resistor:



If you connect an oscilloscope to the power circuit as shown, very bad things will happen, like the oscilloscope's ground clip melting, with lots of sparks!

After replacing the damaged probe assembly, and taking a long break to soothe your nerves, an experienced technician suggests you plug the oscilloscope's power cord into an *isolation transformer* to avoid this problem in the future. Explain what an isolation transformer is, why it prevents the short-circuit problem experienced in this circuit, and what precautions must be taken when using one.

file 00250

Answer 49

An "isolation transformer" neither steps voltage up or down, but rather simply provides electrical isolation between primary and secondary windings. In this particular case, an isolation transformer inserted into the oscilloscope's power circuit breaks a circuit formed by the probe ground clip's connection with the oscilloscope metal chassis, which in turn is connected to the ground prong on the power cord plug, which is connected to earth ground for safety.

If an isolation transformer is used in such a way, it avoids the short-circuit problem, but only at the cost of "ungrounding" the oscilloscope chassis, making it unsafe to touch!!!

Follow-up question: identify a way to safely use an oscilloscope to measure the shunt resistor's voltage, without having to use an isolation transformer.

Notes 49

This lesson on oscilloscope usage is a valuable one, as students are sure to encounter problems with their circuits resulting from earth ground connections through the oscilloscope's chassis ground. Having an oscilloscope and an ohmmeter in the classroom during discussion time would be a good idea, so students may test the common connections themselves.

Question 50

In power distribution systems, it is very important to be able to measure line voltage. You cannot control what you cannot measure, and it is important to control power line voltage so as to not exceed the insulators' ratings.

But how do you safely measure the voltage of a 750 kV power line? Obviously, no voltmeter small enough to be located on a control panel could safely handle 750,000 volts applied to it, as a voltage that high is capable of arcing several feet through the air (not to mention the safety hazards of having wires behind the meter panel connecting straight to the power line!).

In industry, specialized *transformers* are used to safely measure the high voltages on power lines. Describe what is special about these "potential transformers," and how they are implemented to measure dangerous voltages.

file 00755

Answer 50

A "potential transformer," or "PT," is a step-down transformer with a very precise winding turns ratio, so that the secondary voltage is a precise and known fraction of the primary voltage.

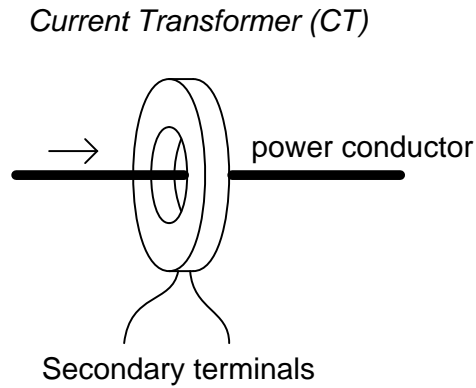
Follow-up question: in addition to stepping the line voltage down to relatively safe levels, potential transformers also provide one more important safety feature for voltage measurement. Describe what this extra feature is, and why it is important. Hint: all transformers except for autotransformers provide this feature!

Notes 50

Ask students to draw a rough schematic diagram of how a potential transformer would be placed in a complete voltage-measurement circuit, with power lines, panel-mounted voltmeter mechanism, safety fuses, etc.

Question 51

A common instrument used for measuring high AC currents in power systems is a *current transformer*, abbreviated "CT". Current transformers usually take the form of a "donut," through which the current-carrying conductor passes:



The purpose of a current transformer is to create a secondary current that is a precise fraction of the primary current, for easier measurement of current in the power conductor.

Given this function, would current transformers be considered a "step-up" or "step-down" transformer? Also, draw how the secondary windings of a current transformer are arranged around its toroidal core.

file 00756

Answer 51

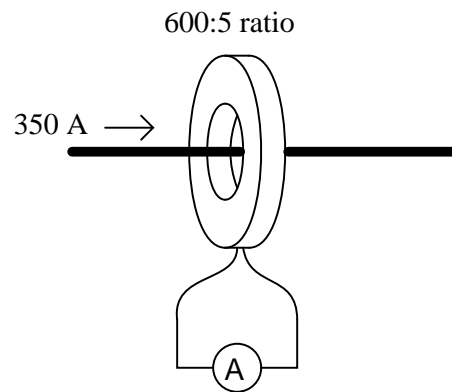
From the perspective of voltage, which is usually how the terms "step-up" and "step-down" are referenced, a current transformer is a "step-up" transformer. Its secondary windings are wound perpendicular to the magnetic flux path, as typical in all transformers.

Notes 51

The question of whether the current transformer is a "step-down" or "step-up" has an important safety implication for students to realize. Ask your students to describe what conditions might prove the most dangerous when working around current transformers, given their "step-up" nature with reference to voltage.

Question 52

How much current will be output by a current transformer if the load current is 350 amps and the CT ratio is 600:5?



file 00758

Answer 52

Secondary current = 2.917 amps

Notes 52

This question is an exercise in mathematical ratios.

Question 53

It is very important that the secondary winding of a *current transformer* (CT) never be open-circuited while in operation! Explain why this is an important safety consideration.

file 00757

Answer 53

An open-circuited secondary winding on a current transformer is capable of generating *extremely* high voltages.

Notes 53

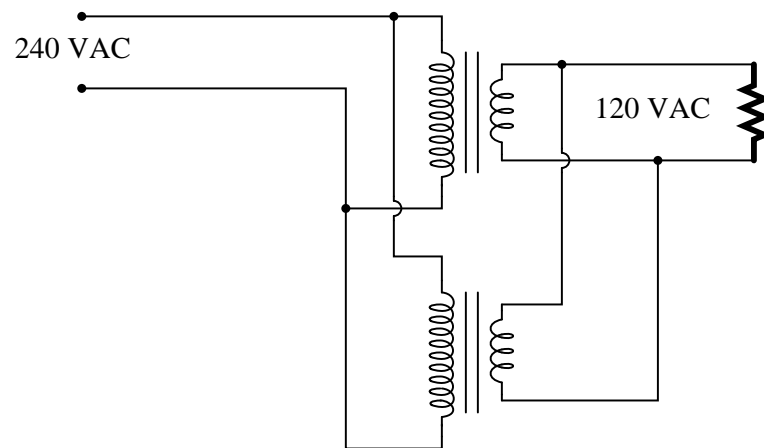
There are a couple of different ways to explain *why* current transformers pose this safety hazard. One could explain it in terms of the winding ratio, or perhaps in terms of its function as an AC "current source". Do not be surprised if your students present multiple explanations for this behavior.

Question 54

Suppose you need to power a 120 volt, 600 watt heating element from a 240 volt source. You happen to have several 240V/120V step-down transformers on hand, but each one is only rated at 400 VA. Draw a schematic diagram showing how multiple transformers could be used to match the 120 volt load to the 240 volt source.

file 00245

Answer 54



Notes 54

In case you students have not yet studied AC power (watts, volt-amps, and volt-amps reactive), let them determine what "VA" means first, and then let them know it is simply equivalent to "watts" for a resistive load.

It is a very realistic problem to have to match available components to a particular task, so this question is worth your students' while to discuss and understand thoroughly.

Question 55

One of the practical uses of transformers is to adapt equipment to conditions not anticipated in their original design. For instance, a heating element (which is essentially nothing more than a resistor with an unusually high power dissipation rating) may need to be operated at a lower power dissipation than designed for.

For example, suppose you have a 1 kW electric heater rated for 208 volt operation, which you intend to operate at a reduced power dissipation of 750 watts. Calculate the proper amount of voltage you would need to achieve this reduced power dissipation, and explain how you could use a transformer to supply this reduced voltage to the heater.

[file 02130](#)

Answer 55

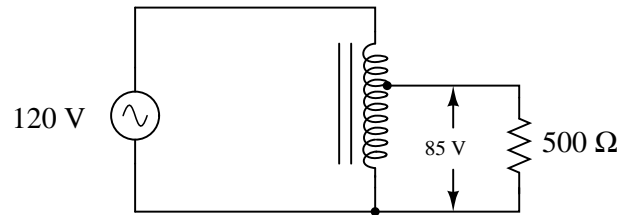
The necessary voltage to make this 1 kW heater operate at only 750 W is approximately 180 volts.

Notes 55

Some students may struggle in calculating the necessary voltage, because this problem does not exactly match most voltage/current/power calculations problems they've seen in the past. The necessary math is almost trivial, but the "trick" is applying well-known equations to something unfamiliar. This is an excellent opportunity to discuss problem-solving strategies, so be sure to have students share their ideas on how to solve for the necessary voltage.

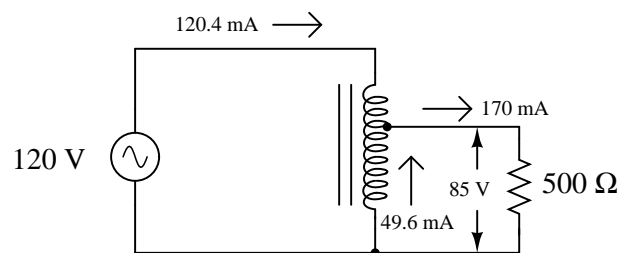
Question 56

Calculate all currents in this autotransformer circuit, assuming perfect (100%) efficiency:



file 00670

Answer 56



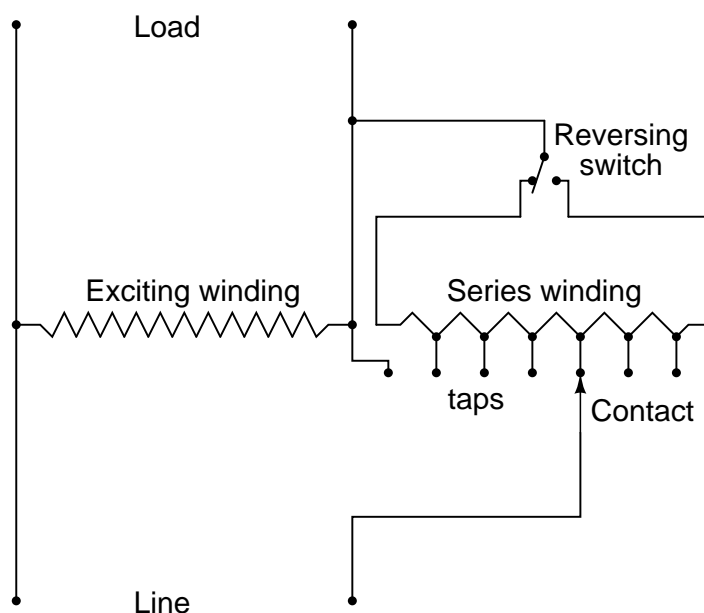
Follow-up question: based on these current figures, what economic advantage does an autotransformer have over a conventional transformer in terms of manufacturing cost?

Notes 56

Discuss with your students the pro's and con's of autotransformers over regular transformers. Of course, there is the obvious disadvantage: loss of isolation between primary and secondary circuits. If this is not a problem, though, there are substantial advantages to be realized in using an autotransformer over a conventional transformer.

Question 57

Devices called *step regulators* are sometimes used in electrical power distribution systems to boost or suppress line voltages, typically to a maximum of 10%:



The "Line" side of this autotransformer is the source of power, and the "Load" side connects to those devices consuming electrical power. The "Reversing switch" alters the transformer's function from boost to buck.

Determine which switch position is "boost" and which is "buck," and then determine which way the moving contact (the arrow symbol) needs to be moved in order to increase the voltage output, and to decrease the voltage output.

[file 00241](#)

Answer 57

When the reversing switch is in the left position, the regulator output voltage is reduced. When the switch is in the right position, the regulator output voltage is increased. Moving the contact further to the right increases the amount of boost or buck, depending on which position the reversing switch is in.

Incidentally, the zig-zag pattern of the windings is not standard for electronic schematic diagrams, though it is more common in electrical power system diagrams. I'll let you research how they draw resistors in these types of diagrams!

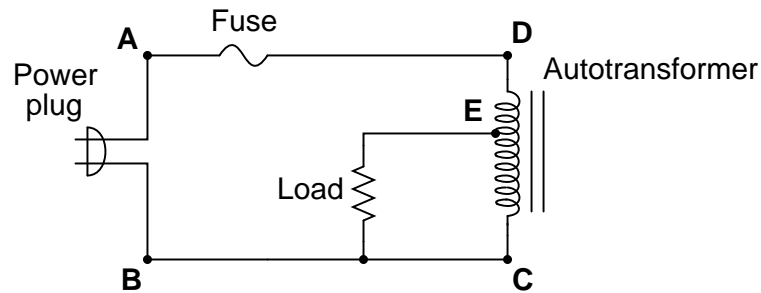
Notes 57

The solution to this question may be easier for some to recognize if the regulator circuit is re-drawn using normal electronic schematic diagrams. Another tip is to simplify the schematic diagram by removing all the different tap positions, and draw the circuit using the full series winding.

It is important for students to realize that there are different *types* of electrical schematic diagrams. Power diagram symbolism is often confusing to people familiar with electronic schematic symbolism, and visa-versa.

Question 58

Suppose the load in this circuit suddenly stops receiving power:



Your first step in troubleshooting is to take some voltage measurements:

- $V_{AB} = 120 \text{ V}$
- $V_{EC} = 0 \text{ V}$
- $V_{DC} = 120 \text{ V}$

Based on these measurements, where do you think the fault is in this circuit, and what type of fault is it?

[file 00669](#)

Answer 58

I'll let you determine the most likely failure on your own!

Notes 58

Ask your students to think of some other possibilities for failure in this circuit besides their first hypothesis. Also, discuss how you would verify (double-check) all hypotheses, with different meter measurements.

Question 59

The majority of the "humming" sound emitted by an unloaded transformer is due to an effect known as *magnetostriction*. What is this effect, exactly?

file 00407

Answer 59

"Magnetostriction" is the physical strain (contraction or expansion) of a material when subjected to a magnetic field.

Notes 59

Ask your students if they discovered whether magnetostrictive materials normally contract or expand with the application of a magnetic field. The answer to this question is quite surprising!

Question 60

Power transformers may "surge" when initially connected to a source of AC voltage, drawing up to several times their rated primary current for a brief period of time. This inrush of current is usually audible, especially if the transformer is a large power distribution unit, and you happen to be standing next to it!

At first, this phenomenon may seem contradictory, based on your knowledge of how inductances respond to transient DC voltage (zero current at first, then the current builds asymptotically to its maximum value). Indeed, even with AC, it is the nature of inductance to *oppose* current by dropping voltage (producing a *counter-EMF*). So why would an unloaded transformer draw a large inrush current when initially connected to a source of AC voltage?

Hint: a transformer will not always surge when first connected to its voltage source. In fact, if you were to open and close the disconnect switch feeding a power transformer's primary winding, you would find the surge phenomenon to be almost random: some times there would be no surge when you closed the switch, and other times there would be surge (to varying degrees) when the switch closed.

[file 00488](#)

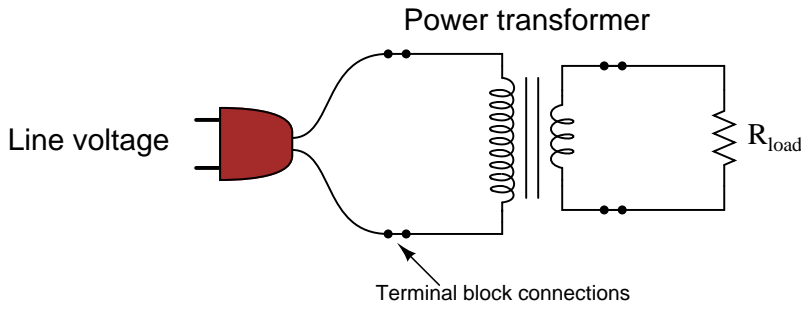
Answer 60

A transformer will surge the most if the switch closes at the exact moment the AC voltage waveform crosses zero volts. It will not surge at all if the switch closes exactly at one of the AC voltage peaks (either positive or negative).

Notes 60

This is a complex question to answer. A full explanation of the "surge" effect requires the use of calculus (integrating the voltage waveform over time) to explain the magnitude of magnetic flux in the transformer core, and how this approaches saturation during a surge.

Despite the highly mathematical nature of the question, it is a very practical one. If and when your students build AC-DC power supplies, they may find that the fuse in series with the primary winding of the transformer occasionally blows when powered up, even though the power supply is unloaded at the time, and despite the fact that the fuse does not blow when the power supply is fully loaded. What causes this random blowing of fuses? Transformer surge!

Competency: Transformer voltage/current ratios		Version:	
Schematic			
 <p style="margin-top: 10px;"><i>There must be no exposed line power conductors!</i></p>			
Given conditions			
Transformer step-down ratio = $V_{\text{line}} =$ $R_{\text{load}} =$			
Parameters			
<i>Procedure for ensuring no shock hazard when connecting meter:</i>			
Description (written by student)		Observed (written by instructor)	
Predicted	Measured	Predicted	Measured
V_{pri}		V_{sec}	
I_{pri}		I_{sec}	

file 01675

Answer 61

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

Notes 61

Use line-frequency power transformers for this exercise, with load resistor values low enough to "swamp" the primary winding's excitation current, so that the primary/secondary current ratio is realistic. Choosing a resistor value low enough to load the transformer near 100 % rated secondary current is a good start. Be careful that your load resistor can handle the power dissipation!

It might be a good idea for students to take careful measurements of primary and secondary voltage in an *unloaded* condition in order to calculate the actual winding turns ratio of their transformer. Knowing this precise ratio will be helpful to them later on when they use their transformers in other performance assessment activities, so their predictions will more closely match their actual measurements.

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: Auto-transformers	Version:												
<div style="border: 1px solid black; padding: 2px; display: inline-block;">Description</div> <p style="text-align: center; margin-top: 20px;">Connect a step-down power transformer in the "buck" auto-transformer configuration, and use it to power a low-resistance load.</p> <p style="text-align: center; margin-top: 10px;"><i>There must be no exposed line power conductors!</i></p>													
<div style="border: 1px solid black; padding: 2px; display: inline-block;">Given conditions</div> <div style="display: flex; justify-content: space-around; margin-top: 10px;"><div>$V_{\text{supply}} =$</div><div>$R_{\text{load}} =$</div><div>Transformer step-down ratio =</div></div>													
<div style="border: 1px solid black; padding: 2px; display: inline-block;">Parameters</div> <table style="margin-top: 10px; width: 100%;"><thead><tr><th></th><th style="text-align: center;">Predicted</th><th style="text-align: center;">Measured</th></tr></thead><tbody><tr><td>I_{supply}</td><td><div style="border: 1px solid black; width: 100px; height: 25px;"></div></td><td><div style="border: 1px solid black; width: 100px; height: 25px;"></div></td></tr><tr><td>V_{load}</td><td><div style="border: 1px solid black; width: 100px; height: 25px;"></div></td><td><div style="border: 1px solid black; width: 100px; height: 25px;"></div></td></tr><tr><td>I_{load}</td><td><div style="border: 1px solid black; width: 100px; height: 25px;"></div></td><td><div style="border: 1px solid black; width: 100px; height: 25px;"></div></td></tr></tbody></table>			Predicted	Measured	I_{supply}	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>	V_{load}	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>	I_{load}	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>
	Predicted	Measured											
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V_{load}	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>											
I_{load}	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>	<div style="border: 1px solid black; width: 100px; height: 25px;"></div>											

file 01611

Answer 62

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

Notes 62

The *real* challenge in this assessment is for students to determine their transformers' "polarities" before connecting them to the AC voltage source! For this, they should have access to a small battery and a DC voltmeter (at their desks).

You may use a Variac at the test bench to provide variable-voltage AC power for the students' transformer circuits. I recommend specifying load resistance values low enough that the load current completely "swamps" the transformer's magnetization current. This may mean using wire-wound power resistors instead of $\frac{1}{4}$ watt carbon composition resistors.

Note that there may very well be a shock hazard associated with this circuit, as the output voltage is not far below the line voltage! Be sure to take this into consideration when specifying load resistor values. You may also want to use low supply voltage levels (turn the Variac *way* down).

In lieu of using a line-powered transformer, you may also do this exercise with a signal generator and an audio-frequency transformer. The principles are the same, and the safety hazard will be vastly reduced. If using a 1000:8 ohm transformer, the winding turns ratio is approximately 11.18 to 1.

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: Auto-transformers	Version:												
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Description</div> <p style="text-align: center; margin-top: 20px;">Connect a step-down power transformer in the "boost" auto-transformer configuration, and use it to power a low-resistance load.</p> <p style="text-align: center; margin-top: 20px;"><i>There must be no exposed line power conductors!</i></p>													
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Given conditions</div> <div style="display: flex; justify-content: space-around; margin-top: 10px;"><div>$V_{\text{supply}} =$</div><div>$R_{\text{load}} =$</div><div>Transformer step-down ratio =</div></div>													
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Parameters</div> <table style="width: 100%; margin-top: 10px;"><thead><tr><th></th><th style="text-align: center;">Predicted</th><th style="text-align: center;">Measured</th></tr></thead><tbody><tr><td style="text-align: right;">I_{supply}</td><td style="border: 1px solid black; width: 100px; height: 30px;"></td><td style="border: 1px solid black; width: 100px; height: 30px;"></td></tr><tr><td style="text-align: right;">V_{load}</td><td style="border: 1px solid black; width: 100px; height: 30px;"></td><td style="border: 1px solid black; width: 100px; height: 30px;"></td></tr><tr><td style="text-align: right;">I_{load}</td><td style="border: 1px solid black; width: 100px; height: 30px;"></td><td style="border: 1px solid black; width: 100px; height: 30px;"></td></tr></tbody></table>			Predicted	Measured	I_{supply}			V_{load}			I_{load}		
	Predicted	Measured											
I_{supply}													
V_{load}													
I_{load}													

Answer 63

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

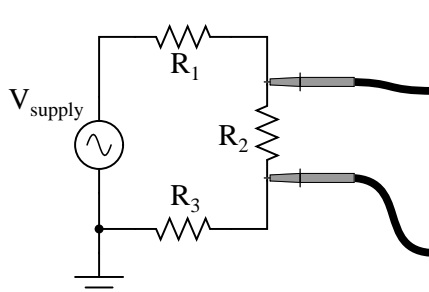
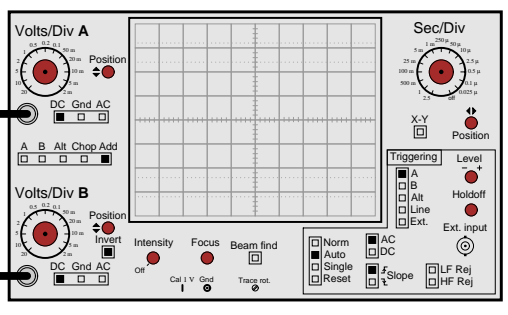
Notes 63

The *real* challenge in this assessment is for students to determine their transformers' "polarities" before connecting them to the AC voltage source! For this, they should have access to a small battery and a DC voltmeter (at their desks).

You may use a Variac at the test bench to provide variable-voltage AC power for the students' transformer circuits. I recommend specifying load resistance values low enough that the load current completely "swamps" the transformer's magnetization current. This may mean using wire-wound power resistors instead of $\frac{1}{4}$ watt carbon composition resistors.

Note that there may very well be a shock hazard associated with this circuit, as you are "boosting" the supply voltage! Be sure to take this into consideration when specifying load resistor values. You may also want to use low supply voltage levels (turn the Variac *way* down).

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: Differential voltage measurement		Version:	
Schematic			
			
Given conditions			
$V_{\text{supply}} =$	$R_1 =$	$R_2 =$	$R_3 =$
Parameters			
V_{R2}	Predicted <div style="border: 1px solid black; width: 100px; height: 30px; margin: 5px;"></div>	Measured <div style="border: 1px solid black; width: 100px; height: 30px; margin: 5px;"></div>	
Fault analysis			
Suppose component <div style="border: 1px solid black; width: 50px; height: 20px; display: inline-block;"></div> fails <div style="display: inline-block; vertical-align: middle; margin-left: 10px;"> <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted </div> <p><i>What will happen in the circuit?</i></p>			

Answer 64

The predicted value should be easy enough to figure out, given this is nothing more than a resistive voltage divider. If you are not configuring the oscilloscope properly, you will not get the correct measurement value!

Notes 64

The nature of the AC signal source is not crucial, so long as an accurate peak measurement may be obtained. I recommend specifying equal-value resistors to make the voltage drop calculation as easy as possible. The purpose of this exercise is not how to calculate voltage divider outputs, but rather how to utilize both inputs of a dual-trace oscilloscope to perform *differential* voltage measurements.

Question 65

NAME: _____

Project Grading Criteria

PROJECT: _____

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

100 % (*Must meet or exceed all criteria listed*)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

0 % (*If any of the following conditions are true*)

- A. Fails final safety inspection (improper grounding, fusing, and/or power cord strain relieving)
 - B. Intended project function poses a safety hazard
 - C. Project function violates any law, ordinance, or school policy
- file 03173

Answer 65

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

Notes 65

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 66

When an electric current is passed through a coil of wire, what phenomenon occurs?
file 00460

Answer 66

Electromagnetism.

Notes 66

Be sure that students understand the answer to this question beyond saying the word, "electromagnetism." What, exactly, does this word mean? Reciting an equation is not a sufficient explanation, either. Ask them what some of the factors are that influence the strength of the electromagnetic effect.

Question 67

When a coil of wire "cuts through" magnetic lines of flux, what phenomenon occurs?
file 00461

Answer 67

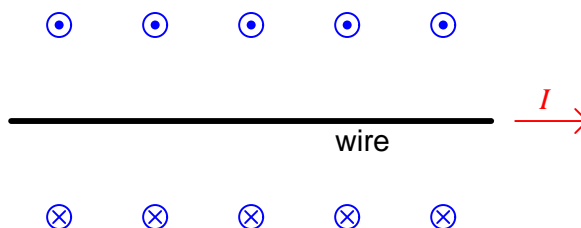
Electromagnetic induction.

Notes 67

Be sure that students understand the answer to this question beyond saying the phrase, "electromagnetic induction." What, exactly, does this phrase mean? Reciting an equation is not a sufficient explanation, either. Ask them what some of the factors are that influence the strength of the inductive effect.

Question 68

When engineers and physicists draw pictures illustrating the magnetic field produced by a straight current-carrying wire, they usually do so using this notation:



Explain what the circle-and-dot and circle-and-cross symbols mean, with reference to the *right-hand rule*.

file 03498

Answer 68

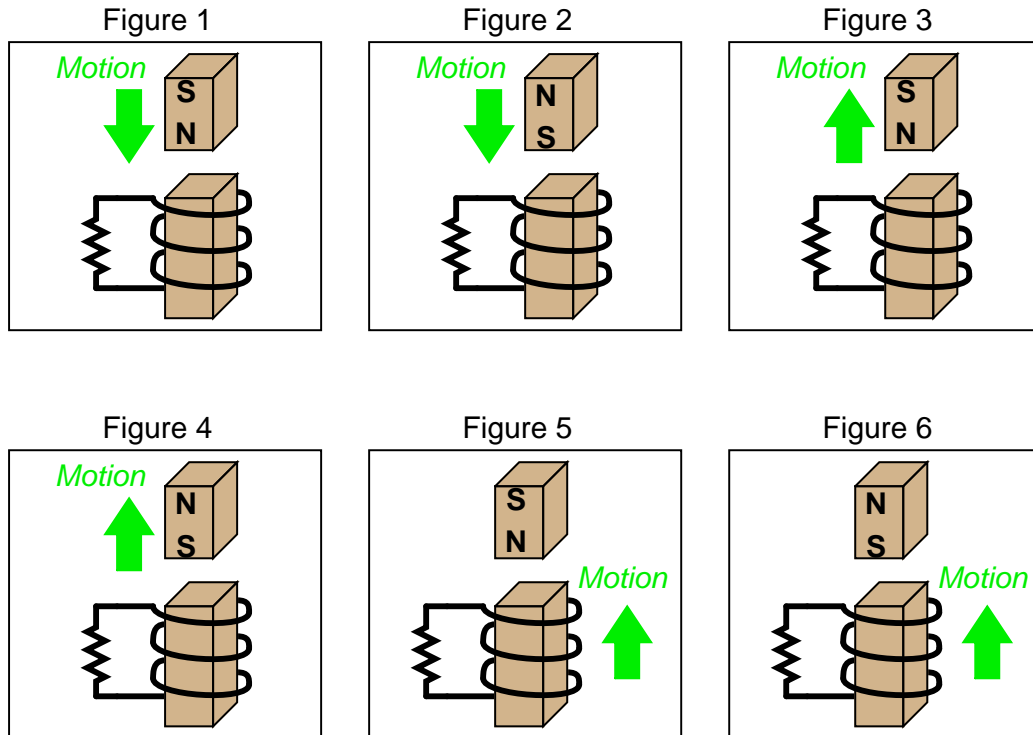
The circles with dots show the magnetic flux vectors coming at you from out of the paper. The circles with crosses show the magnetic flux vectors going away from you into the paper. Think of these as images of arrows with points (dots) and fletchings (crosses).

Notes 68

As a follow-up to this question, you might wish to draw current-carrying wires at different angles, and with current moving in different directions, as practice problems for your students to draw the corresponding arrow points and tails.

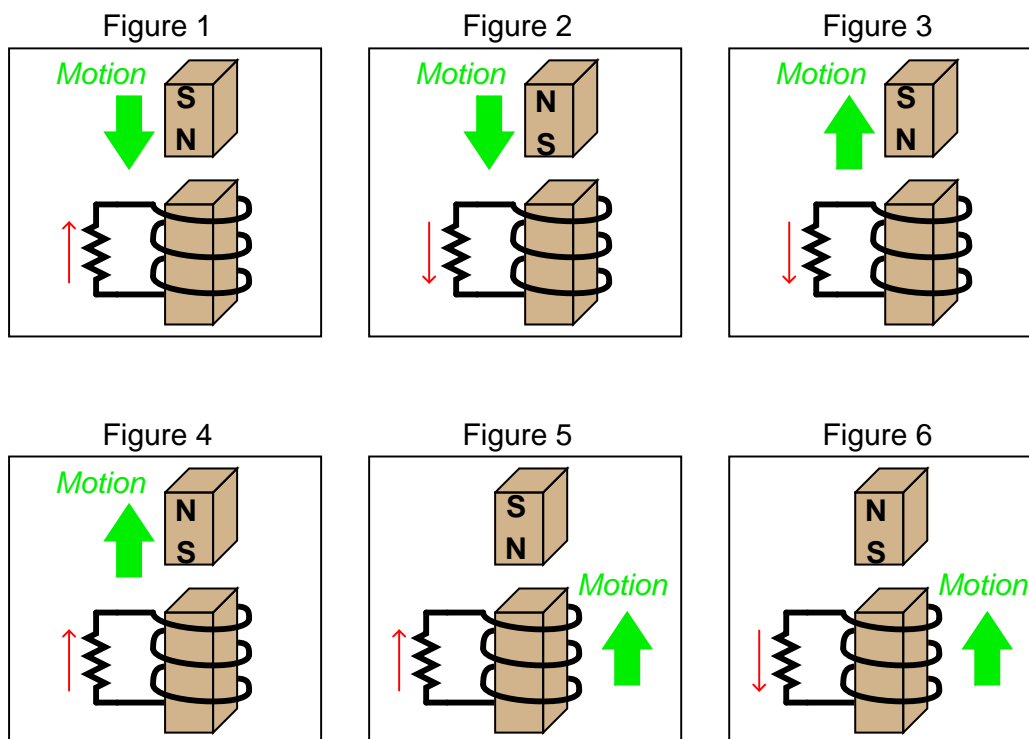
Question 69

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



file 01787

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



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

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

Question 70

Determine the polarity of the coil's induced voltage for each of the following examples. Be careful to note the direction each coil is wrapped around its core – the coils are not all identical!

Figure 1

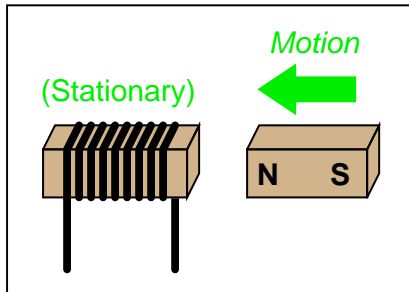


Figure 2

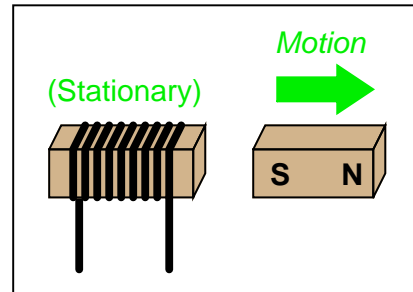


Figure 3

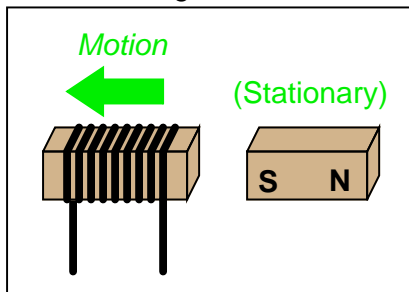
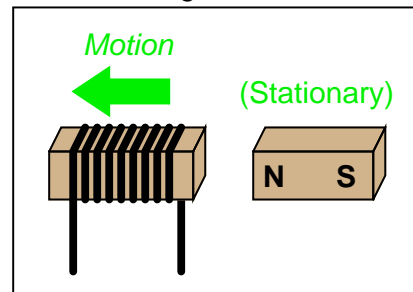


Figure 4



file 01788

Figure 1

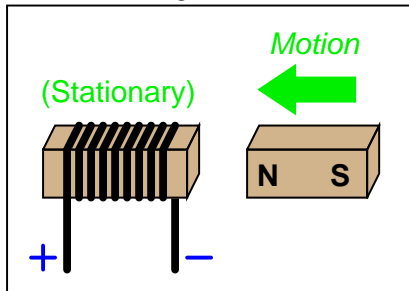


Figure 2

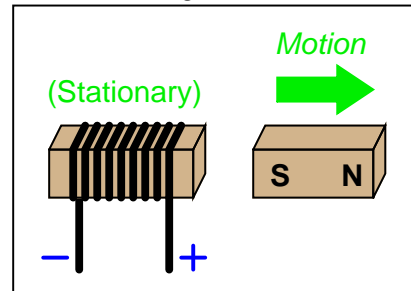


Figure 3

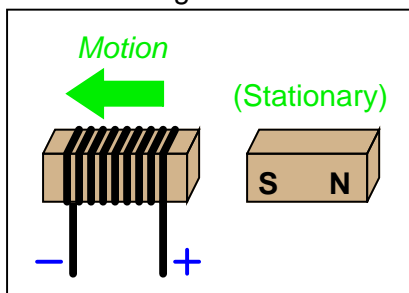
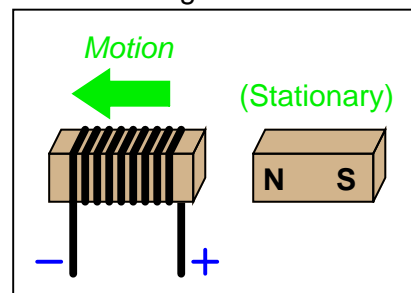


Figure 4



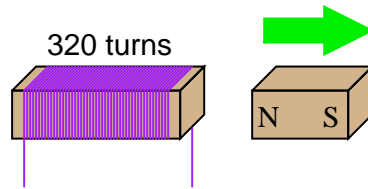
Notes 70

It might help students to visualize the polarity if they imagine a resistive load connected between the two output terminals, and then figured out which direction induced *current* would go through that load. Once that determination is made, voltage polarity (considering the coil as an energy source) should be easier to visualize. A mistake many beginning students make when doing this, though, is to fail to recognize the coil as the *source* of electrical energy and the resistor as the *load*, so be prepared to address this misunderstanding.

If this does not help, suggest they first identify the magnetic polarity of the coil's induced field: determine which end of the coil is "trying" to be North and which is "trying" to be South. Of course, no induced field will form unless the coil has a complete circuit to sustain the induced current, but it is still helpful to imagine a load resistor or even a short completing the circuit so that induced current and thus induced magnetic polarity may be visualized.

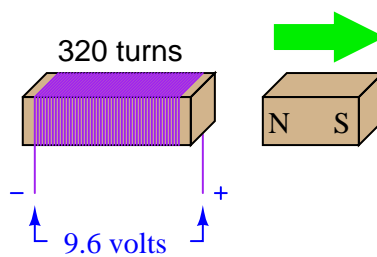
Question 71

If a wire coil with 320 turns is exposed to a magnetic flux decreasing at a rate of 0.03 Webers per second (as shown in the illustration), how much voltage will be induced across the coil, and what will its polarity be?



file 03272

Answer 71

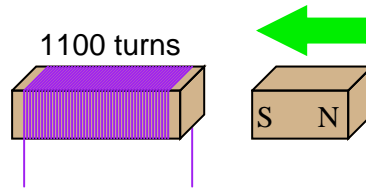


Notes 71

This question is both a quantitative application of Faraday's Law and an application of Lenz's Law.

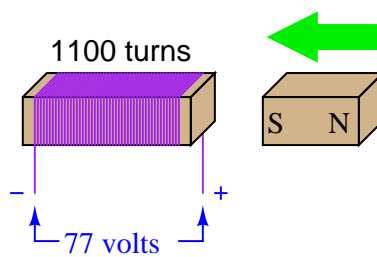
Question 72

If a wire coil with 1100 turns is exposed to a magnetic flux increasing at a rate of 0.07 Webers per second (as shown in the illustration), how much voltage will be induced across the coil, and what will its polarity be?



file 03273

Answer 72

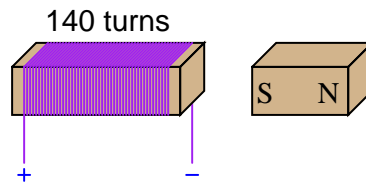


Notes 72

This question is both a quantitative application of Faraday's Law and an application of Lenz's Law.

Question 73

Calculate the necessary magnetic flux rate-of-change over time (in units of Webers per second) as well as the direction of magnet motion (either toward or away from the coil) to induce a voltage of 13.5 volts in the polarity shown:



[file 03274](#)

Answer 73

$\frac{d\phi}{dt}$ must be equal to 0.0964 Webers per second, with the magnet moving away from the coil.

Notes 73

This question is both a quantitative application of Faraday's Law and an application of Lenz's Law.

Question 74

Explain how the construction of a *step-down* transformer differs from that of a *step-up* transformer.
[file 02205](#)

Answer 74

Step-down transformers have fewer secondary turns than primary turns, while step-up transformers have more secondary turns than primary turns.

Notes 74

Ask your students to explain the relationship between primary and secondary turns, and how this affects the voltage transformation ratio, based on mutual inductance.

Question 75

Explain how the construction of an *isolation* transformer differs from that of a *step-up* or *step-down* transformer.

file 02209

Answer 75

Step-down transformers have fewer secondary turns than primary turns, while step-up transformers have more secondary turns than primary turns. Isolation transformers have equal turns in both windings.

Notes 75

Ask your students to explain the relationship between primary and secondary turns, and how this affects the voltage transformation ratio, based on mutual inductance.

Question 76

When calculating power in transformer circuits, how do the primary and secondary circuit powers ($P_{\text{primary}} = V_{\text{primary}}I_{\text{primary}}$ and $P_{\text{secondary}} = V_{\text{secondary}}I_{\text{secondary}}$) compare with each other? Is one greater than the other? If so, which one, and why?

[file 02211](#)

Answer 76

Ideally, $P_{\text{secondary}} = P_{\text{primary}}$, although this equivalence is never quite exact. In practice, $P_{\text{secondary}}$ will always be a little bit less than P_{primary} .

Notes 76

The simplest answer to this question is that $P_{\text{secondary}} = P_{\text{primary}}$, and this is a useful principle when doing transformer circuit calculations. Even when it is not precisely true, it is still a useful tool for checking the veracity of our calculations. Ask your students why this is.

Question 77

A mechanic goes to school and takes a course in AC electric circuits. Upon learning about step-up and step-down transformers, he makes the remark that "Transformers act like electrical versions of gears, with different ratios."

What does the mechanic mean by this statement? What exactly is a "gear ratio," and how does this relate to the subject of impedance matching?

file 00671

Answer 77

Just as meshing gears with different tooth counts transform mechanical power between different levels of speed and torque, electrical transformers transform power between different levels of voltage and current.

The concept of "impedance" is just as valid in mechanical systems as in electrical systems: a "low impedance" mechanical load requires high speed and low torque, whereas a "high impedance" load requires high torque and low speed. Gear systems provide impedance matching between mechanical power sources and loads in the same way that transformers provide impedance matching between (AC) electrical power sources and loads.

Notes 77

Not only is this a sound analogy, but one that many mechanically-minded people relate with easily! If you happen to have some mechanics in your classroom, provide them with the opportunity to explain the concept of gear ratios to those students who are unaware of gear system mathematics.

I normally do not elaborate this much in my answers, but in this case I believe it may be necessary, as this is quite a cognitive leap for some people. It is a leap well worth making, however, since it connects two (seemingly) disparate phenomenon in a way that provides a sound context for understanding the concept of impedance matching.

Question 78

Explain why transformers are used extensively in long-distance power distribution systems. What advantage do they lend to a power system?

file 02213

Answer 78

Transformers are used to step voltage up for efficient transportation over long distances, and used to step the high voltage down again for point-of-use circuits.

Notes 78

Ask your students to explain the answer in detail, rather than just repeating what the given answer states. Why is high-voltage power distribution more efficient than low-voltage distribution? Why would high voltage have to be stepped down for point-of-use applications?

Question 79

Are the transformers connecting power plant generators to high-voltage power lines considered *step-up* or *step-down*? Explain your answer.

file 02214

Answer 79

They are considered *step-up*.

Notes 79

Ask your students to define "step-up" and "step-down" in reference to power system transformers.

Question 80

A *soldering gun* is a tool used to quickly heat electrical connections for soldering. Too bulky for printed-circuit board (PCB) applications, it is better suited for point-to-point wiring applications where large wires are to be joined to metal lugs and to other wires.

In addition to being a useful soldering tool, this device is also an excellent example of a *step-down transformer*. Explain how the construction of a soldering gun employs a step-down transformer (with a very large step ratio!) to generate high temperatures at the soldering tip.

file 02167

Answer 80

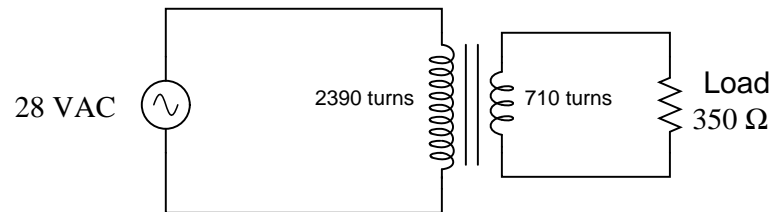
This question is best answered through disassembly and inspection of a real soldering gun. These tools are fairly easy to take apart and reassemble, so there should be little concern of damage from such exploration. Although it should go without saying, *never disassemble an electrical device that is still connected to line power!*

Notes 80

For students lacking soldering guns to take apart, and for those who do not want to take any chances ruining a tool through improper disassembly/reassembly, it is not difficult to find photographs of soldering gun internals. The step-down transformer assembly should be obvious when inspected.

Question 81

Calculate the load current and load voltage in this transformer circuit:



$$I_{load} =$$

$$V_{load} =$$

file 02210

Answer 81

$$I_{load} = 23.77 \text{ mA}$$

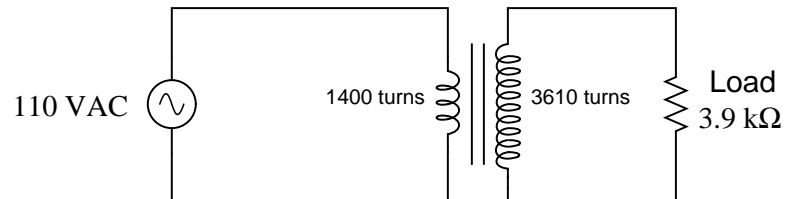
$$V_{load} = 8.318 \text{ V}$$

Notes 81

Most transformer problems are nothing more than ratios, but some students find ratios difficult to handle. Questions such as this are great for having students come up to the board in the front of the classroom and demonstrating how they obtained the results.

Question 82

Calculate the source current and load current in this transformer circuit:



$$I_{source} =$$

$$I_{load} =$$

file 02212

Answer 82

$$I_{source} = 187.5 \text{ mA}$$

$$I_{load} = 72.73 \text{ mA}$$

Notes 82

Most transformer problems are nothing more than ratios, but some students find ratios difficult to handle. Questions such as this are great for having students come up to the board in the front of the classroom and demonstrating how they obtained the results.

Question 83

Calculate the number of turns needed in the secondary winding of a transformer to transform a primary voltage of 300 volts down to a secondary voltage of 180 volts, if the primary winding has 1150 turns of wire.

$$N_{secondary} =$$

file 02215

Answer 83

$$N_{secondary} = 690 \text{ turns}$$

Notes 83

Most transformer problems are nothing more than ratios, but some students find ratios difficult to handle. Questions such as this are great for having students come up to the board in the front of the classroom and demonstrating how they obtained the results.

Question 84

Suppose you wished to measure the current of an AC motor, the full-load current of which should be about 150 amps. This current is much too great to measure directly with your only AC ammeter (rated 0 to 5 amps), and the only current transformers you have available are rated at 1200:5, which would not produce enough output current to drive the 0-5 amp meter movement very far at a load current of 150 amps. Sure, you would get a measurement, but it wouldn't be very accurate.

Figure out a way to overcome this measurement problem, so that a motor current of 150 amps will produce a more substantial deflection on the 0-5 amp meter movement scale.

[file 00759](#)

Answer 84

Perhaps the easiest solution is to wrap the power conductor so it goes through the CT toroid several times, thus changing its effective ratio.

Notes 84

The "multiple wrap" solution is a neat trick I've used more than once to measure current with an oversized current transformer. Discuss the effect of multiple "turns" of primary conductor on the ratio of a CT with your students, calculating the new ratios formed by doing so.

Although the "multiple wrap" solution is simple, it is not the only possible solution to this problem. Another solution would be to use multiple current transformers, but I'll leave that up to you and your students to figure out!

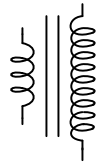
Question 85

Suppose you were using a 600 watt, 120 volt electric heater to pre-heat the oil in a hydraulic system, but determined later that this heater delivered too much heat to the oil. A 400 watt heater would be more appropriate for the task, but unfortunately another heater is not available in that power rating.

You realize that the power output of this 600 watt heater could be reduced by supplying it with less voltage. You also realize that a transformer could be used to reduce the AC voltage delivered to the heater without incurring the large power losses of a voltage-dropping resistor.

The following transformer types are available to use for the task:

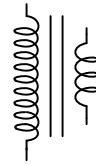
120 V / 10 kV
75 VA



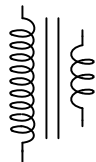
120 V / 120 V
isolation
0.5 kVA



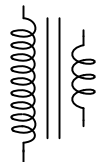
120 V / 24 V
150 VA



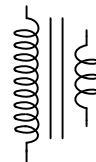
480 V / 120 V
0.6 kVA



120 V / 22 V
50 VA



208 V / 50 V
1.5 kVA



Design a circuit that uses one or more of these transformers to reduce the line voltage (120 VAC) down to an appropriate level so that the 600 watt heater will only output (approximately) 400 watts.

file 00094

Answer 85

You should have calculated a heater voltage of 98 volts necessary to produce 400 watts from the same heater that outputs 600 watts at 120 volts. It is possible to reduce 120 volts down to approximately 98 volts using the transformers shown here. Perhaps the most direct solution is to connect one of these units in a "bucking" configuration.

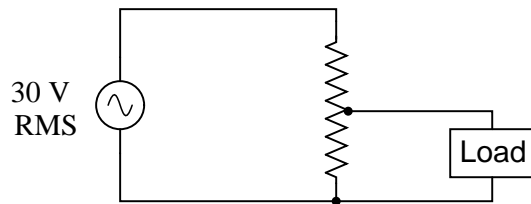
There is more than one possible solution to this problem using the transformer types available. You should realize, though, that there is more to consider than just getting the right voltage. Equally important to the solution is the transformers' ability to handle the current demanded by the heater.

Notes 85

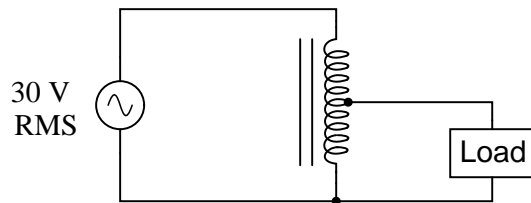
A problem such as this is very realistic: having to engineer a solution to a practical dilemma with a limited choice of components. Let your students know that solving problems in real life involves *creativity* just as much as it involves mathematical calculations and other "closed form" (single right answer) methods.

Question 86

It should be obvious that the load voltage in this resistive voltage divider circuit will be less than 30 volts AC (RMS):



Likewise, it should be apparent that the load voltage in this *inductive* voltage divider circuit will be less than 30 volts AC (RMS):



From this brief analysis it would appear these two voltage divider circuits are equivalent to one another. However, there is a very important difference in terms of *current*: load versus supply. Estimate the load and source currents in each of these divider circuits, and comment on the difference(s) between the two.

file 03219

Answer 86

In the resistive circuit, the load current will be less than the supply current. In the inductive (autotransformer) circuit, though, the load current will exceed the source current!

Notes 86

Ask your students to determine which voltage divider circuit will be more energy-efficient.

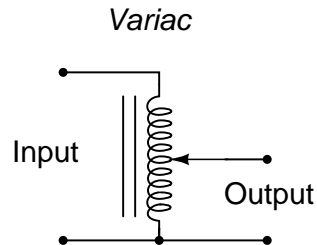
Question 87

A popular piece of electrical bench test equipment is the *Variac*. Explain what a Variac is, how it works, and what applications it might be used for.

file 03220

Answer 87

Here is the schematic diagram for a Variac:



I'll let you research the answers to the other parts of this question!

Notes 87

If you have a Variac in your lab, be sure to bring it to class for the discussion period so students may directly see what one looks like. If time permits, let your students experiment with it during discussion, to test their hypotheses about its function.

Question 88

A step-down transformer has a winding turns ratio of 20:1. Calculate the impedance ratio from primary to secondary. Also, determine the amount of impedance "seen" at the primary winding if the secondary winding is connected to a 90 ohm load.

Impedance ratio = $Z_{primary}$ =

file 02216

Answer 88

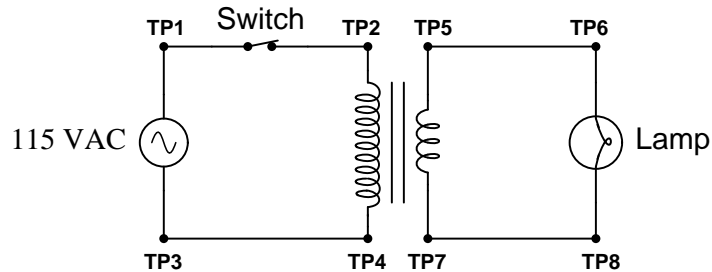
Impedance ratio = 400:1 $Z_{primary} = 36 \text{ k}\Omega$

Notes 88

Most transformer problems are nothing more than ratios, but some students find ratios difficult to handle. Questions such as this are great for having students come up to the board in the front of the classroom and demonstrating how they obtained the results. In this particular case there is more to the solution than just a simple ratio, which is even more reason to have students show their different solution techniques!

Question 89

The circuit shown here has a problem: the lamp does not light up, even though the AC power source is known to be good. You know that the circuit used to work just fine, so it is designed properly. Something in it has failed:



Identify one component or wire fault that could account for the lamp not lighting, and describe how you would use test equipment to verify that fault.

- One failed wire or component in the circuit that could possibly account for the problem, and the type of fault (open or short) you suspect it would be.
- Identify the type of test measurement you would take on this circuit, and where you would take it (identify the test points you would measure between) to verify the suspected fault.

file 02218

Answer 89

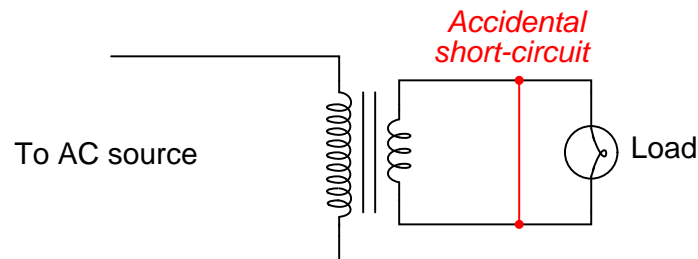
There are multiple possibilities here, and so I leave this up to you to determine!

Notes 89

Of course, faults in this circuit having nothing to do with the transformer could also prevent the light bulb from lighting. If time permits, it would be good to analyze a few failure scenarios with your students, challenging them to locate the source of the trouble as efficiently as possible.

Question 90

Suppose a step-down transformer fails due to an accidental short-circuit on the secondary (load) side of the circuit:



That the transformer actually failed as a result of the short is without any doubt: smoke was seen coming from it, shortly before current in the circuit stopped. A technician removes the burned-up transformer and does a quick continuity check of both windings to verify that it has failed open. What she finds is that the primary winding is open but that the secondary winding is still continuous. Puzzled at this finding, she asks you to explain how the *primary* winding could have failed open while the secondary winding is still intact, if indeed the short occurred on the secondary side of the circuit. What would you say? How is it possible that a fault on one side of the transformer caused the *other* side to be damaged?

[file 03587](#)

Answer 90

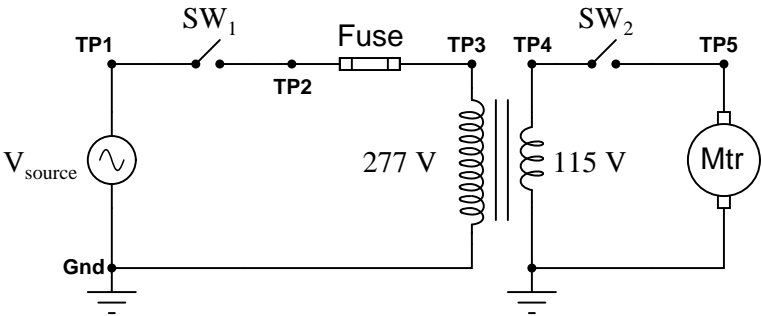
A short-circuit would cause current in *both* windings of the transformer to increase.

Notes 90

It is important for students to realize that a transformer "reflects" load conditions on the secondary side to the primary side, so that the source "feels" the load in all respects. What happens on the secondary (load) side will indeed be reflected on the primary (source) side.

Question 91

An AC motor receives reduced voltage through a step-down transformer so it may properly operate on a 277 volt source:



After years of trouble-free operation, something fails. Now, the motor refuses to operate when both switches are closed. A technician takes four voltage measurements between the following test points with both switches in the "on" position:

Step	Measurement
1	$V_{TP2-Gnd} = 277\text{ V}$
2	$V_{TP3-Gnd} = 277\text{ V}$
3	$V_{TP5-Gnd} = 0\text{ V}$
4	$V_{TP4-Gnd} = 0\text{ V}$

Complete this expanded table, following the technician's steps in the same order as the voltage measurements were taken, labeling each component's status as either "O" (possibly open), "S" (possibly shorted), or "OK" (known to be good). The first row of the table should contain many possible fault labels (because with little data there are many possibilities), but as more measurements are taken you should be able to limit the possibilities. Assume that only one component is faulted.

Step	Measurement	SW ₁	Fuse	Primary	Secondary	SW ₂	Motor
1	$V_{TP2-Gnd} = 277\text{ V}$						
2	$V_{TP3-Gnd} = 277\text{ V}$						
3	$V_{TP5-Gnd} = 0\text{ V}$						
4	$V_{TP4-Gnd} = 0\text{ V}$						

file 03588

Answer 91

Step	Measurement	SW ₁	Fuse	Primary	Secondary	SW ₂	Motor
1	$V_{TP2-Gnd} = 277 \text{ V}$	OK	O	O	O	O	O
2	$V_{TP3-Gnd} = 277 \text{ V}$	OK	OK	O	O	O	O
3	$V_{TP5-Gnd} = 0 \text{ V}$	OK	OK	O	O	O	OK
4	$V_{TP4-Gnd} = 0 \text{ V}$	OK	OK	O	O	OK	OK

Either the primary or the secondary winding is failed open!

Follow-up question: describe what you would measure next in this circuit to determine whether it is the primary or secondary winding that has failed open.

Notes 91

Students may ask why it is possible for us to say that the second switch and motor are okay after the technician measured 0 volts before each. Certainly we know something has failed *before* the points where 0 volts is measured, but that does not tell us the health of components after those points! The answer to this very good question is the assumption stated at the end of the question: that we are to assume *only one component fault in the circuit*. If either switch 2 or the motor were failed open, it would still not account for a lack of voltage between TP4 and ground. A shorted motor might, but then the fuse would have blown, resulting in 0 volts between TP3 and ground. So, we assume the motor and switch 2 must be okay because only some *other* single fault could cause the measurements we are reading.

Question 92

Explain what *leakage inductance* is, in a system of two or more mutually coupled inductors (such as a *transformer*). In a transformer, is leakage inductance a good thing or a bad thing?

file 01061

Answer 92

"Leakage inductance" is inductance that is *not* mutual between coupled inductors. It is caused by magnetic flux produced by one coil that does not "link" with turns of the other coil(s).

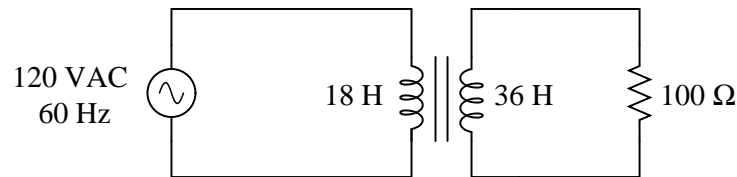
In power distribution transformers, leakage inductance is undesirable. However, there are some applications where leakage inductance is a desirable attribute. Step-up transformers used to power gas-discharge lights, for example, are purposely built to have significant amounts of leakage inductance.

Notes 92

After discussing the nature of leakage inductance (what causes it, and how it manifests itself in a transformer circuit), ask your students to explain why we do not want to have leakage inductance in a power distribution transformer, and why we do want to have it in a gas-discharge lighting transformer.

Question 93

Calculate the primary winding current (magnitude and phase angle) for this resistively loaded transformer, with a primary inductance of 18 Henrys and a secondary inductance of 36 Henrys:



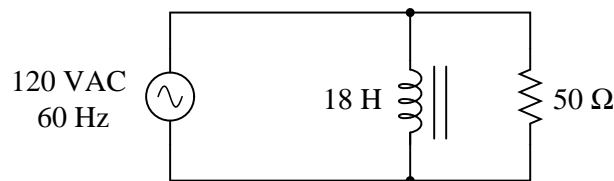
Also, draw an equivalent schematic diagram (with no transformer in it) illustrating the impedance "seen" by the AC power source. Assume no winding resistance in either transformer winding, and a magnetic coupling coefficient between the two windings of exactly 1.

file 01884

Answer 93

$$I_{primary} = 2.4001 \text{ A} \angle -0.42^\circ$$

Equivalent (transformerless) circuit



Follow-up question: what is the "step" ratio of this transformer, and is it step-up or step-down?

Notes 93

This question illustrates how reflected load impedance is "seen" by the source, and how it interacts with the transformer's intrinsic winding impedance.

Question 94

An unloaded power transformer draws a primary current of 85 mA from its 240 volt, 60 Hz source. Neglecting any power losses, calculate the inductance of the primary winding. Also, calculate the inductance of the secondary winding given a step-down voltage ratio of 8:1.

$$L_{primary} =$$

$$L_{secondary} =$$

file 02217

Answer 94

$$L_{primary} = 7.49 \text{ H}$$

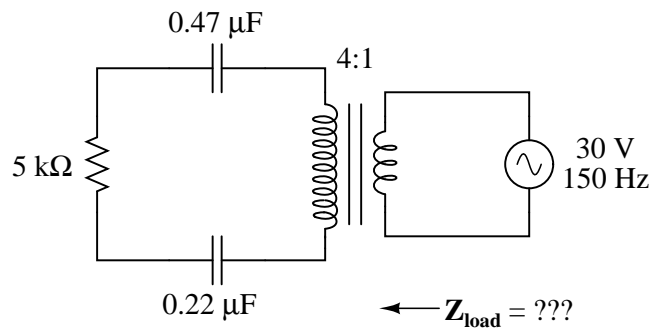
$$L_{secondary} = 117 \text{ mH}$$

Notes 94

Ask your students to describe the mathematical relationship between winding turns ratio and inductance ratio.

Question 95

Calculate the load impedance "seen" by the source, through the ideal transformer with a winding turns ratio of 4:1.



file 01060

Answer 95

$$\mathbf{Z_{load} = 541.7\text{ }\Omega \angle -54.77^\circ}$$

Notes 95

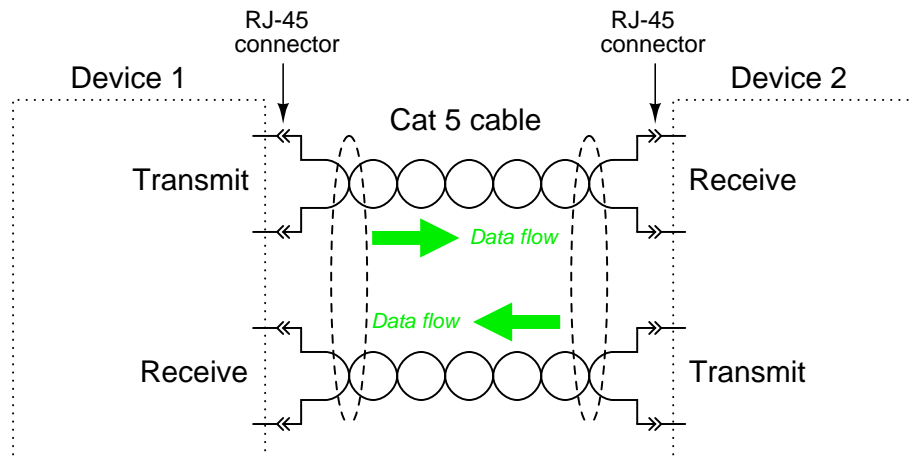
Ask your students to describe the effect of the transformer's step-up ratio on impedance magnitude and on impedance phase angle. They may do this by comparing the impedance of the C-R-C circuit on the transformer's secondary side versus the impedance "seen" at the voltage source terminals. Ask them to explain why one of these parameters is affected but the other is not.

Then, pose the scenario of a real transformer, complete with leakage inductance. Ask your students to explain what effect would leakage inductance have on the load impedance of this circuit.

Question 96

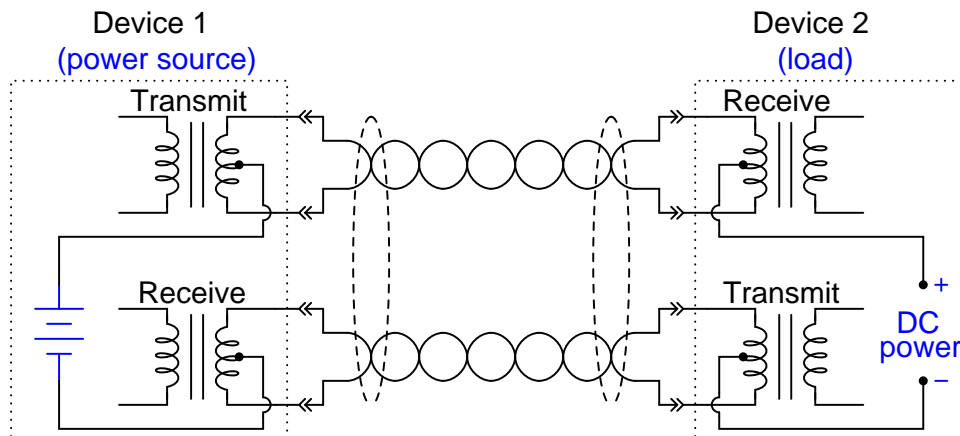
Ethernet is a popular communications standard for many digital devices, personal computers included. Originally, Ethernet was intended to be a network standard for conveying digital data only, without power. In later years, however, upgrades to the standard allowed DC power to be conveyed over the same wire pairs. The IEEE standard 802.3af is one example of a power-over-Ethernet standard.

Shown here is a schematic showing how two Ethernet devices connect together over a Category 5 ("Cat 5") twisted-pair cable, with no DC power conveyed over the cabling:



Digital data consists of voltage pulses over time (AC, essentially), conducted between the two devices over two sets of twisted-pair wires.

The next schematic shows the 802.3af standard allowing both DC power and digital data to be communicated over the same pairs of wires. Note the use of transformers at each device:



Explain what function(s) the transformers provide in this system, and how they allow DC power to travel through the wire pairs from source to load without interfering with the Ethernet data signals, which are AC.

file 02123

Answer 96

Trace the DC current from source to load and you will see that there is zero net magnetic flux in the transformer cores resulting from the DC, meaning that the transformers do not "see" the DC current for all practical purposes.

Notes 96

This is an interesting application of transformers: isolation of DC allowing a form of "power line carrier" system to be made without the use of filter networks.

Actually, there is more to the **802.3af** standard than what is shown in the second schematic diagram. This standard also allows the use of the other two pairs of wires in Cat 5 cable as dedicated power conductors. I omit this aspect for simplicity.

Question 97

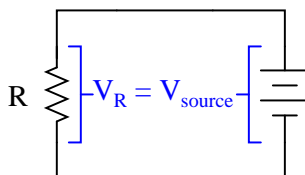
$\int f(x) dx$ Calculus alert!

In a simple resistor circuit, the current may be calculated by dividing applied voltage by resistance:



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

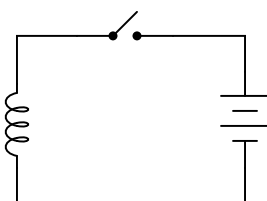
Although an analysis of this circuit probably seems trivial to you, I would like to encourage you to look at what is happening here from a fresh perspective. An important principle observed many times in the study of physics is that of *equilibrium*, where quantities naturally "seek" a state of balance. The balance sought by this simple circuit is equality of voltage: the voltage across the resistor must settle at the same value as the voltage output by the source:



If the resistor is viewed as a source of voltage seeking equilibrium with the voltage source, then current *must* converge at whatever value necessary to generate the necessary balancing voltage across the resistor, according to Ohm's Law ($V = IR$). In other words, *the resistor's current achieves whatever magnitude it has to in order to generate a voltage drop equal to the voltage of the source.*

This may seem like a strange way of analyzing such a simple circuit, with the resistor "seeking" to generate a voltage drop equal to the source, and current "magically" assuming whatever value it must to achieve that voltage equilibrium, but it is helpful in understanding other types of circuit elements.

For example, here we have a source of DC voltage connected to a large coil of wire through a switch. Assume that the wire coil has negligible resistance ($0\ \Omega$):



Like the resistor circuit, the coil will "seek" to achieve voltage equilibrium with the voltage source once the switch is closed. However, we know that the voltage induced in a coil is not directly proportional to current as it is with a resistor – instead, a coil's voltage drop is proportional to the *rate of change of magnetic flux over time* as described by Faraday's Law of electromagnetic induction:

$$v_{coil} = N \frac{d\phi}{dt}$$

Where,

v_{coil} = Instantaneous induced voltage, in volts

N = Number of turns in wire coil

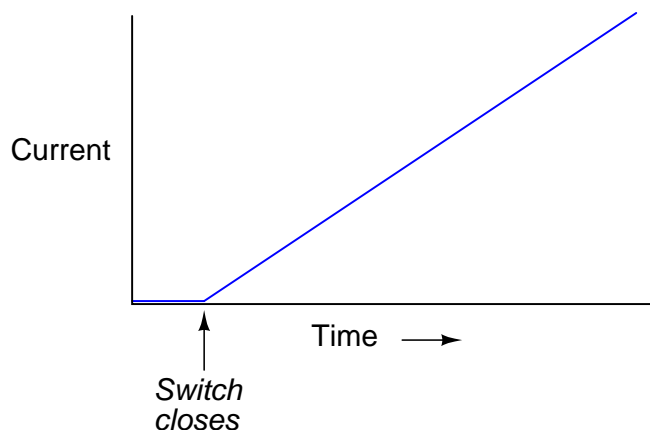
$\frac{d\phi}{dt}$ = Instantaneous rate of change of magnetic flux, in webers per second

Assuming a linear relationship between coil current and magnetic flux (i.e. ϕ doubles when i doubles), describe this simple circuit's current over time after the switch closes.

file 01560

Answer 97

When the switch closes, current will steadily increase at a linear rate over time:



Challenge question: real wire coils contain electrical resistance (unless they're made of superconducting wire, of course), and we know how voltage equilibrium occurs in resistive circuits: the current converges at a value necessary for the resistance to drop an equal amount of voltage as the source. Describe, then, what the current does in a circuit with a *real* wire coil, not a superconducting wire coil.

Notes 97

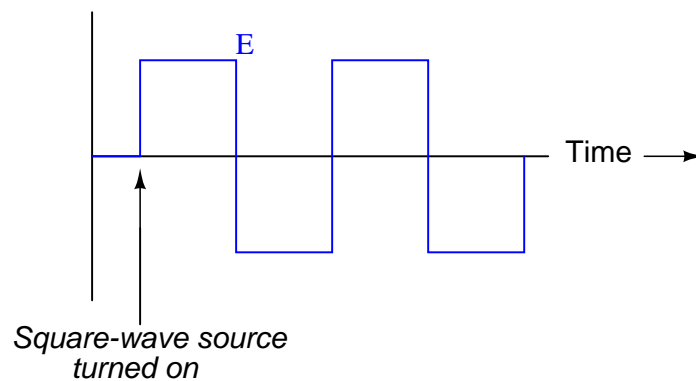
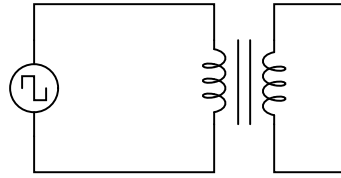
Students who do not yet understand the concept of inductance may be inclined to suggest that the current in this circuit will be infinite, following Ohm's Law ($I = E/R$). One of the purposes of this question is to reveal such misunderstandings, so that they may be corrected.

This circuit provides an excellent example of the calculus principle *integration*, where the application of a steady voltage across the inductor results in a steadily *increasing* current. Whether or not you should touch on this subject depends on the mathematical aptitude of your students.

Question 98

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

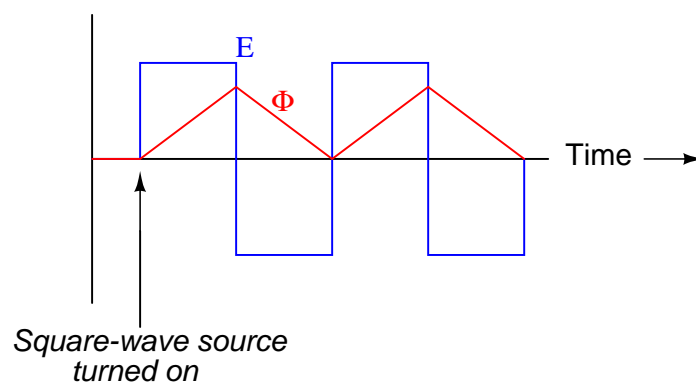
Plot the magnetic flux (Φ) over time in the core of an ideal transformer, given a square-wave voltage applied to the primary winding:



Hint: The output voltage (measured at the secondary winding) will also be a square wave, perfectly in-phase with the source (primary) voltage.

[file 01669](#)

Answer 98



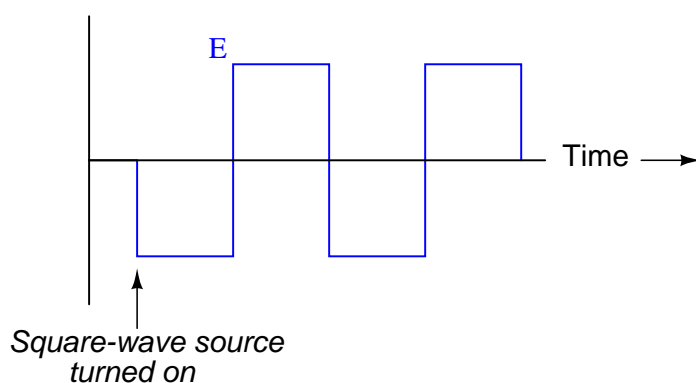
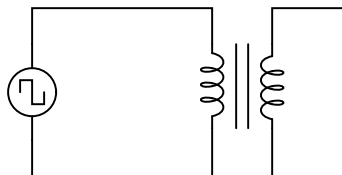
Notes 98

Have students relate the equation $E_L = N \frac{d\phi}{dt}$ to this problem, discussing the flux wave-shape in terms of rate-of-change over time.

Question 99

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

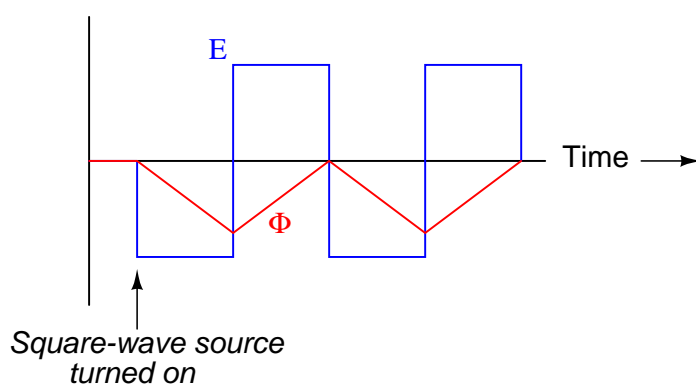
Plot the magnetic flux (Φ) over time in the core of an ideal transformer, given a square-wave voltage applied to the primary winding:



Hint: The output voltage (measured at the secondary winding) will also be a square wave, perfectly in-phase with the source (primary) voltage.

[file 01671](#)

Answer 99



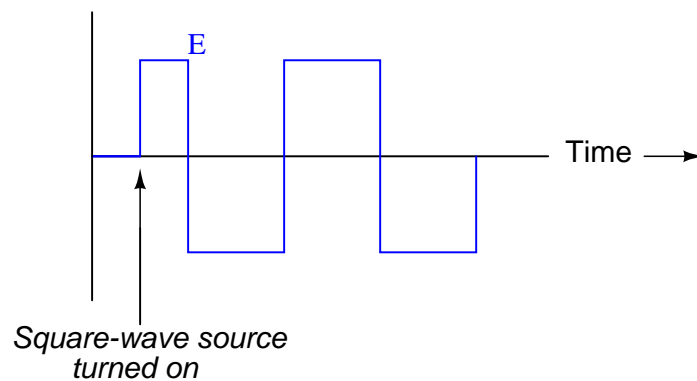
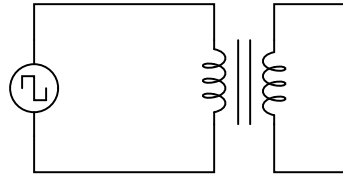
Notes 99

Have students relate the equation $E_L = N \frac{d\phi}{dt}$ to this problem, discussing the flux wave-shape in terms of rate-of-change over time.

Question 100

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

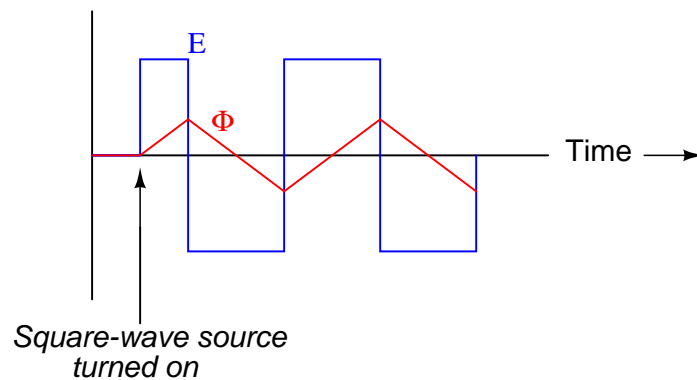
Plot the magnetic flux (Φ) over time in the core of an ideal transformer, given a square-wave voltage applied to the primary winding:



Important: note the point in time where the square-wave source is energized. The first pulse of applied voltage to the primary winding is not full-duration!

[file 01670](#)

Answer 100



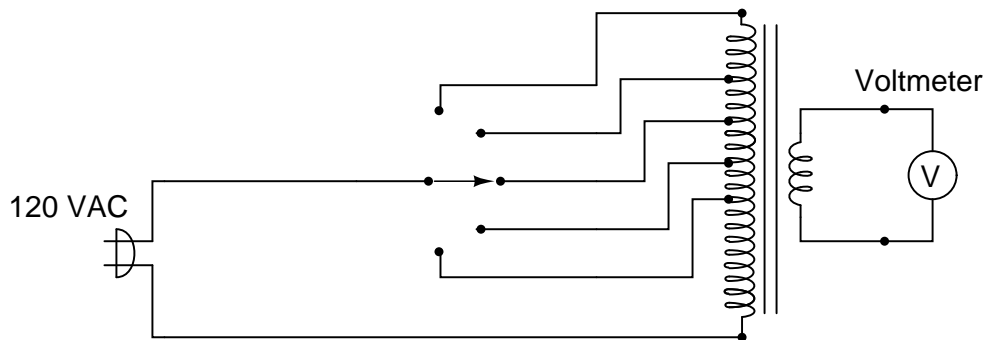
Follow-up question: explain why the flux waveform is symmetrical about the zero line (perfectly balanced between positive and negative half-cycles) in this particular scenario. How would this situation differ if the square-wave voltage source were energized at a slightly different point in time?

Notes 100

Have students relate the equation $E_L = N \frac{d\phi}{dt}$ to this problem, discussing the flux wave-shape in terms of rate-of-change over time.

Question 101

Suppose you were testing this step-down transformer, moving the selector switch between its various positions and measuring the transformer's output voltage at each switch position:



You notice something strange: when the switch is moved to the position producing the greatest output voltage, the transformer audibly "buzzes." It produces no noticeable noise in any of the other switch positions. Why is this happening?

Hint: if the switch is left in the "buzzing" position for any substantial amount of time, the transformer temperature begins to increase.

[file 00056](#)

Answer 101

The transformer core is *saturating* when the switch is in that one position. This accounts for both the noise and the heating.

Notes 101

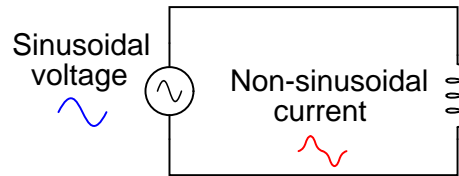
Discuss with your students *why* the transformer core saturates only in that one switch position. Why not in any of the other switch positions?

In a non-tapped transformer, what condition(s) lead to core saturation? How does this relate to the scenario shown here with a tapped transformer?

Ideally, power transformer circuits should be designed to avoid core saturation, but this is not always the case in cheap designs. I once encountered a tapped transformer, much like the one shown in the diagram, from an automotive battery charger which acted like this. It was an excellent example for my students to feel and hear magnetic saturation.

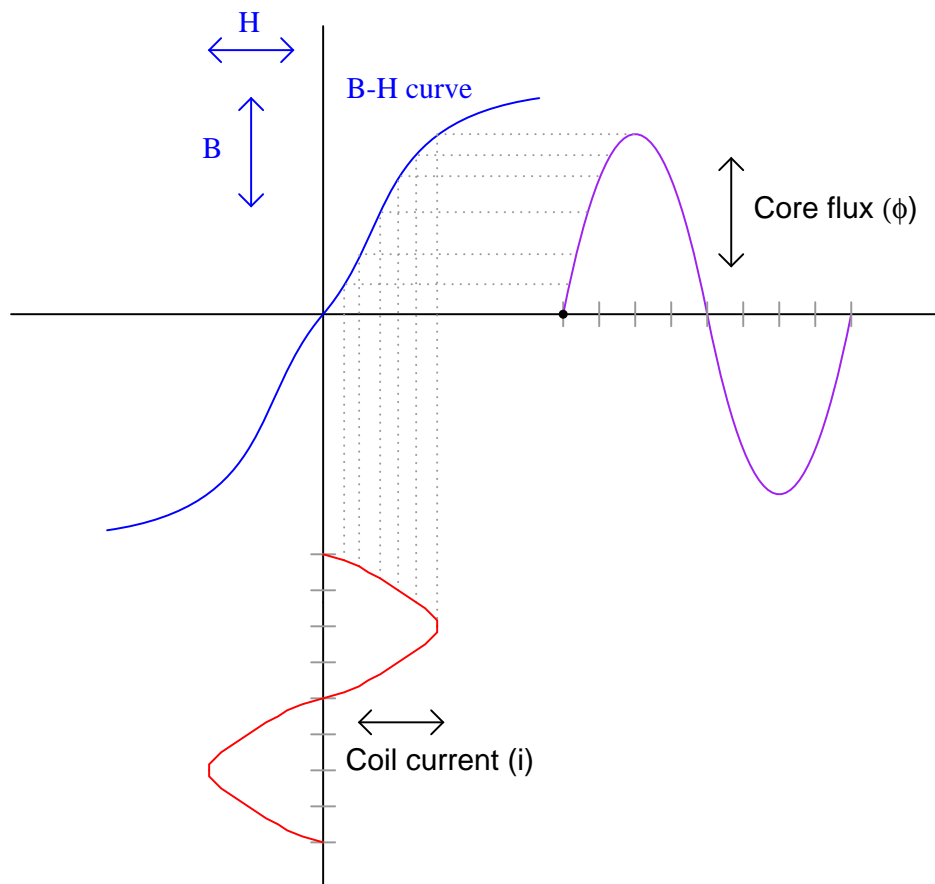
Question 102

It is a known fact that the nonlinearity of a ferromagnetic material's B-H curve will cause an inductor's current to be non-sinusoidal, even when the voltage impressed across the inductor is perfectly sinusoidal:



Unless coil resistance is substantial, the core flux waveform (ϕ) over time will be just as sinusoidal as the voltage waveform, because without resistance to drop voltage, the relationship between voltage and flux is $e = N \frac{d\phi}{dt}$, the rate-of-change of a perfect sine wave being a perfect cosine wave.

Knowing that the core flux waveform will be sinusoidal allows us to derive the inductor current waveform from the B-H curve using a graphical "trick": using the B-H curve to correlate instantaneous values of flux over time with instantaneous values of coil current over time. When used in this manner, the B-H curve is called a *transfer characteristic*, because it is used as a map to "transfer" points on one waveform to points on another waveform. We know that ϕ is directly proportional to B because $B = \frac{\Phi}{A}$, and the core area is constant. We also know that i is directly proportional to H , because $\mathcal{F} = NI$ and $H = \frac{\mathcal{F}}{l}$, and both the core length and the number of turns of wire are constant:



Notice that the flux waveform is nice and sinusoidal, while the current waveform is not.

Based on what you see here, describe how an inductor designer can minimize the current distortion in an inductor. What conditions make this distortion better, and what conditions make it worse?

file 00696

Answer 102

The key to minimizing current distortion is to keep the core flux amplitudes within the straightest portions of the core's B-H curve. Anything that causes the flux to reach greater amplitudes, and get closer to the "saturated" portion of the B-H curve, will create more distortion of the current waveform.

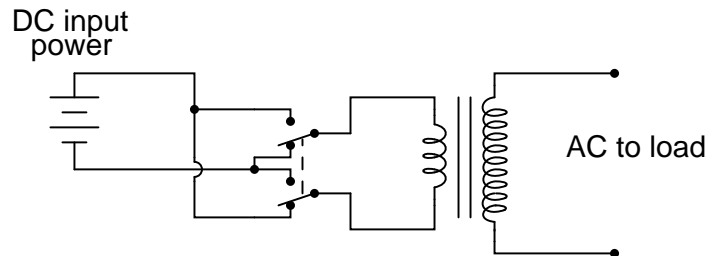
Notes 102

I wrote this question for the purpose of introducing students to a technique commonly found in older textbooks, but not found in newer textbooks quite as often: graphically generating a plot by the comparison of one waveform against a static function, in this case the comparison of the flux waveform against the B-H curve. Not only is this technique helpful in analyzing magnetic nonlinearities, but it also works well to analyze semiconductor circuit nonlinearities.

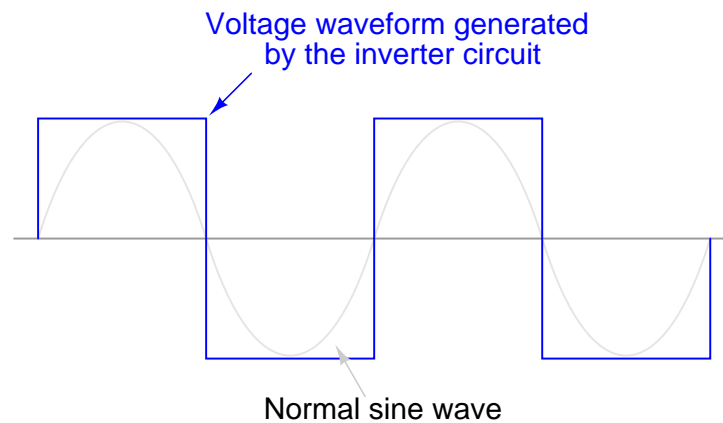
Question 103

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

Electronic power conversion circuits known as *inverters* convert DC into AC by using transistor switching elements to periodically reverse the polarity of the DC voltage. Usually, inverters also increase the voltage level of the input power by applying the switched-DC voltage to the primary winding of a step-up transformer. You may think of an inverter's switching electronics as akin to double-pole, double-throw switch being flipped back and forth many times per second:

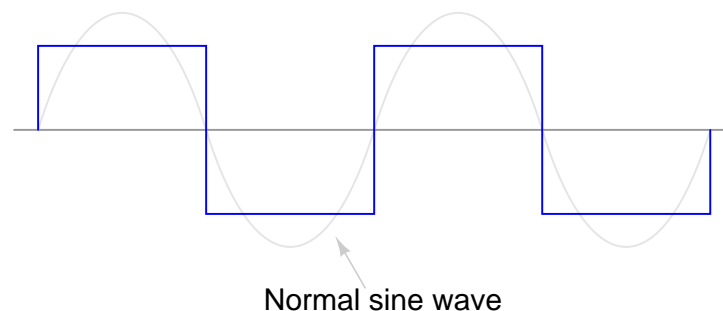


The first commercially available inverters produced simple square-wave output:

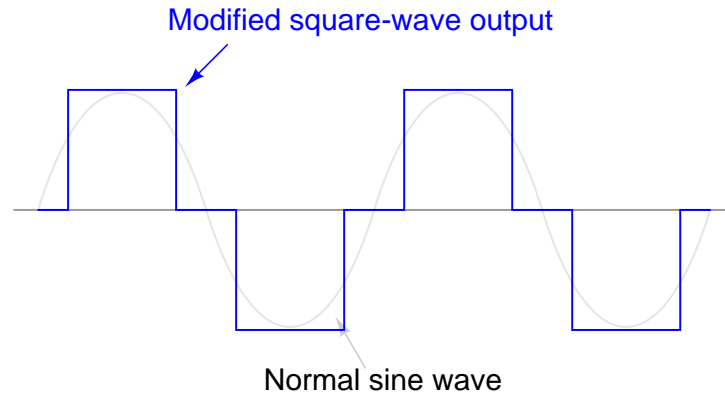


However, this caused problems for most power transformers designed to operate on sine-wave AC power. When powered by the square-wave output of such an inverter, most transformers would *saturate* due to excessive magnetic flux accumulating in the core at certain points of the waveform's cycle. To describe this in the simplest terms, a square wave possesses a greater *volt-second product* than a sine wave with the same peak amplitude and fundamental frequency.

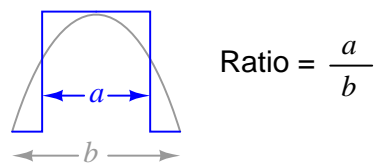
This problem could be avoided by decreasing the peak voltage of the square wave, but then some types of powered equipment would experience difficulty due to insufficient (maximum) voltage:



A workable solution to this dilemma turned out to be a modified duty cycle for the square wave:



Calculate the fraction of the half-cycle for which this modified square wave is "on," in order to have the same volt-second product as a sine wave for one-half cycle (from 0 to π radians):



Hint: it is a matter of calculating the respective *areas* underneath each waveform in the half-cycle domain.

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Answer 103

$$\text{Fraction} = \frac{2}{\pi} \approx 0.637$$

Challenge question: prove that the duty cycle fraction necessary for the square wave to have the same *RMS value* as the sine wave is exactly $\frac{1}{2}$. Hint: the volts-squared-second product of the two waveforms must be equal for their RMS values to be equal!

Notes 103

This problem is a great example of how integration is used in a very practical sense. Even if your students are unfamiliar with calculus, they should at least be able to grasp the concept of equal volt-second products for the two waveforms, and be able to relate that to the amount of magnetic flux accumulating in the transformer core throughout a cycle.