ELTR 120 (Semiconductors 1), section 3

Recommended schedule

Day 1

Topics: *Clipper, clamper, and voltage multiplier circuits*
Questions: *1 through 10*
Lab Exercise: *Diode clipper circuit (question 51)*

Day 2

Topics: *Thyristor devices*
Questions: *11 through 20*
Lab Exercise: *Work on project*

Day 3

Topics: *Thyristor power control circuits*
Questions: *21 through 30*
Lab Exercise: *SCR latch circuit (question 52)*

Day 4

Topics: *Pulse-width modulation power control*
Questions: *31 through 40*
Lab Exercise: *PWM power controller, discrete (question 53)*

Day 5

Topics: *Switching power supply circuits*
Questions: *41 through 50*
Lab Exercise: *Work on project*

Day 6

Exam 3: *includes thyristor latch circuit performance assessment*
Project due
Question 54: Sample project grading criteria

Troubleshooting practice problems

Questions: *55 through 64*

General concept practice and challenge problems

Questions: *65 through the end of the worksheet*

Skill standards addressed by this course section

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

D Technical Skills – Discrete Solid-State Devices
D.15 Understand principles and operations of thyristor circuitry (SCR, TRIAC, DIAC, etc.).
D.16 Fabricate and demonstrate thyristor circuitry (SCR, TRIAC, DIAC, etc.).
D.17 Troubleshoot and repair thyristor circuitry (SCR, TRIAC, DIAC, etc.).
E Technical Skills – Analog Circuits
E.07 Understand principles and operations of linear power supplies and filters.
E.08 Fabricate and demonstrate linear power supplies and filters.
E.09 Troubleshoot and repair linear power supplies and filters.
E.16 Understand principles and operations of regulated and switching power supply circuits.
E.29 Demonstrate an understanding of motor phase shift control circuits.

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

Common areas of confusion for students

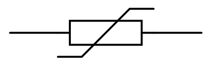
Difficult concept: *Reactive components as sources versus loads.*

The relationship between direction of current and polarity of voltage drop is simple and straightforward for resistors, because resistors always dissipate power. That is, a resistor will always act as a load. Things are not so simple for reactive components such as inductors and capacitors, however, because these components *store* and *release* energy while (ideally) dissipating none. This means they sometimes act as sources and other times act as loads. Since DC-DC converter circuits exploit the energy storage inherent to inductors and/or capacitors, this becomes a very important concept for students to grasp.

Question 1

What type of electronic component do these symbols represent, and what special function does it perform?

Alternative symbols



file 01985

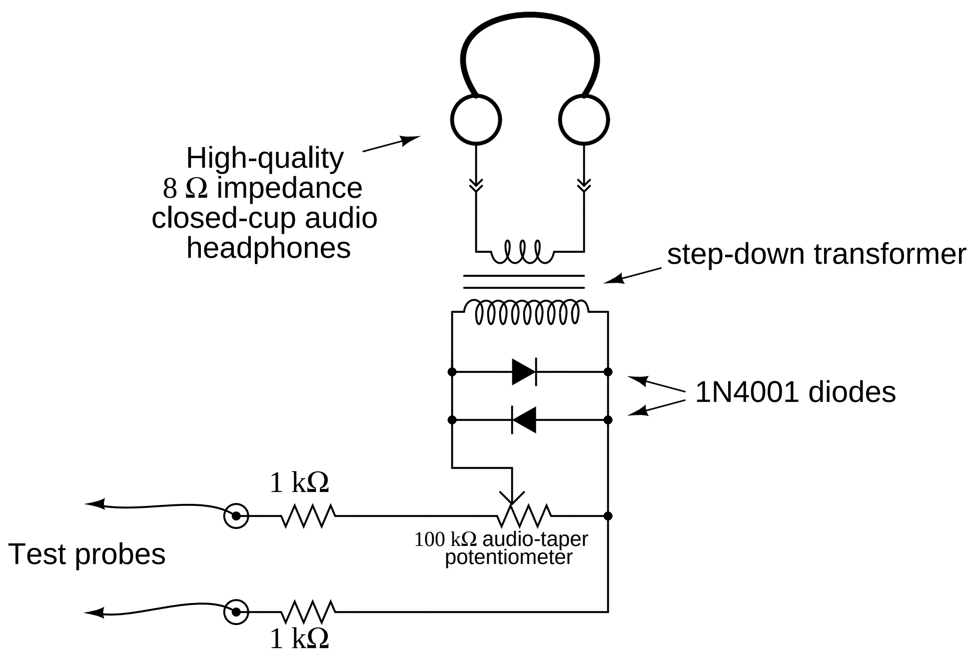
Question 2

Explain how a *surge protector* functions: the kind of device used to protect electronic equipment against common power line voltage transients. Draw a schematic diagram to accompany your explanation.

file 01110

Question 3

A technician builds her own audio test set for use in troubleshooting audio electronic circuitry. The test set is essentially a sensitive detector, allowing low-power audio signals to be heard:

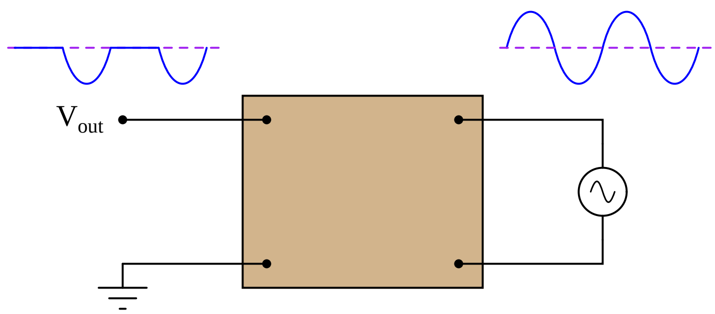


What purpose do the two diodes serve in this circuit? Hint: if you remove the diodes from the circuit, you will not be able to hear the difference in most cases!

file 00983

Question 4

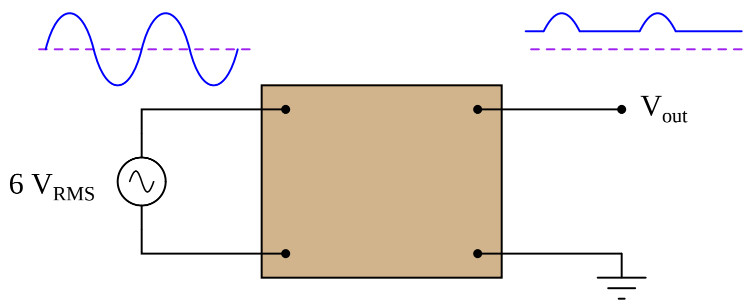
Design a clipper circuit that eliminates the positive portion of this AC waveform, leaving only the negative half-cycles to appear on the output:



file 01109

Question 5

Design a clipper circuit that clips any portion of the input AC waveform below +4 volts:



file 01113

Question 6

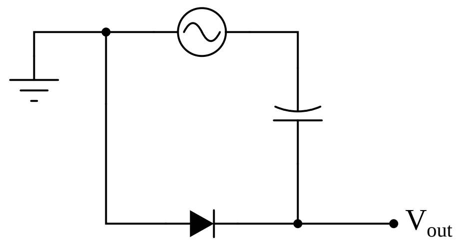
Clamper circuits are sometimes referred to as *DC restorer* circuits. Explain why.

Does a "clamper" circuit change the shape of a voltage waveform, like a "clipper" circuit does? Explain why or why not.

file 01116

Question 7

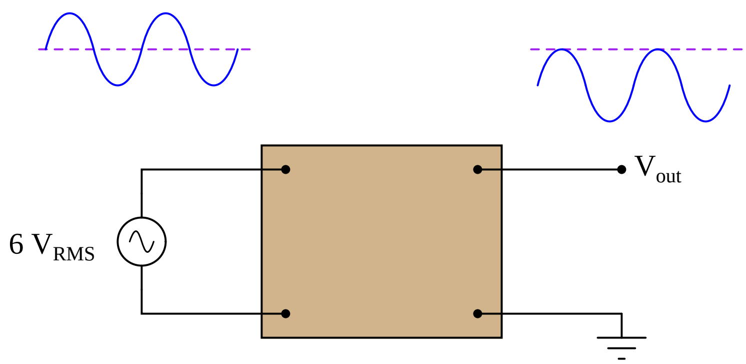
Draw the output waveform shape for this circuit, assuming an ideal diode (no forward voltage drop and no reverse leakage):



file 01115

Question 8

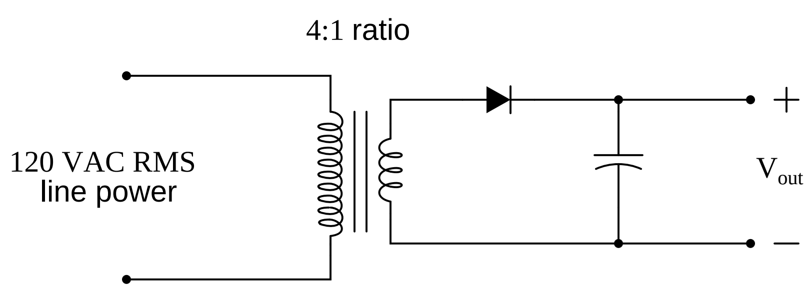
Design a clamper circuit that biases the AC waveform so it lies completely *below* (negative) the zero line:



file 02128

Question 9

A technician builds a simple half-wave rectifier circuit for a project, but is surprised to find that the diode keeps failing:

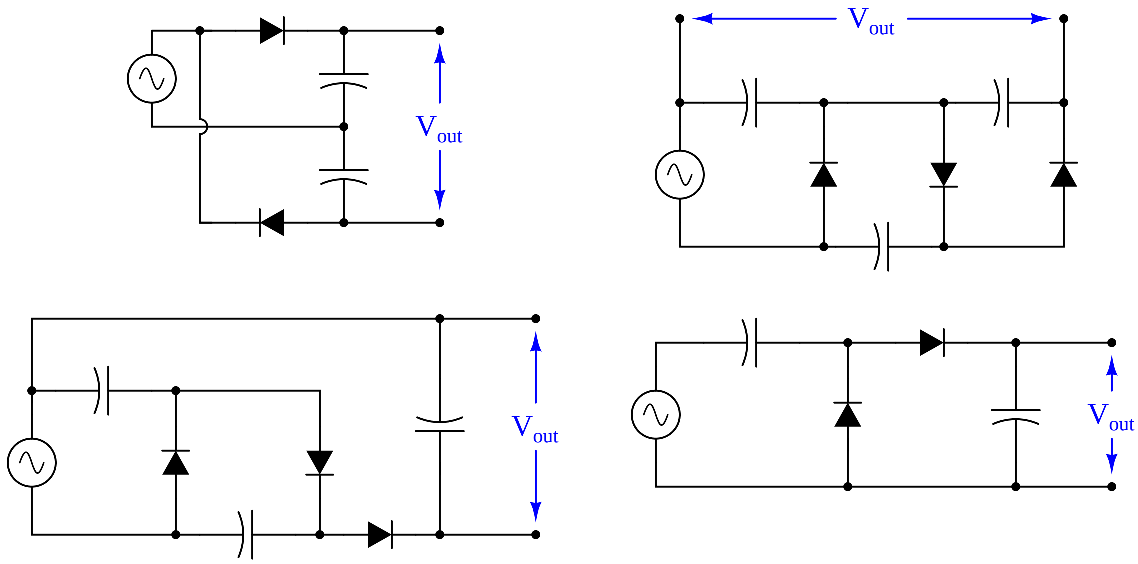


This comes as a surprise because the diode has a repetitive peak reverse voltage rating of 50 volts, which the technician knows is greater than the peak voltage output by the step-down transformer. However, the technician has overlooked something very important in this circuit design. Explain what the problem is, and how to solve it.

file 02007

Question 10

Diodes and capacitors may be interconnected to form a type of circuit that *boosts* voltage in the process of rectification. This type of circuit is generally known as a *voltage multiplier*. Shown here are a few different voltage multiplier circuits:



Determine the degree of voltage multiplication (double, triple, etc.) provided by each circuit.

file 02011

Question 11

All thyristor devices exhibit the property of *hysteresis*. From an electrical perspective, what is "hysteresis"? How does this behavior differ from that of "normal" active semiconductor components such as bipolar or field-effect transistors?

file 01089

Question 12

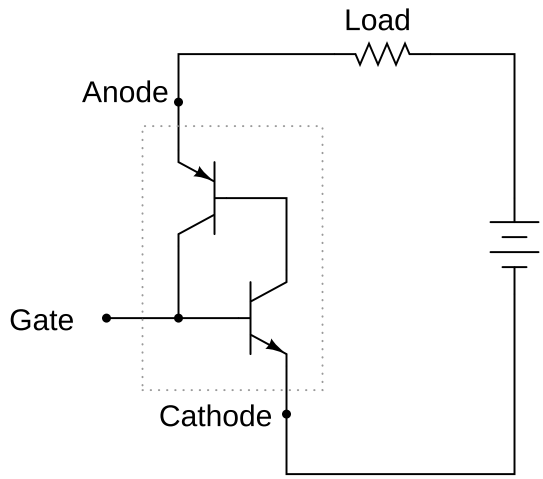
What is required to make a *Shockley diode* or *DIAC* begin conducting current? What condition(s) have to be met in order for electrical conduction to occur through one of these devices?

Also, explain what must be done to stop the flow of electric current through a Shockley diode or a DIAC.

file 01090

Question 13

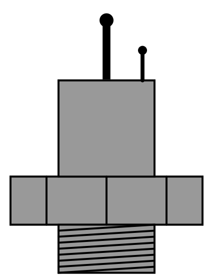
Silicon-controlled rectifiers (SCRs) may be modeled by the following transistor circuit. Explain how this circuit functions, in the presence of and absence of a "triggering" voltage pulse at the gate terminal:



file 01088

Question 14

Shown here is an illustration of a large "stud mount" type of SCR, where the body is threaded so as to be fastened to a metal base like a bolt threads into a nut:

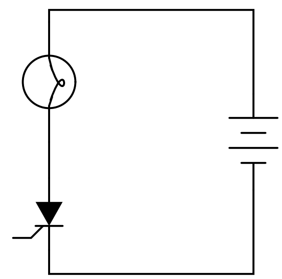


With no test instrument other than a simple continuity tester (battery and light bulb connected in series, with two test leads), how could you determine the identities of the three terminals on this SCR?

Hint: The threaded metal base of the SCR constitutes one of the three terminals.
file 01087

Question 15

Explain what must be done to the SCR to make it turn on and send power to the light bulb:



Next, explain what must be done to turn the SCR off so that the light bulb de-energizes.

file 02136

Question 16

Explain what a *TRIAC* is, and how it is at once similar and different from an SCR. What applications might a TRIAC be used in that an SCR would be inappropriate for?

file 02138

Question 17

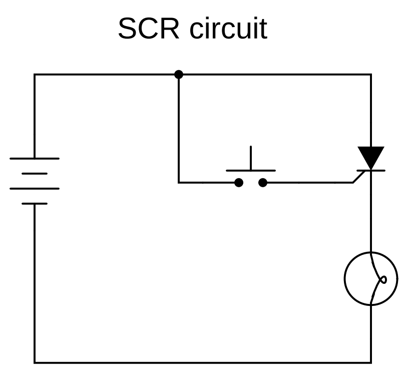
Identify three different ways that an SCR or a TRIAC may be triggered into its "on" (conducting) state:

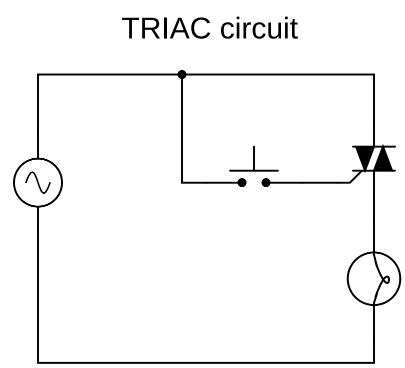
1.
2.
3.

file 02347

Question 18

Explain what happens in each of these circuits when the pushbutton switch is actuated and then released:

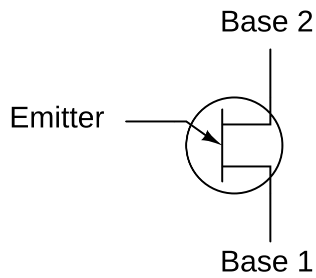




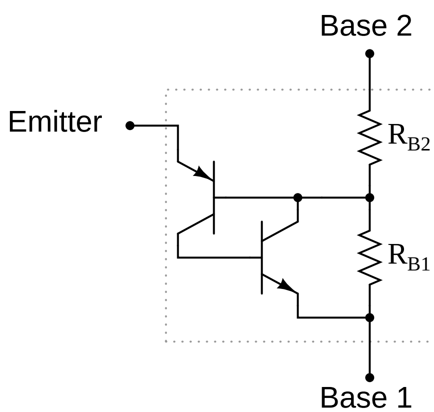
file 01094

Question 19

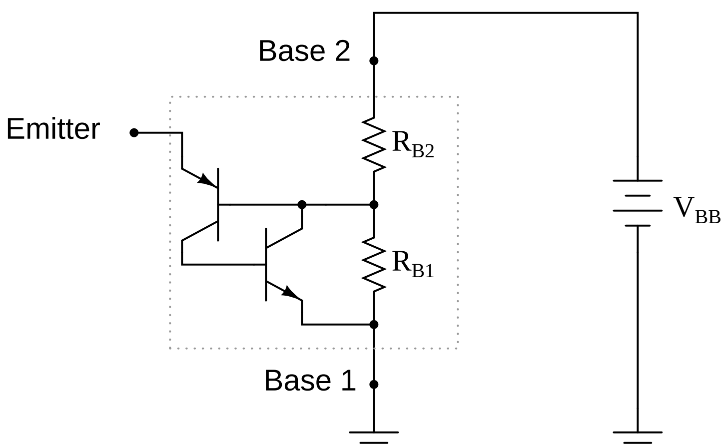
The *unijunction transistor*, or *UJT*, is an interesting device, exhibiting hysteresis just like SCRs and TRIACs. Its schematic symbol is as follows:



One equivalent circuit diagram for the UJT uses a pair of transistors and a pair of resistors:



When the two base terminals of a UJT are connected across a source of DC voltage, the two base resistances (R_{B1} and R_{B2}) form a voltage divider, splitting the applied voltage into lesser portions:

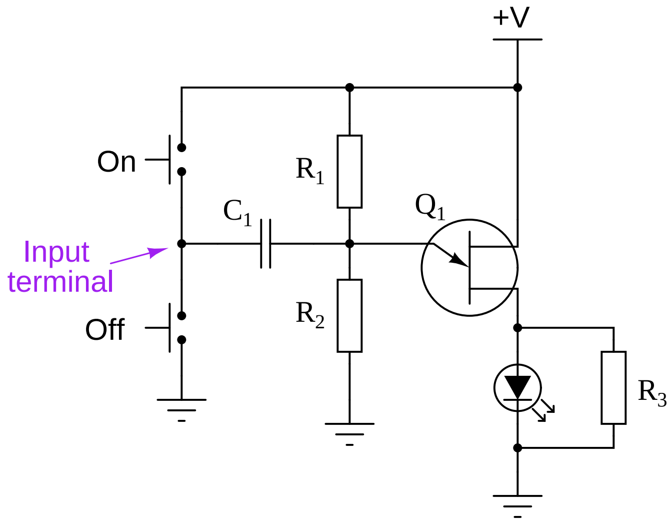


How much voltage, and of what polarity, must be applied to the emitter terminal of the UJT to turn it on? Write an equation solving for the magnitude of this triggering voltage (symbolized as V_P), given R_{B1}, R_{B2}, and V_{BB}.

file 02139

Question 20

This circuit uses a *unijunction transistor* (UJT) to latch an LED in the "on" state with a positive pulse at the input terminal. A negative voltage pulse at the input terminal turns the LED off:

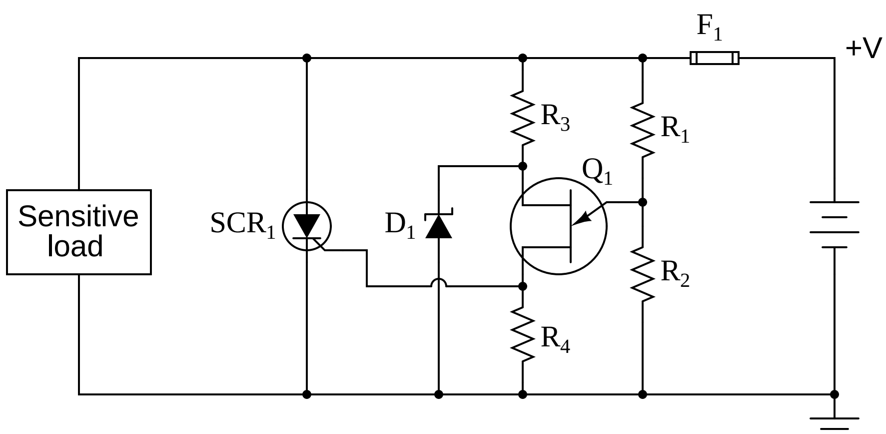


Explain how the unijunction transistor functions in this circuit.

file 01128

Question 21

The following schematic diagram shows a simple *crowbar circuit* used to protect a sensitive DC load from accidental overvoltages in the supply power (+V):

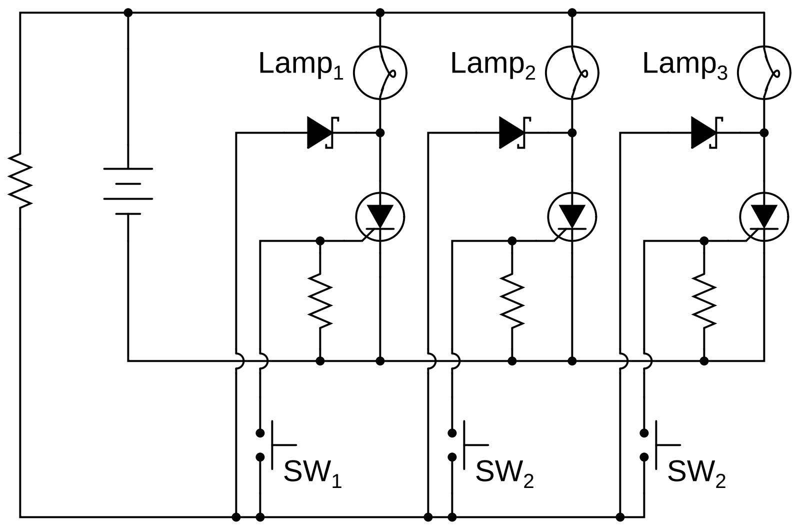


Here, the UJT serves as an overvoltage detection device, triggering the SCR when necessary. Explain how this circuit works, and what the function of each of its components is.

file 02143

Question 22

The circuit shown here indicates which pushbutton switch has been actuated *first*. After actuating any one of the three pushbutton switches (and energizing its respective lamp), none of the other lamps can be made to energize:

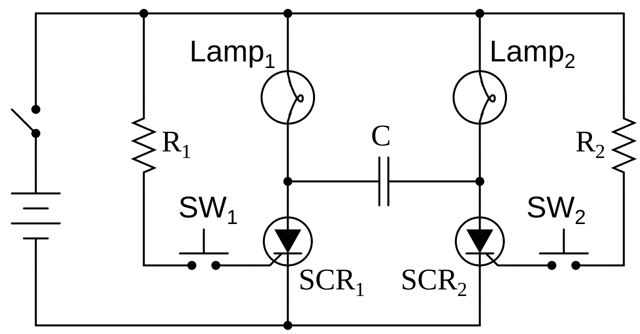


Explain how this circuit works. Why can't any of the other lamps turn on once any one of them has been energized? Also, explain how the circuit could be modified so as to provide a "reset" to turn all lamps off again.

file 01096

Question 23

The following circuit exhibits very interesting behavior:



When the power is first turned on, neither lamp will energize. If either pushbutton switch is then momentarily actuated, the lamp controlled by that SCR will energize. If, after one of the lamps has been energized, the *other* pushbutton switch is then actuated, its lamp will energize *and the other lamp will de-energize*.

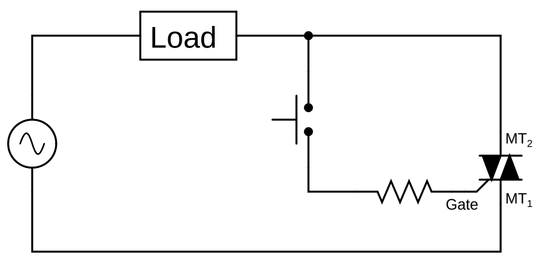
Stated simply, each pushbutton switch not only serves to energize its respective lamp, but it also serves to de-energize the other lamp as well. Explain how this is possible. It should be no mystery to you why each switch turns on its respective lamp, but how is the other switch able to exert control over the other SCR, to turn it off?

Hint: the secret is in the capacitor, connected between the two SCRs' anode terminals.

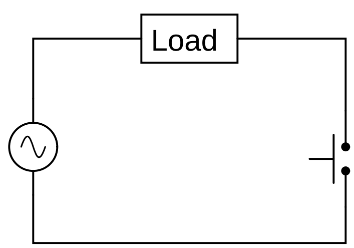
file 01095

Question 24

What purpose does the TRIAC serve in this circuit?



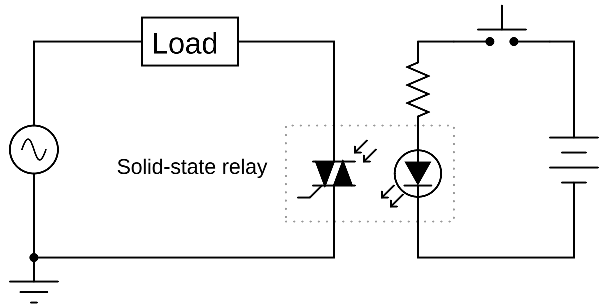
Why use a TRIAC at all? Why not just use the switch to directly handle load current as in this next circuit?



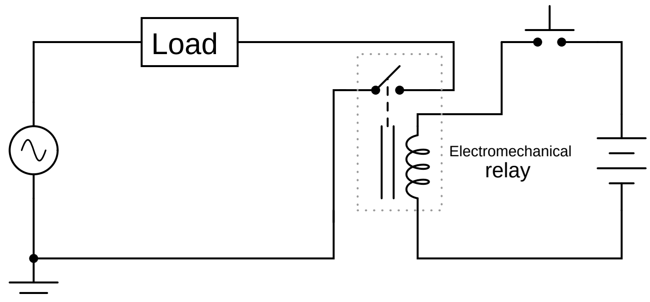
file 02145

Question 25

Optically-isolated TRIACs are available for use as *solid-state relays*, suitable for replacing electromechanical relays in many AC power switching applications:



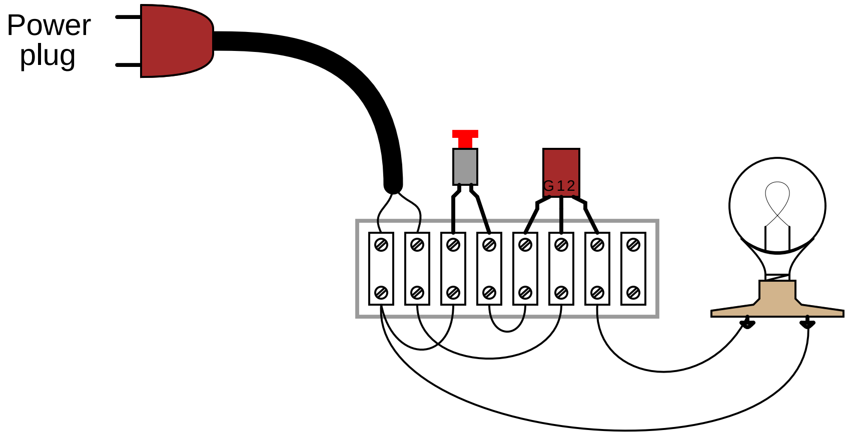
Describe some of the advantages of using a solid-state relay for switching AC power instead of using an electromechanical relay as shown here:



Also describe any disadvantages to using a solid-state relay, if they exist.
file 02146

Question 26

This TRIAC circuit has a serious problem. Whenever the pushbutton switch is actuated, the TRIAC explodes!

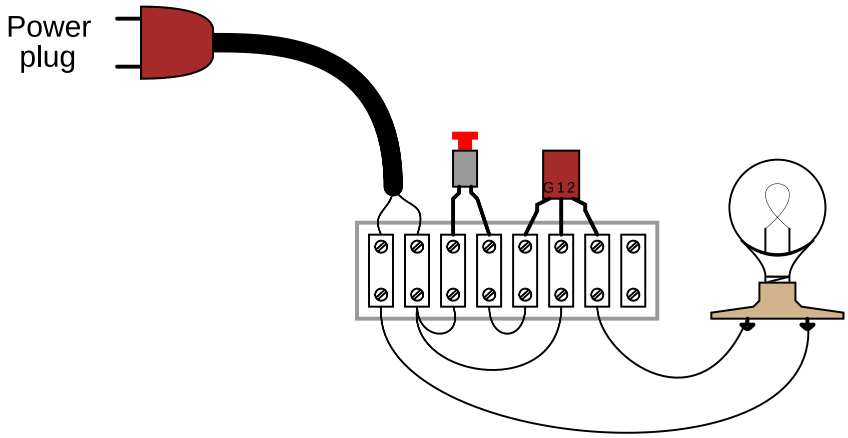


Explain why this happens, and what must be done to fix the problem.

file 01092

Question 27

Suppose a student builds the following TRIAC circuit and finds that it does not work:

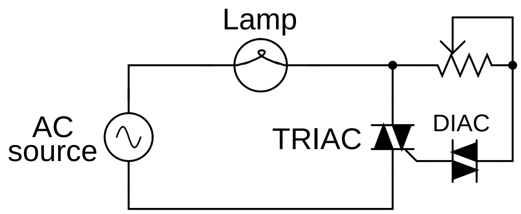


When the pushbutton switch is actuated, nothing happens. What is wrong with this circuit? Hint: the problem in this circuit is very subtle, and may be very difficult to discern.

file 01091

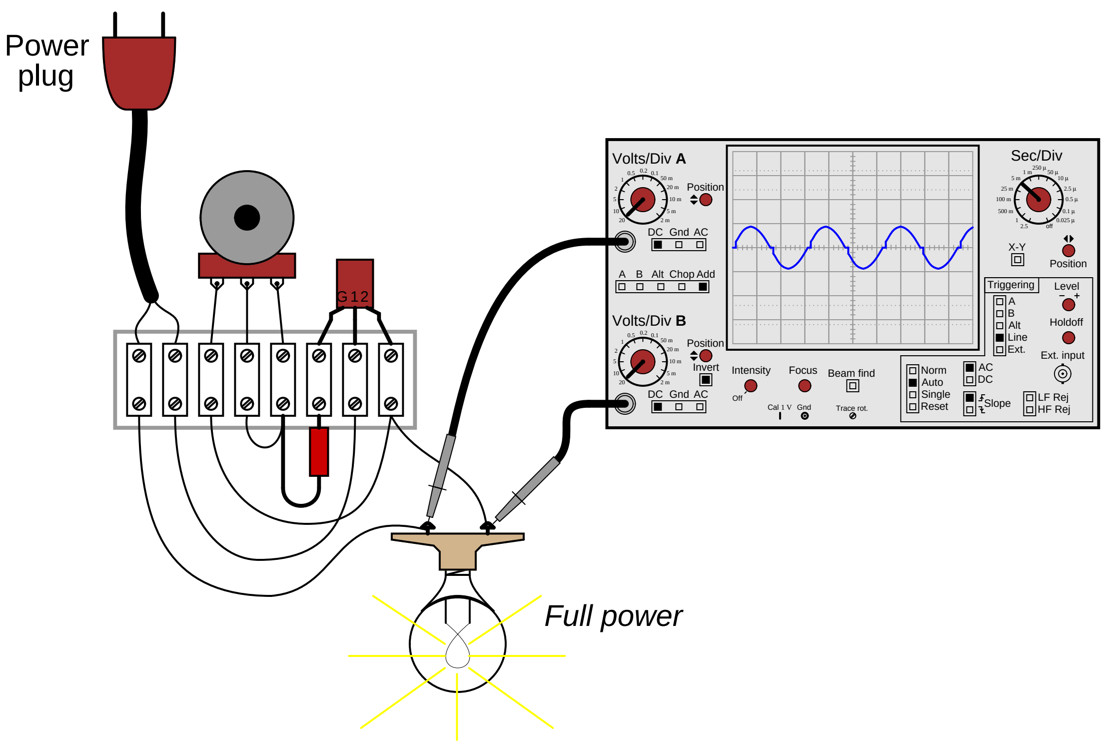
Question 28

A student builds this simple TRIAC power control circuit to dim a light bulb:

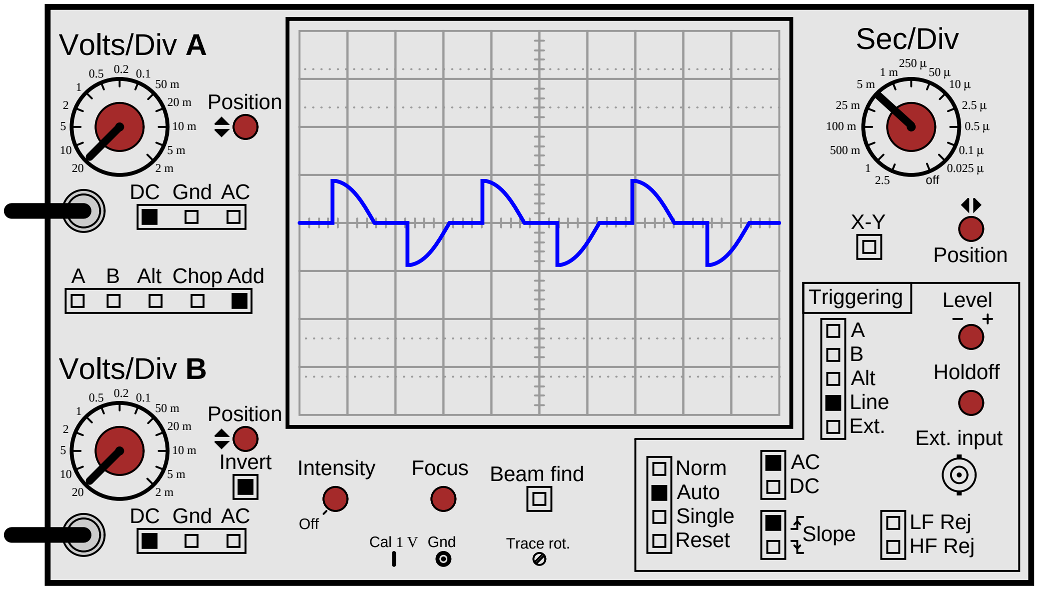


The only problem with it is the lack of full control over the light bulb's brightness. At one extreme of the potentiometer's range, the light bulb is at full brightness. As the potentiometer is moved toward the direction of dimming, though, the light bulb approaches a medium level of intensity, then suddenly de-energizes completely. In other words, this circuit is incapable of providing fine control of power from "off" to "full" light. The range of control seems to be from full brightness to half-brightness, and nothing below that.

Connecting an oscilloscope across the light bulb terminals (using both channels of the oscilloscope to measure voltage drop in the "differential" mode), the waveform looks like this at full power:



When the potentiometer is adjusted to the position giving minimum light bulb brightness (just before the light bulb completely turns off), the waveform looks like this:

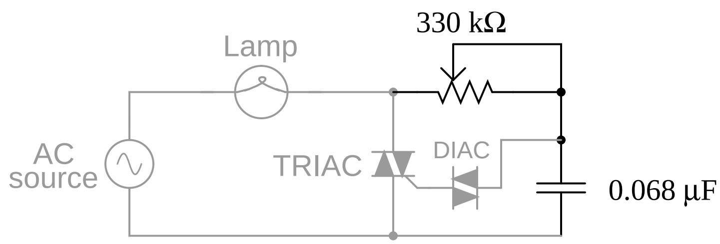


Explain why this circuit cannot provide continuous adjustment of light bulb brightness below this level.

file 02149

Question 29

In this circuit, a series resistor-capacitor network creates a phase-shifted voltage for the "gate" terminal of a power-control device known as a *TRIAC*. All portions of the circuit except for the RC network are "shaded" for de-emphasis:

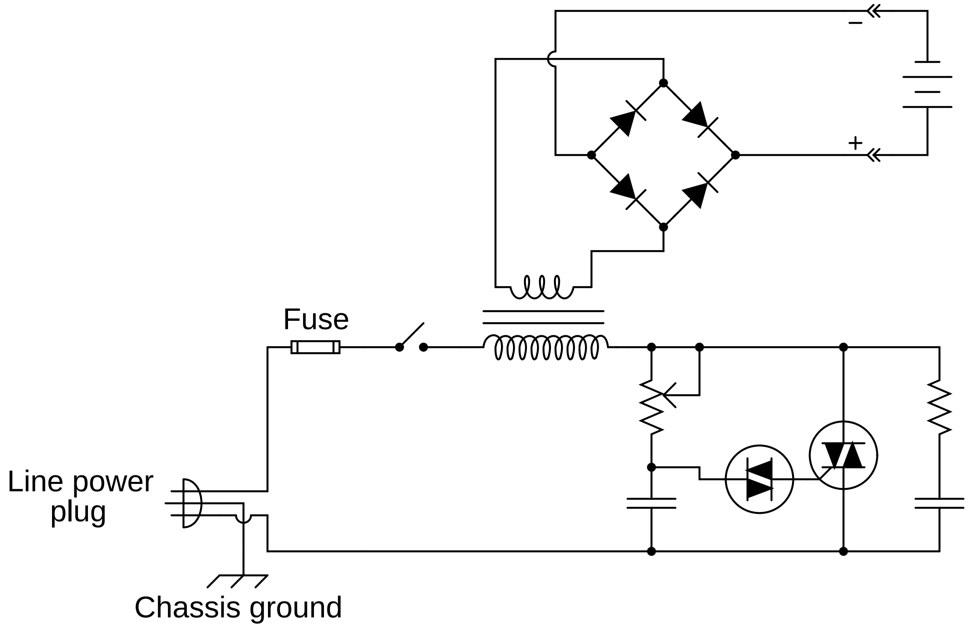


Calculate how many degrees of phase shift the capacitor's voltage is, compared to the total voltage across the series RC network, assuming a frequency of 60 Hz, and a 50% potentiometer setting.

file 00637

Question 30

Explain how this battery charger circuit uses a TRIAC to control *DC* power to the battery:



Also, identify some component failures in this circuit that could prevent DC power from getting to the battery.

file 02148

Question 31

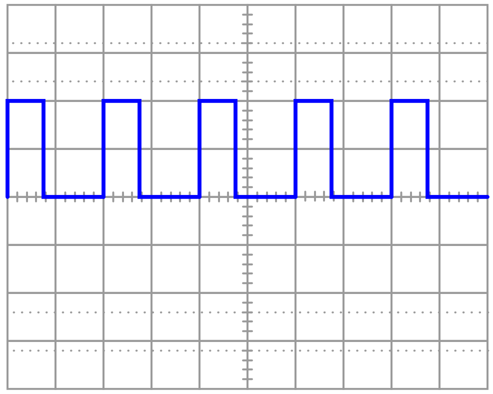
An important measurement of pulse waveforms is *duty cycle*. Give a precise. mathematical definition for this term.

Also, write an equation solving for pulse width given duty cycle (D) and frequency (f).

file 01432

Question 32

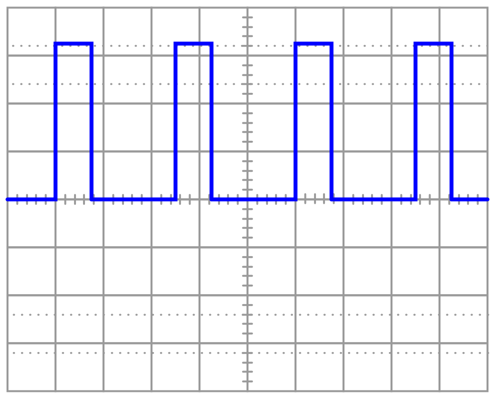
Determine the *duty cycle* of this square wave signal:



file 02150

Question 33

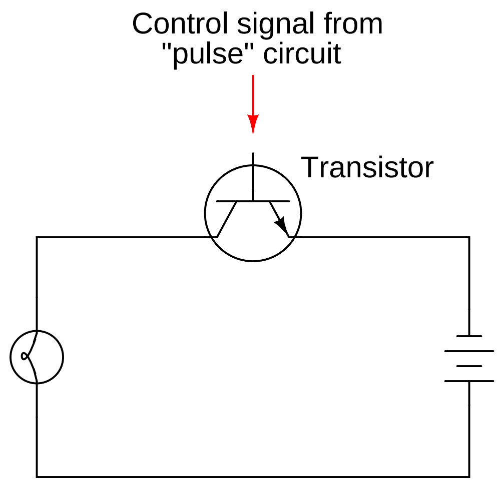
Determine the *duty cycle* of this square wave signal:



file 02151

Question 34

A modern method of electrical power control involves inserting a fast-operating switch in-line with an electrical load, to switch power on and off to it very rapidly over time. Usually, a solid-state device such as a *transistor* is used:



This circuit has been greatly simplified from that of a real, pulse-control power circuit. Just the transistor is shown (and not the "pulse" circuit which is needed to command it to turn on and off) for simplicity. All you need to be aware of is the fact that the transistor operates like a simple, single-pole single-throw (SPST) switch, except that it is controlled by an electrical current rather than by a mechanical force, and that it is able to switch on and off millions of times per second without wear or fatigue.

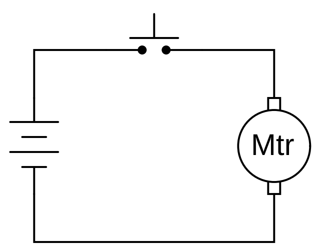
If the transistor is pulsed on and off fast enough, power to the light bulb may be varied as smoothly as if controlled by a variable resistor. However, there is very little energy wasted when using a fast-switching transistor to control electrical power, unlike when a variable resistance is used for the same task. This mode of electrical power control is commonly referred to as *Pulse-Width Modulation*, or *PWM*.

Explain why PWM power control is much more efficient than controlling load power by using a series resistance.

file 00105

Question 35

How would a permanent-magnet DC motor respond if the switch in this circuit were repeatedly closed and opened at a very high frequency?

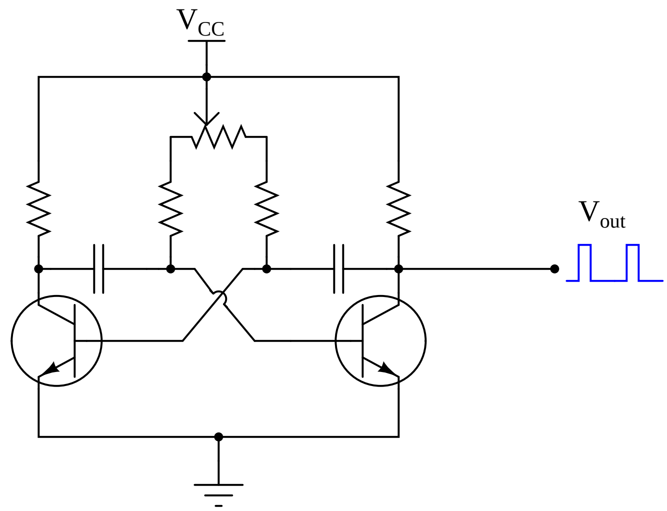


Would it rotate at full speed, just the same as if the switch were closed all the time? Would it rotate at all? Explain your answer.

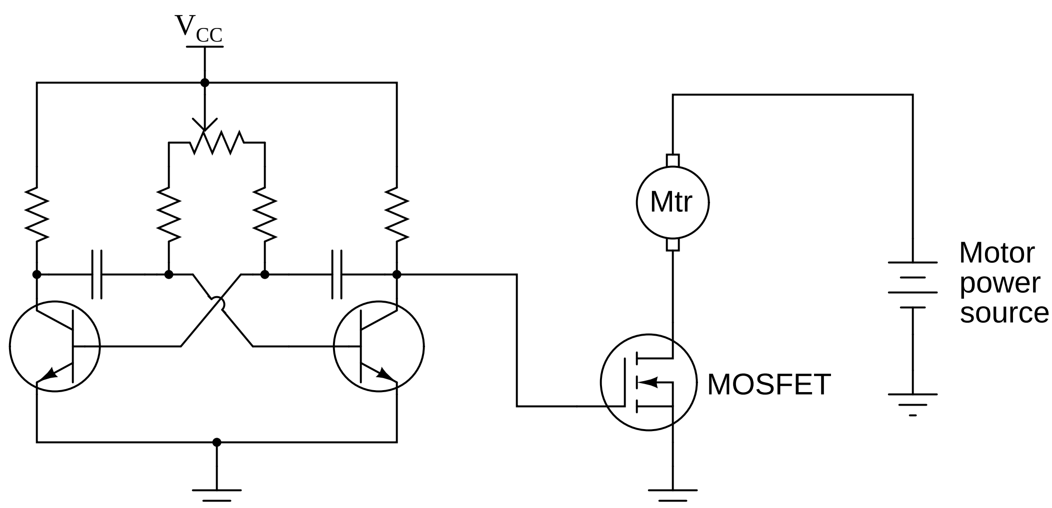
file 01104

Question 36

The *oscillator* circuit in this diagram generates a square wave with an adjustable duty cycle:



A student desires to use this circuit as the basis for a *pulse-width modulation* (PWM) power controller, to vary the amount of power delivered to a DC load. Since the oscillator circuit is built to produce weak signals and not deliver power directly to a load, the student adds a power MOSFET to switch heavy load currents:



Correlate the duty cycle of the oscillator's output signal with motor power. In other words, describe how increases and decreases in signal duty cycle affect the amount of power delivered to the electric motor.

file 02152

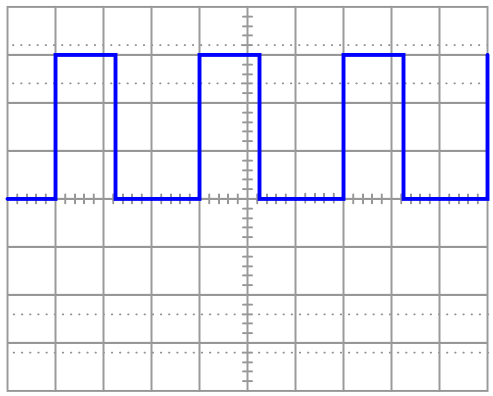
Question 37

Explain why it is important for the final power transistor(s) in a PWM power control circuit to operate at full cutoff and full saturation, and not in the linear (active) mode in between those two extremes. What might happen if the power transistor(s) were to be less than cut-off or less than saturated when carrying load current?

file 02155

Question 38

A resistive DC load receives pulse-width modulated (PWM) power from a controller circuit, and an oscilloscope shows the load voltage waveform as such:



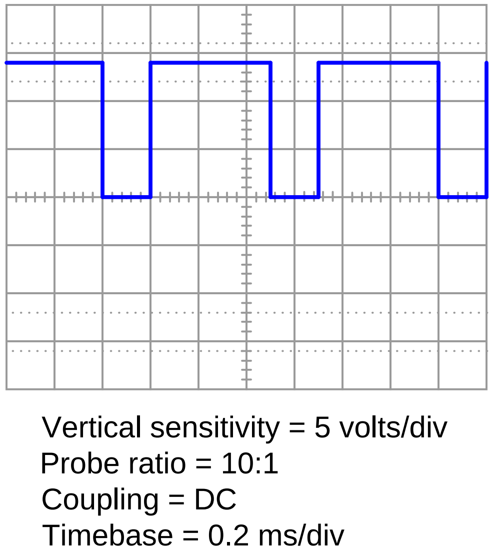
Vertical sensitivity = 1 volt/div
Probe ratio = 1:1
Coupling = DC
Timebase = 0.5 ms/div

Calculate the duty cycle of this waveform, and also the average power dissipated by the load assuming a load resistance of 2.5 Ω.

file 02153

Question 39

A resistive DC load receives pulse-width modulated (PWM) power from a controller circuit, and an oscilloscope shows the load voltage waveform as such:



Calculate the duty cycle of this waveform, and also the average power dissipated by the load assuming a load resistance of 40.7 Ω.

file 02154

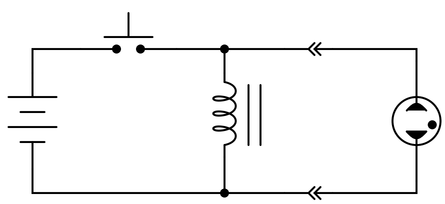
Question 40

How is pulse-width modulation power control similar to the form of control exerted by TRIACs and SCRs in AC power circuits? How does it differ?

file 02157

Question 41

This circuit generates a pulse of DC voltage sufficient to energize the neon lamp, every time the switch is opened:



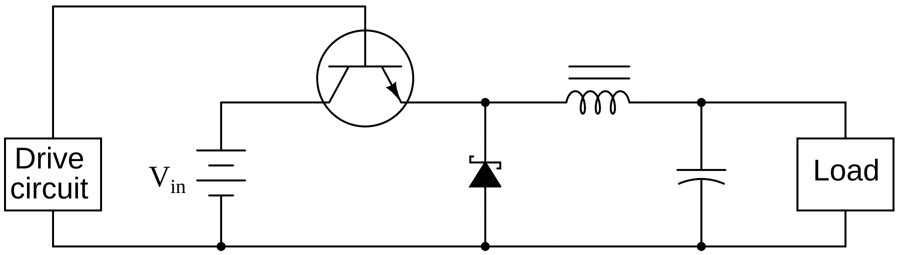
Describe the principle of operation for this simple circuit, and also how it could be modified to produce *continuous high-voltage* DC power.

Hint: how does a common AC-DC power supply circuit convert *pulses* of rectified DC into a relatively "smooth" DC output?

file 01100

Question 42

The schematic diagram shown here is for a *"buck" converter circuit*, a type of DC-DC "switching" power conversion circuit:



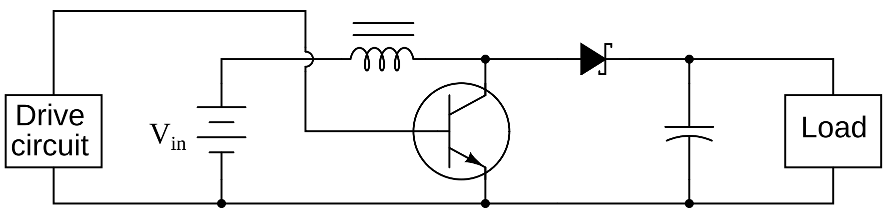
In this circuit, the transistor is either fully on or fully off; that is, driven between the extremes of saturation or cutoff. By avoiding the transistor's "active" mode (where it would drop substantial voltage while conducting current), very low transistor power dissipations can be achieved. With little power wasted in the form of heat, "switching" power conversion circuits are typically very efficient.

Trace all current directions during both states of the transistor. Also, mark the inductor's voltage polarity during both states of the transistor.

file 01102

Question 43

The schematic diagram shown here is for a *"boost" converter circuit*, a type of DC-DC "switching" power conversion circuit:



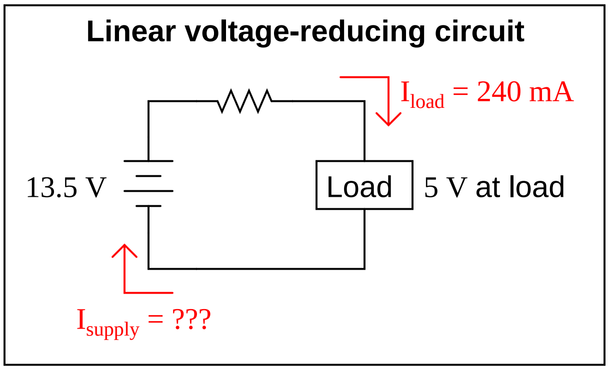
In this circuit, the transistor is either fully on or fully off; that is, driven between the extremes of saturation or cutoff. By avoiding the transistor's "active" mode (where it would drop substantial voltage while conducting current), very low transistor power dissipations can be achieved. With little power wasted in the form of heat, "switching" power conversion circuits are typically very efficient.

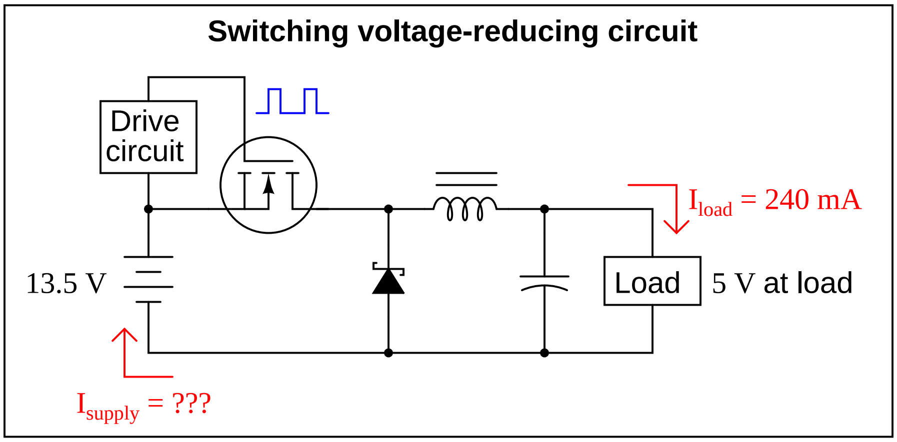
Trace all current directions during both states of the transistor. Also, mark the inductor's voltage polarity during both states of the transistor.

file 01103

Question 44

Shown here are two voltage-reducing circuits: both reducing a supply voltage of 13.5 volts down to 5 volts for a load.



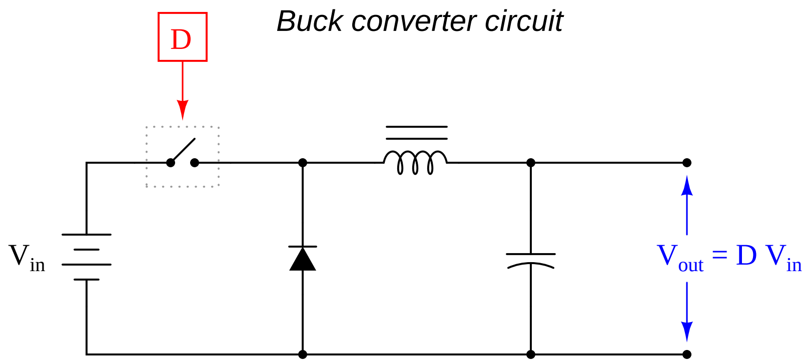


Calculate the average supply current (I_{supply}) for both of these circuits. Assume that the switching circuit has negligible power losses in the transistor, inductor, capacitor, and diode. If the 13.5 volt source were an electrochemical battery, which battery would last longer powering the same load?

file 02479

Question 45

The output voltage of a *buck converter* circuit is a function of the input voltage and the duty cycle of the switching signal, represented by the variable D (ranging in value from 0% to 100%), where $D = \frac{t_{on}}{t_{on}+t_{off}}$:



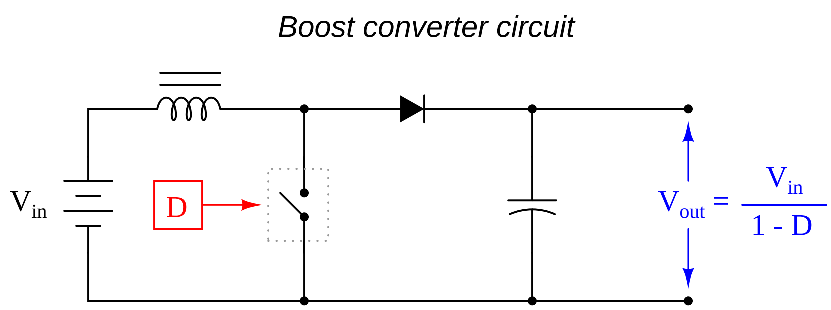
Based on this mathematical relationship, calculate the output voltage of this converter circuit at these duty cycles, assuming an input voltage of 40 volts:

- $D = 0\%$; $V_{out} =$
- $D = 25\%$; $V_{out} =$
- $D = 50\%$; $V_{out} =$
- $D = 75\%$; $V_{out} =$
- $D = 100\%$; $V_{out} =$

file 02158

Question 46

The output voltage of a *boost converter* circuit is a function of the input voltage and the duty cycle of the switching signal, represented by the variable D (ranging in value from 0% to 100%), where $D = \frac{t_{on}}{t_{on}+t_{off}}$:



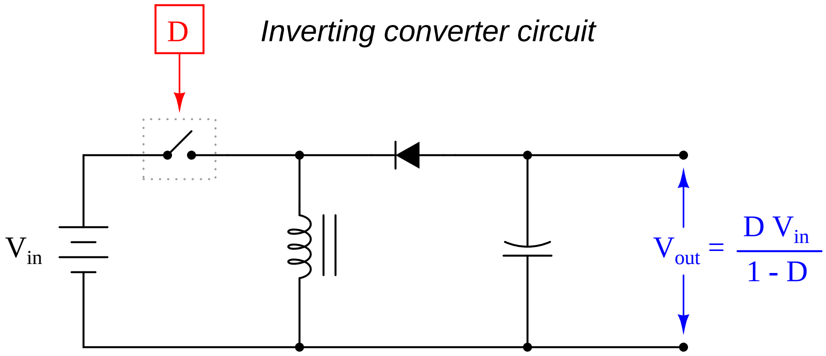
Based on this mathematical relationship, calculate the output voltage of this converter circuit at these duty cycles, assuming an input voltage of 40 volts:

- $D = 0\%$; $V_{out} =$
- $D = 25\%$; $V_{out} =$
- $D = 50\%$; $V_{out} =$
- $D = 75\%$; $V_{out} =$
- $D = 100\%$; $V_{out} =$

file 02159

Question 47

The output voltage of an *inverting converter* circuit is a function of the input voltage and the duty cycle of the switching signal, represented by the variable D (ranging in value from 0% to 100%), where $D = \frac{t_{on}}{t_{on}+t_{off}}$:



Based on this mathematical relationship, calculate the output voltage of this converter circuit at these duty cycles, assuming an input voltage of 40 volts:

- $D = 0\%$; $V_{out} =$
- $D = 25\%$; $V_{out} =$
- $D = 50\%$; $V_{out} =$
- $D = 75\%$; $V_{out} =$
- $D = 100\%$; $V_{out} =$

file 02160

Question 48

The following equations solve for the output voltage of various switching converter circuits (unloaded), given the switch duty cycle D and the input voltage:

$$V_{out} = D\,V_{in} \qquad \text{(Buck converter circuit)}$$

$$V_{out} = \frac{V_{in}}{1-D} \qquad \text{(Boost converter circuit)}$$

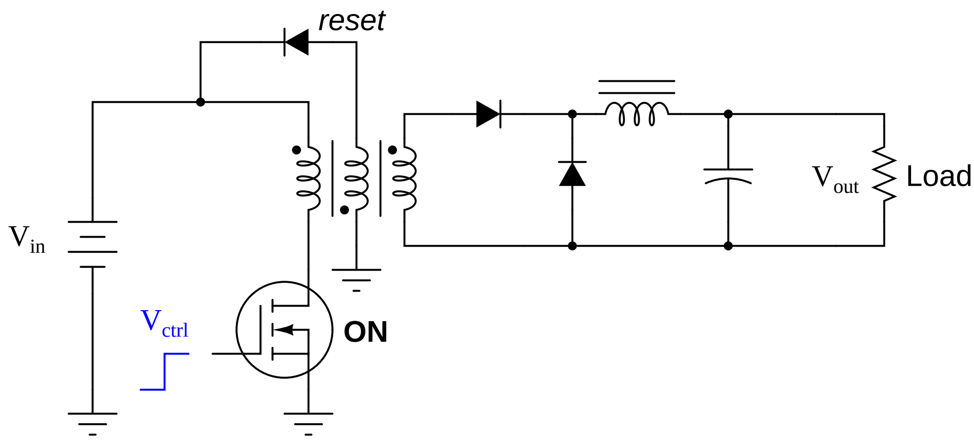
$$V_{out} = \frac{D\,V_{in}}{1-D} \qquad \text{(Inverting or Cuk converter circuit)}$$

Manipulate each of these equations to solve for duty cycle (D) in terms of the input voltage (V_{in}) and desired output voltage (V_{out}). Remember that duty cycle is always a quantity between 0 and 1, inclusive.

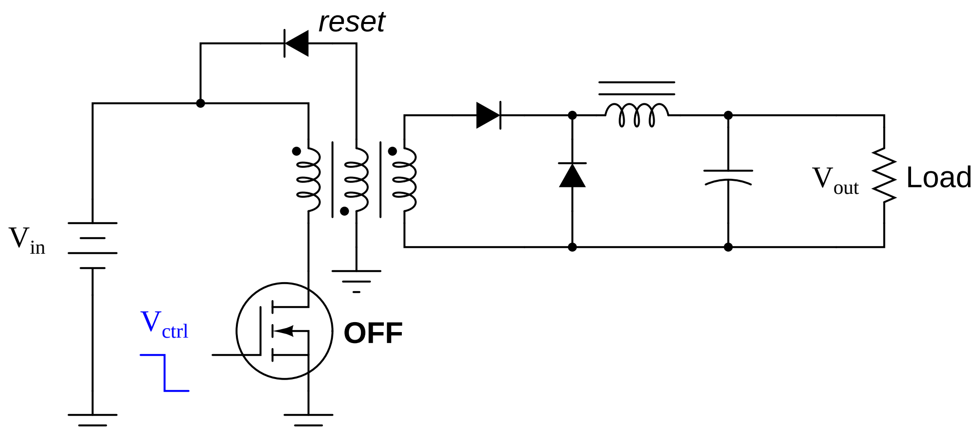
file 02161

Question 49

The following DC-DC converter circuit is called a *forward converter*. It is called this because the energy transfer from input to output occurs while the transistor is conducting, not while it is off. Verify this feature of the circuit by tracing current through all portions of it while the transistor is on:



Now, trace current through the circuit while the transistor is off, and explain the purpose of the *reset* winding in the transformer:



file 03724

Question 50

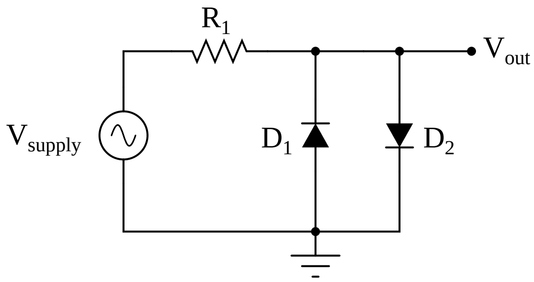
While simple "brute-force" AC-DC power supply circuits (transformer, rectifier, filter, regulator) are still used in a variety of electronic equipment, another form of power supply is more prevalent in systems where small size and efficiency are design requirements. This type of power supply is called a *switching power supply*.

Explain what a "switching power supply" is, and provide a schematic diagram of one for presentation and discussion. (Hint: most electronic computers use "switching" power supplies instead of "brute force" power supplies, so schematic diagrams should not be difficult to find.)

file 01107

Competency: **Diode clipper circuit** Version:

Schematic



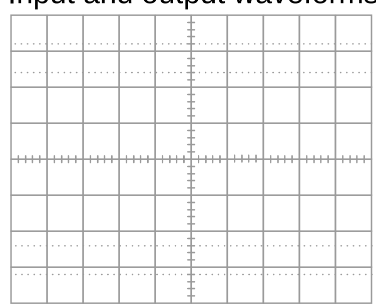
Given conditions

V_{supply} = R_1 = V_F (typical) =

Parameters

	Predicted	Measured
V_{out}		

Input and output waveforms



Fault analysis

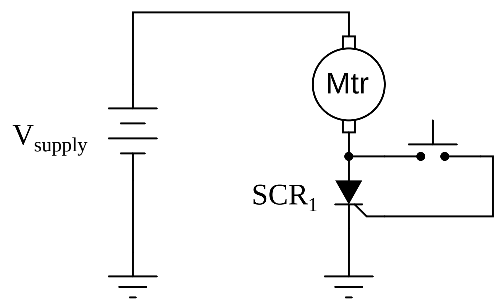
Suppose component ☐ fails ☐ open ☐ shorted ☐ other ____________

What will happen in the circuit?

file 01979

Competency: **SCR latch circuit** Version:

Schematic



Given conditions

V_{supply} =

Parameters

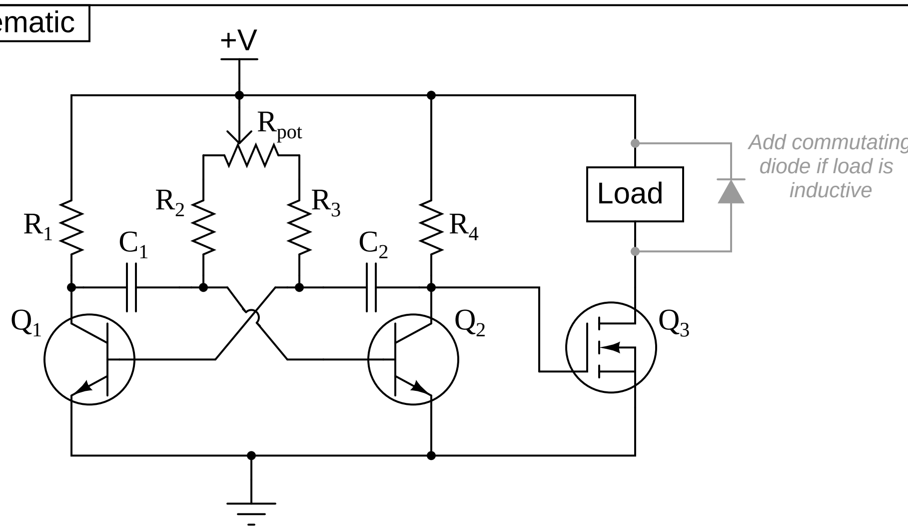
	Predicted	Measured
V_{motor} (on)		
I_{supply} (on)		

	Calculated
P_{SCR1}	

file 01987

Competency: **PWM power controller, discrete** Version:

Schematic



Given conditions

+V =	R_1 =	R_2 =	R_{pot} =	C_1 =
	R_4 =	R_3 =		C_2 =

Parameters

	Predicted	Measured	
V_{load} (avg.)			Duty cycle = ____ %
V_{load} (avg.)			Duty cycle = ____ %
V_{load} (avg.)			Duty cycle = ____ %
V_{load} (avg.)			Duty cycle = ____ %

file 01991

Question 54

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)

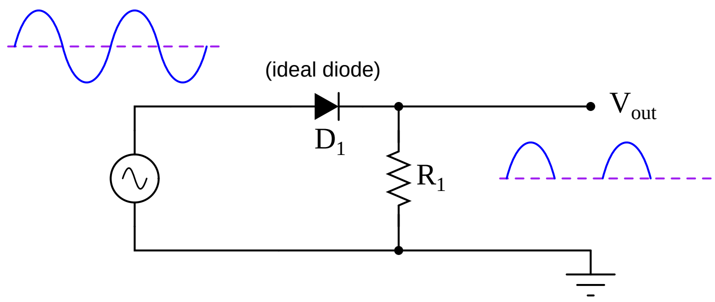
0 % *(If any of the following conditions are true)*

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

Question 55

Predict how the operation of this clipper circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):

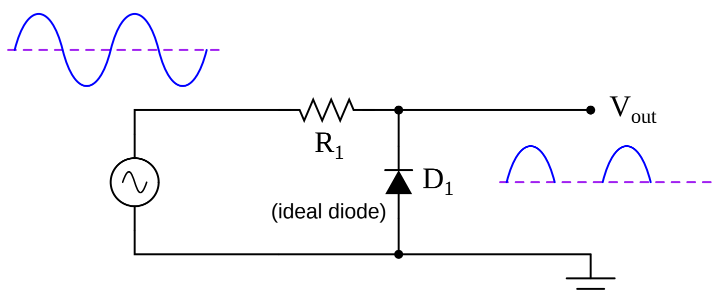


- Diode D_1 fails open:
- Diode D_1 fails shorted:
- Resistor R_1 fails open:
- Resistor R_1 fails shorted:

For each of these conditions, explain *why* the resulting effects will occur.
file 03727

Question 56

Predict how the operation of this clipper circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):

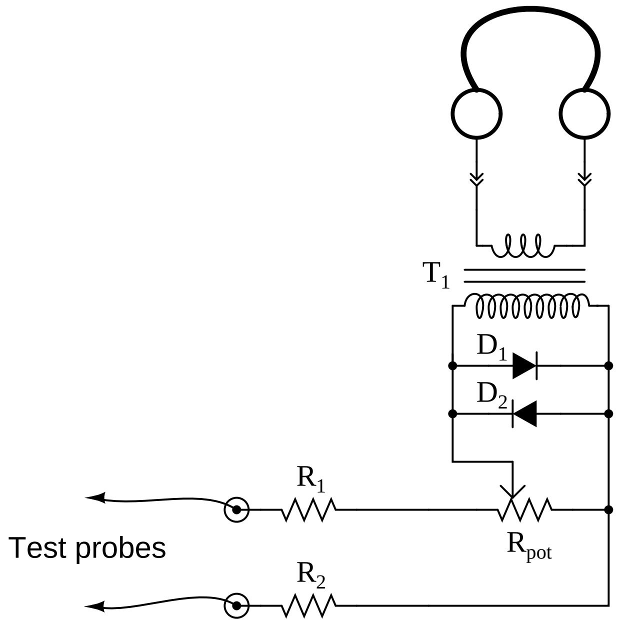


- Diode D_1 fails open:
- Diode D_1 fails shorted:
- Resistor R_1 fails open:
- Resistor R_1 fails shorted:

For each of these conditions, explain *why* the resulting effects will occur.
file 03728

Question 57

Predict how the operation of this sensitive audio detector circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):

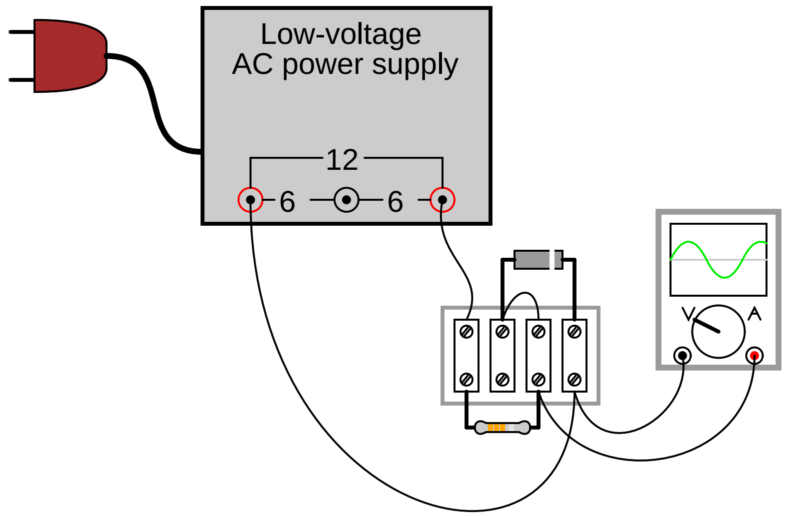


- Diode D_1 fails open:
- Diode D_1 fails shorted:
- Transformer T_1 primary winding fails open:
- Resistor R_1 fails open:
- Solder bridge (short) past resistor R_1:
- Wiper fails to contact slide in potentiometer:

For each of these conditions, explain *why* the resulting effects will occur.
file 03726

Question 58

There is a problem with this clipper circuit, as evidenced by the output waveform:

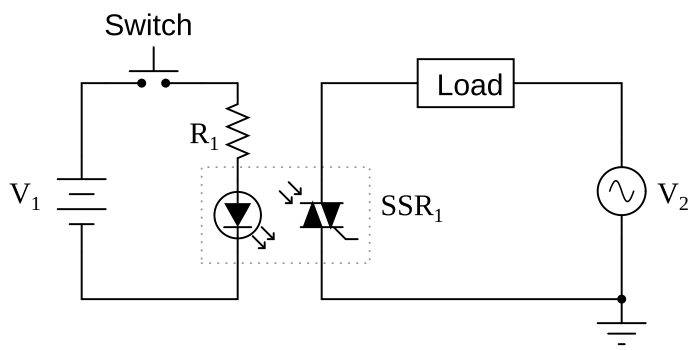


What is the most likely cause of this problem, and how would you verify your conclusion with further measurements?

file 01114

Question 59

Predict how the operation of this AC power control circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



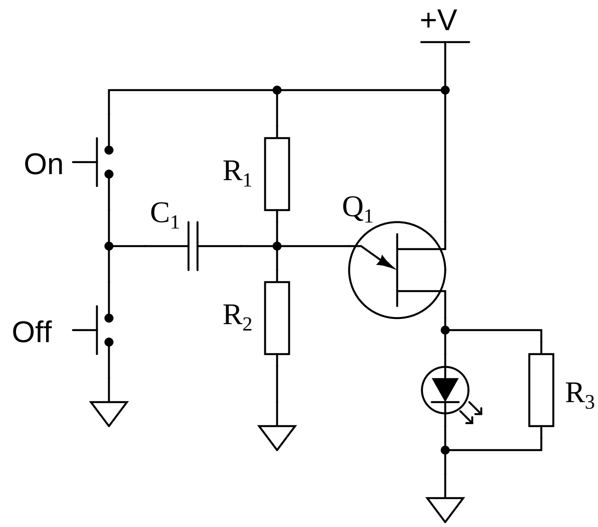
- Switch contacts fail open:
- Switch contacts fail shorted:
- Resistor R_1 fails open:
- Solder bridge (short) past resistor R_1:
- Battery (V_1) dies:

For each of these conditions, explain *why* the resulting effects will occur.

file 03730

Question 60

Predict how the operation of this UJT latch circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):

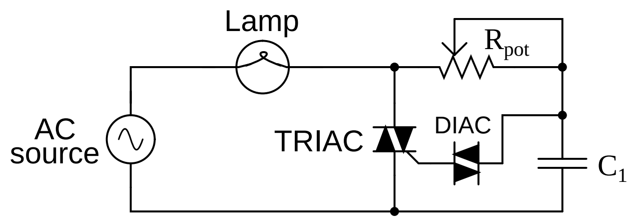


- Capacitor C_1 fails open:
- Capacitor C_1 fails shorted:
- Resistor R_1 fails open:
- Solder bridge (short) past resistor R_1:
- Resistor R_2 fails open:
- Solder bridge (short) past resistor R_2:

For each of these conditions, explain *why* the resulting effects will occur.
file 03729

Question 61

Predict how the operation of this AC lamp dimmer circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):

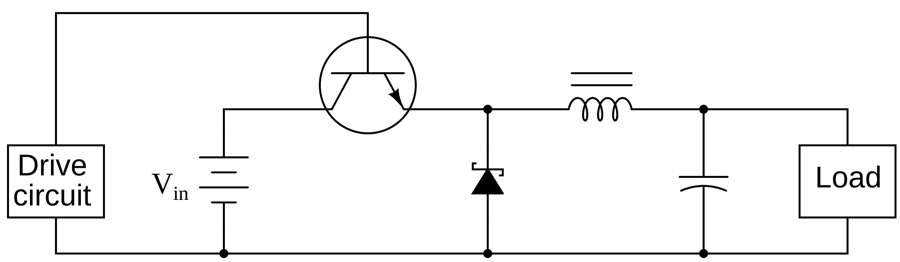


- Potentiometer R_{pot} fails open:
- Capacitor C_1 fails shorted:
- Capacitor C_1 fails open:
- DIAC fails open:
- TRIAC fails shorted:

For each of these conditions, explain *why* the resulting effects will occur.
file 03731

Question 62

Predict how the operation of this buck converter circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):

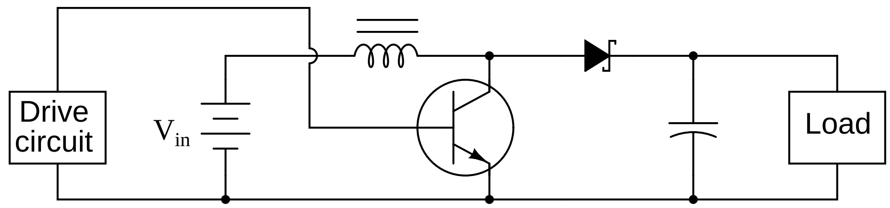


- Drive circuit fails with a constant "low" (0 volts) output signal:
- Drive circuit fails with a constant "high" (+V) output signal:
- Diode fails shorted:
- Inductor fails open:
- Capacitor fails shorted:

For each of these conditions, explain *why* the resulting effects will occur.
file 03732

Question 63

Predict how the operation of this boost converter circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



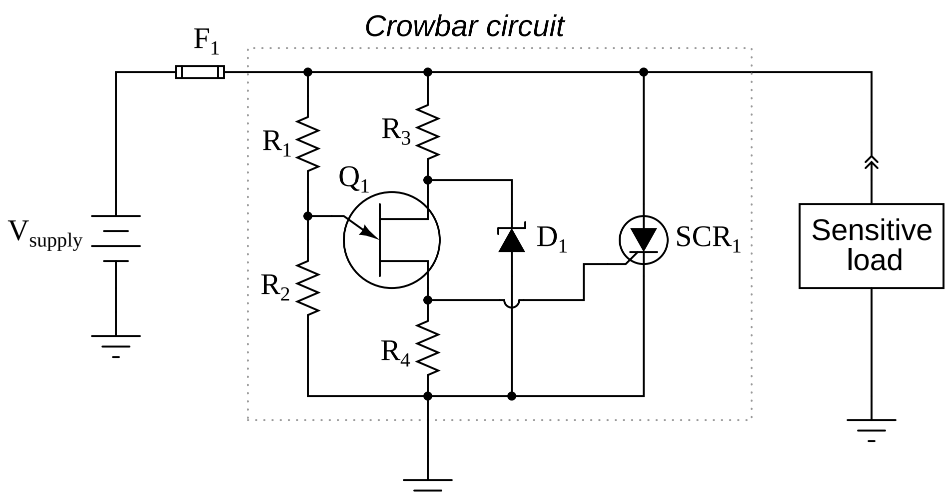
- Drive circuit fails with a constant "low" (0 volts) output signal:
- Drive circuit fails with a constant "high" (+V) output signal:
- Diode fails shorted:
- Inductor fails open:
- Capacitor fails shorted:

For each of these conditions, explain *why* the resulting effects will occur.

file 03733

Question 64

This crowbar circuit has a problem. It used to work just fine, and then one day it blew the fuse. Upon replacing the fuse, the new fuse immediately blew:



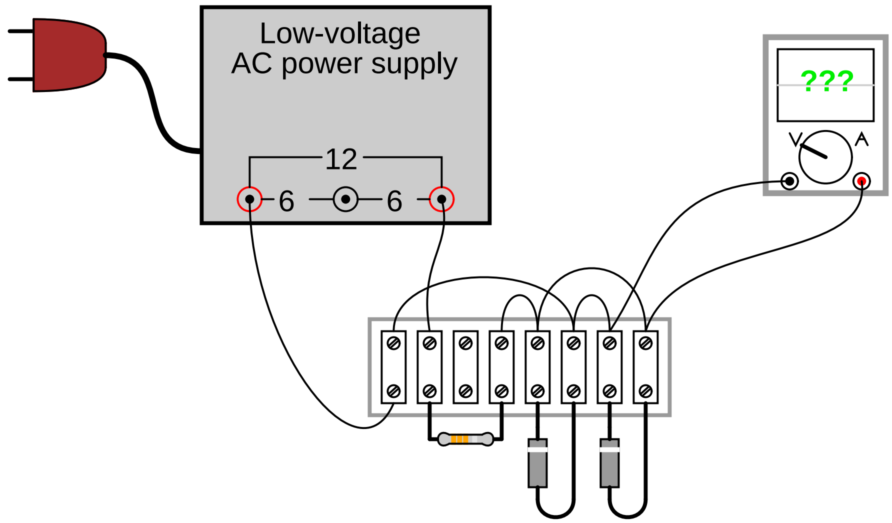
Measuring the supply voltage with a voltmeter, everything checks out well. There does not appear to be an overvoltage condition causing a legitimate "crowbar" event in the circuit. Disconnecting the load from the crowbar circuit and powering it up with a standard bench-top laboratory power supply reveals the load to be in perfect condition. Thus, both the source and the load have been eliminated as possibilities that may have blown the fuse(s).

Moving on to the crowbar circuit itself, identify some component faults that could (each, independently) account for the problem, and explain your reasoning.

file 03734

Question 65

Determine both the waveshape and amplitude of the AC signal measured by the oscilloscope at the output of this circuit:

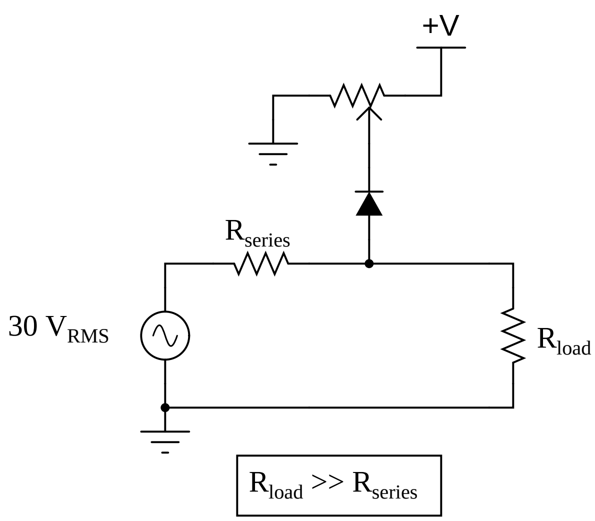


The diodes are model 1N4001, each. The resistor's color code is Brown, Black, Orange, Silver.

file 01108

Question 66

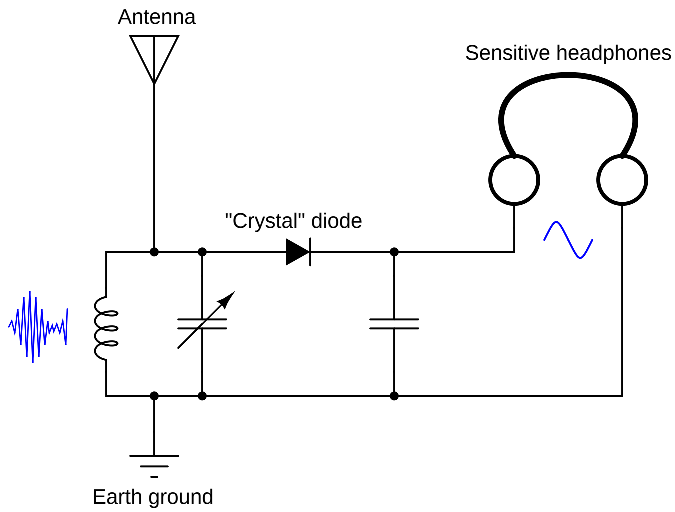
Describe what happens to the shape of the load voltage waveform when the potentiometer is adjusted in this clipper circuit:



file 01111

Question 67

The simplest form of AM radio receiver is the so-called *crystal* receiver circuit. It gets its name from the very early days of solid-state electronics, when crude signal rectifying diodes were constructed from certain types of mineral crystals:

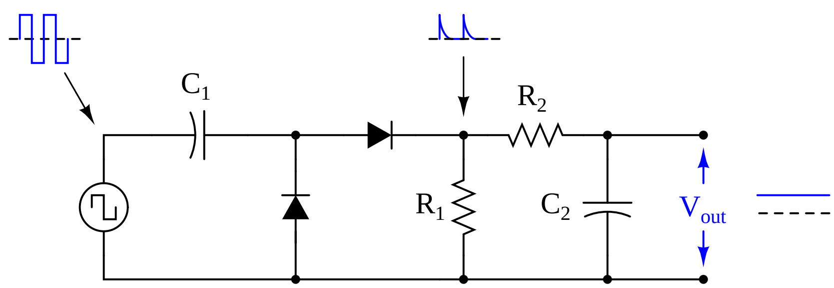


Explain how the AM radio signal becomes "demodulated" into an audio-frequency signal, through the clipping action of the diode.

file 01112

Question 68

In this circuit, the values of capacitor C_1 and resistor R_1 are chosen to provide a short time constant, so they act as a differentiator network. This results in a brief pulse of voltage across R_1 at each leading edge of the square wave input. Capacitor C_2 and resistor R_2 are sized to provide a long time constant, so as to form an integrator network. This time-averages the brief pulses into a final DC output voltage relatively free of ripple.



Explain what happens to the output voltage as the input frequency is increased, assuming the input voltage amplitude does not change. Can you think of any practical applications for a circuit such as this?

file 02129

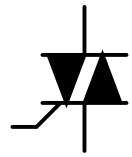
Question 69

When an SCR latches "on," it drops very little voltage between anode and cathode. Explain why this is, and what advantage this gives SCRs over transistors when conducting heavy load currents.

file 02141

Question 70

Label the terminals on a TRIAC with their proper designations:



file 03723

Question 71

Some SCRs and TRIACs are advertised as *sensitive-gate* devices. What does this mean? What is the difference between a "sensitive gate" SCR and an SCR with a "non-sensitive gate"?

file 01093

Question 72

Explain what a *crowbar* circuit is, and how it employs an SCR to protect a circuit from excessive voltage.

file 02137

Question 73

A student of electronics has just recently learned how to build audio amplifier circuits, and this inspires dreams of designing a super-powerful amplifier for a home entertainment system. One day, this student comes across a donation of electronic components from a local business, and in this donation are several industrial SCRs, rated at 20 amps each.

"Wow," says the student, "these components look like really big transistors, but they're rated for a lot of current. I could build a *huge* amplifier with these!"

The student approaches you for advice, because you've just recently learned how SCRs function in your electronics class. What do you tell the student, concerning the use of SCRs as audio amplification devices? How do you explain to this excited student that these devices will not work in an amplifier circuit?

file 01086

Question 74

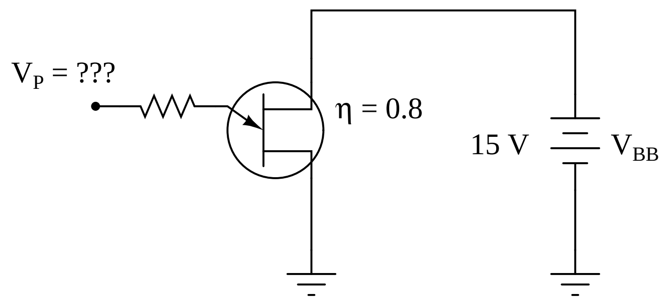
One way that SCRs may be triggered into their "on" state is by a *transient* voltage applied between the anode and cathode terminals. Normally, this method of triggering is considered a flaw of the device, as it opens the possibility of unwanted triggering resulting from disturbances in the power supply voltage.

Explain why a high $\frac{dv}{dt}$ present on the power supply rail is able to trigger an SCR, with reference to the SCR's equivalent circuit. Also suggest what means might be employed to prevent false triggering from power supply transients.

file 02142

Question 75

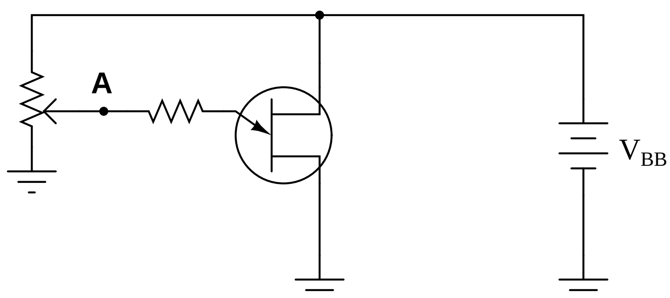
A unijunction transistor with an intrinsic standoff ratio (η) of 0.8 is powered by a 15 volt DC source. Calculate the emitter voltage needed to "trigger" this UJT into its conductive state.



file 02140

Question 76

Describe what happens to the UJT as the potentiometer is slowly adjusted upward to provide a variable voltage at point **A** in this circuit, starting from 0 volts and ending at the trigger voltage V_P:



Now describe what must be done to the potentiometer to cause the UJT to turn back off again.

file 02144

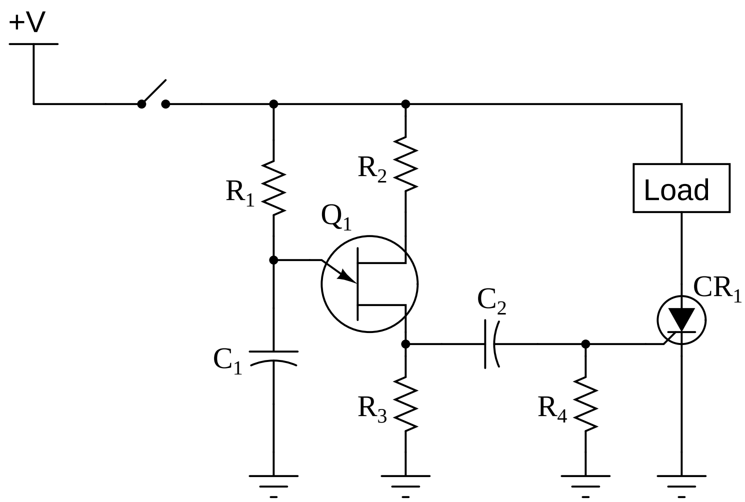
Question 77

Commutation is an important issue in any kind of thyristor circuit, due to the "latching" nature of these devices. Explain what "commutation" means, and how it may be achieved for various thyristors.

file 02147

Question 78

The following schematic diagram shows a timer circuit made from a UJT and an SCR:

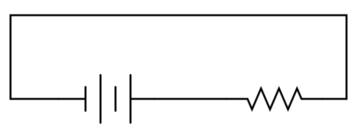


Together, the combination of R_1, C_1, R_2, R_3, and Q_1 form a *relaxation oscillator*, which outputs a square wave signal. Explain how a square wave oscillation is able to perform a simple time-delay for the load, where the load energizes a certain time *after* the toggle switch is closed. Also explain the purpose of the RC network formed by C_2 and R_4.

file 03222

Question 79

Draw the direction of current in this circuit, and also identify the polarity of the voltage across the battery and across the resistor. Then, compare the battery's polarity with the direction of current through it, and the resistor's polarity with the direction of current through it.

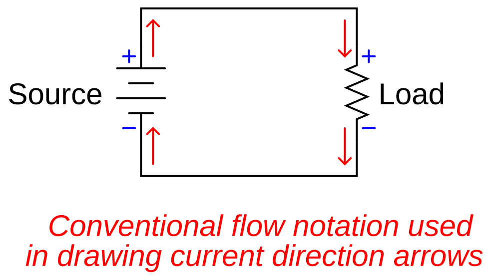


What do you notice about the relationship between voltage polarity and current direction for these two different types of components? Identify the fundamental distinction between these two components that causes them to behave differently.

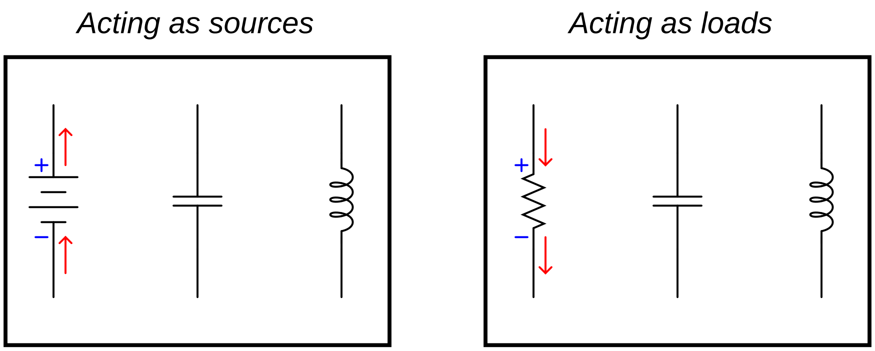
file 01555

Question 80

Capacitors and inductors alike have the ability to both *store* and *release* energy. This makes them more complicated than resistors, which merely dissipate energy. As a consequence, the relationship between direction of current and polarity of voltage is a bit more complex for capacitors and inductors than it is for power sources and resistors:



Draw current arrows and voltage polarity marks (+ and - symbols) next to each of the following components, the left group representing a battery, capacitor, and inductor all acting as *energy sources* and the right group representing a resistor, capacitor, and inductor all acting as *energy loads*:

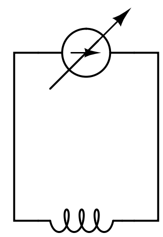


file 03725

Question 81

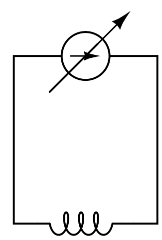
Suppose an inductor is connected directly to an adjustable-current source, and the current of that source is steadily *increased* over time. We know that an increasing current through an inductor will produce a magnetic field of increasing strength. Does this increase in magnetic field constitute an *accumulation* of energy in the inductor, or a *release* of energy from the inductor? In this scenario, does the inductor act as a *load* or as a *source* of electrical energy?

Current *increasing*



Now, suppose the adjustable current source is steadily *decreased* over time. We know this will result in a magnetic field of decreasing strength in the inductor. Does this decrease in magnetic field constitute an *accumulation* of energy in the inductor, or a *release* of energy from the inductor? In this scenario, does the inductor act as a *load* or as a *source* of electrical energy?

Current *decreasing*



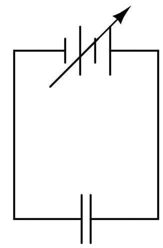
For each of these scenarios, label the inductor's voltage drop polarity.

file 00209

Question 82

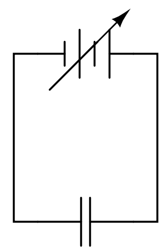
Suppose a capacitor is connected directly to an adjustable-voltage source, and the voltage of that source is steadily *increased* over time. We know that an increasing voltage across a capacitor will produce an electric field of increasing strength. Does this increase in electric field constitute an *accumulation* of energy in the capacitor, or a *release* of energy from the capacitor? In this scenario, does the capacitor act as a *load* or as a *source* of electrical energy?

Voltage *increasing*



Now, suppose the adjustable voltage source is steadily *decreased* over time. We know this will result in an electric field of decreasing strength in the capacitor. Does this decrease in electric field constitute an *accumulation* of energy in the capacitor, or a *release* of energy from the capacitor? In this scenario, does the capacitor act as a *load* or as a *source* of electrical energy?

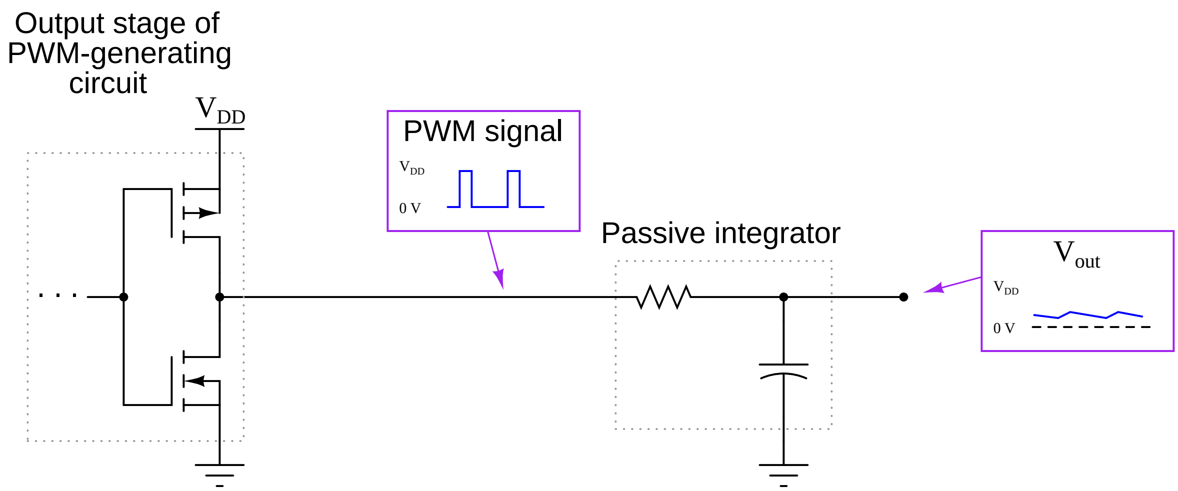
Voltage *decreasing*



For each of these scenarios, label the direction of current in the circuit.
file 00190

Question 83

If a pulse-width modulated (PWM) signal is sent to a passive integrator circuit from a circuit capable of both sourcing and sinking current (as is the case with the dual-MOSFET output stage), the output will be a DC voltage (with some ripple):



Determine the relationship between the PWM signal's duty cycle and the DC voltage output by the integrator. What does this suggest about PWM as a means of communicating information, such as analog data from a measuring device?

file 02156

Question 84

Describe what a *dynamotor* is, and what its purpose might be in an electrical system.

file 01098

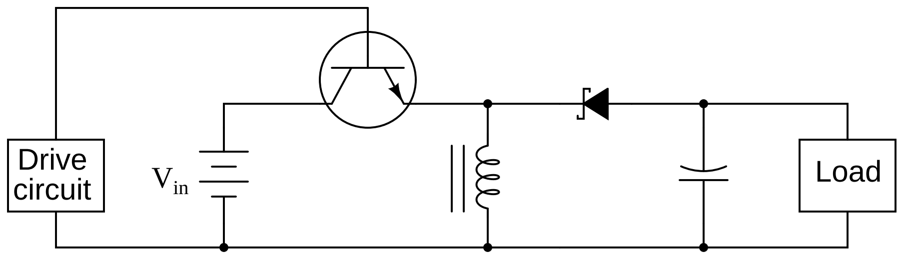
Question 85

What is a *DC-DC converter* circuit, and what applications might such a circuit be used for?

file 01097

Question 86

The schematic diagram shown here is for an *"inverting" converter circuit*, a type of DC-DC "switching" power conversion circuit:



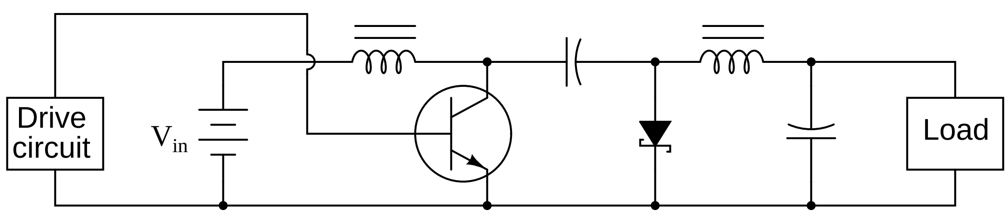
In this circuit, the transistor is either fully on or fully off; that is, driven between the extremes of saturation or cutoff. By avoiding the transistor's "active" mode (where it would drop substantial voltage while conducting current), very low transistor power dissipations can be achieved. With little power wasted in the form of heat, "switching" power conversion circuits are typically very efficient.

Trace all current directions during both states of the transistor. Also, mark the inductor's voltage polarity during both states of the transistor.

file 02285

Question 87

The schematic diagram shown here is for a *"Cuk" converter circuit*, a type of DC-DC "switching" power conversion circuit:



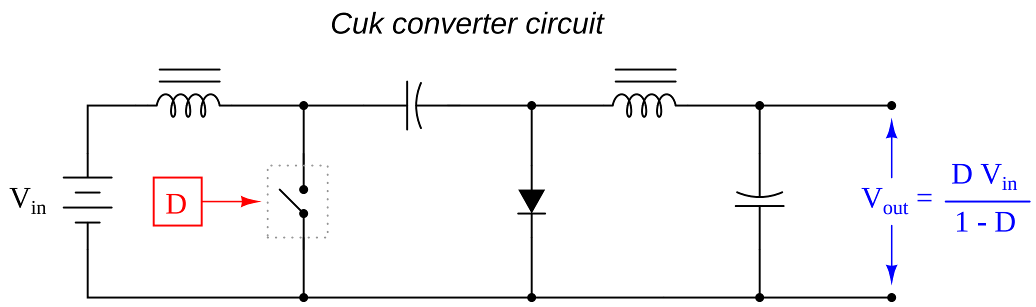
In this circuit, the transistor is either fully on or fully off; that is, driven between the extremes of saturation or cutoff. By avoiding the transistor's "active" mode (where it would drop substantial voltage while conducting current), very low transistor power dissipations can be achieved. With little power wasted in the form of heat, "switching" power conversion circuits are typically very efficient.

Trace all current directions during both states of the transistor. Also, mark the both inductors' voltage polarities during both states of the transistor.

file 02478

Question 88

The output voltage of a *Cuk converter* circuit (named after the engineer who invented it) is a function of the input voltage and the duty cycle of the switching signal, represented by the variable D (ranging in value from 0% to 100%), where $D = \frac{t_{on}}{t_{on}+t_{off}}$:



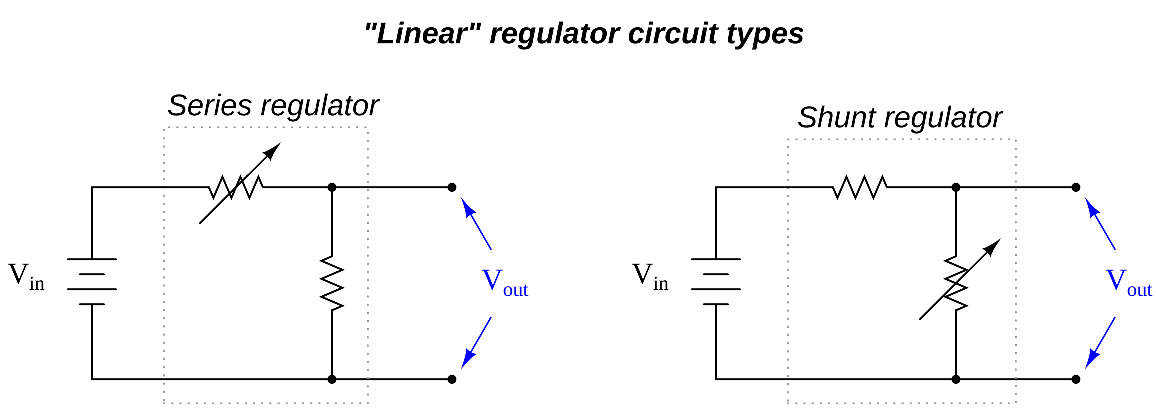
Based on this mathematical relationship, calculate the output voltage of this converter circuit at these duty cycles, assuming an input voltage of 25 volts:

- $D = 0\%$; $V_{out} =$
- $D = 25\%$; $V_{out} =$
- $D = 50\%$; $V_{out} =$
- $D = 75\%$; $V_{out} =$
- $D = 100\%$; $V_{out} =$

file 02477

Question 89

So-called *linear* regulator circuits work by adjusting either a series resistance or a shunt resistance to maintain output voltage at some fractional value of input voltage:



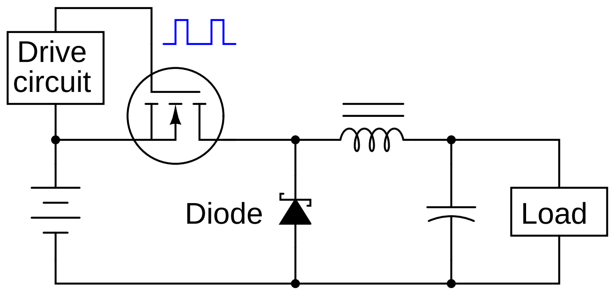
Typically, these variable resistances are provided by transistors rather than actual rheostats, which would have to be manually controlled.

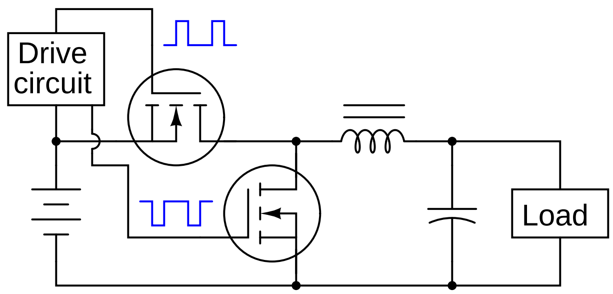
Explain why a *switching* regulator circuit would perform the same task as a linear regulator circuit at a much greater efficiency. Also, identify which type(s) of switching regulator circuit would be best suited for the task of reducing an input voltage to a lesser output voltage.

file 02162

Question 90

Many switching converter circuits use a switched MOSFET in place of a free-wheeling diode, like this:





The diode is a simple solution for providing the inductor a path for current when the main switching transistor is off. Why would anyone use another MOSFET in place of it, especially if this means the drive circuit has to become more complex (to drive two transistors at different times instead of just one transistor) to do the same task?

file 02480

Question 91

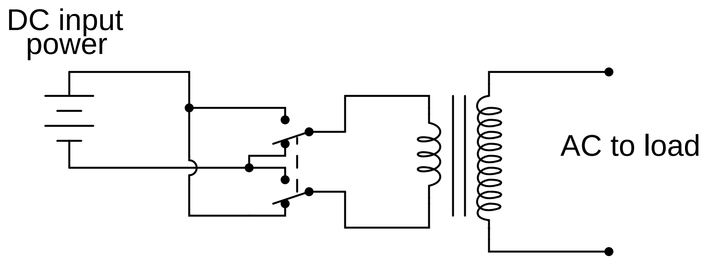
The energy efficiency (η) of switching converter circuits typically remains fairly constant over a wide range of voltage conversion ratios. Describe how a switching *regulator* circuit (controlling load voltage to a pre-set value) "appears" to a power source of changing voltage if the regulator's load is constant. In other words, as the input voltage changes, what does the input current do?

file 02359

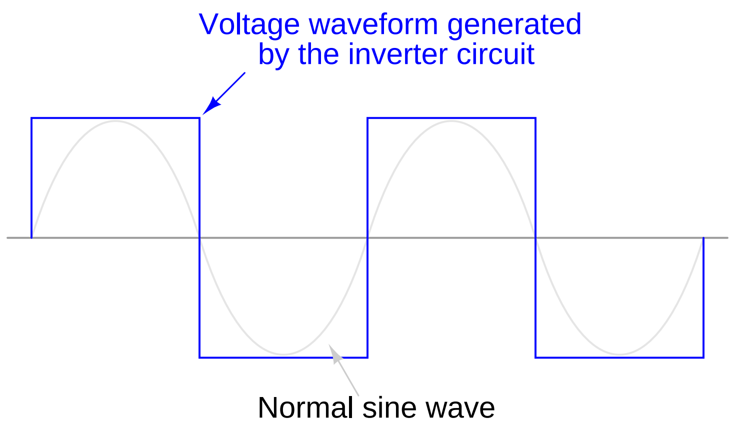
Question 92

$\boxed{\int f(x)\,dx \quad \textit{Calculus alert!}}$

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:

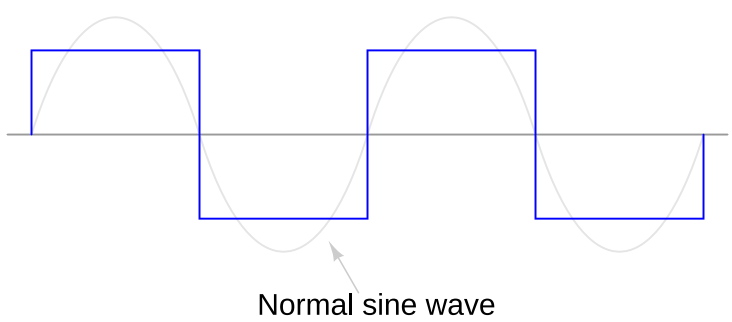


The first commercially available inverters produced simple square-wave output:

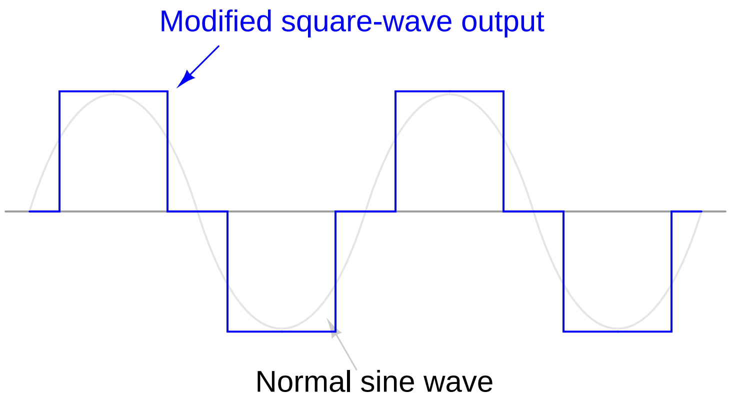


However, this caused problems for most power transformers designed to operate on sine-wave AC power. When powered by the square-wave output of such an inverter, most transformers would *saturate* due to excessive magnetic flux accumulating in the core at certain points of the waveform's cycle. To describe 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.

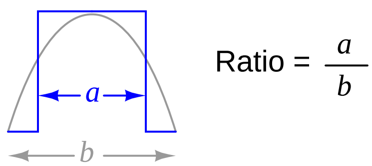
This problem could be avoided by decreasing the peak voltage of the square wave, but then some types of powered equipment would experience difficulty due to insufficient (maximum) voltage:



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.

file 01489

Question 93

Suppose a friend of yours recently purchased an off-road vehicle. This friend also purchased a military-surplus spotlight, which he thinks would be a great accessory for off-road illumination at night. The only problem is, the spotlight is rated for 24 volts, while the electrical system in his vehicle is 12 volt.

Your friend asks you to engineer a solution for powering the 24-volt spotlight with the 12 volts available on his vehicle. Of course, you are not allowed to modify the vehicle's electrical system (change it to 24 volt generator, battery, starter motor, etc.), because it is new and still under warranty. What do you recommend to your friend?

Draw a component-level schematic diagram of your solution to this problem.

file 01099

Answer 1

These are *varistors*. Sometimes they are referred to by the acronym *MOV*, which stands for Metal Oxide Varistor. I'll let you research what is unique about the behavior of these devices.

Follow-up question: plot an approximate graph of current versus voltage for a varistor, and comment on how this compares to the current/voltage characteristic of a normal resistor.

Answer 2

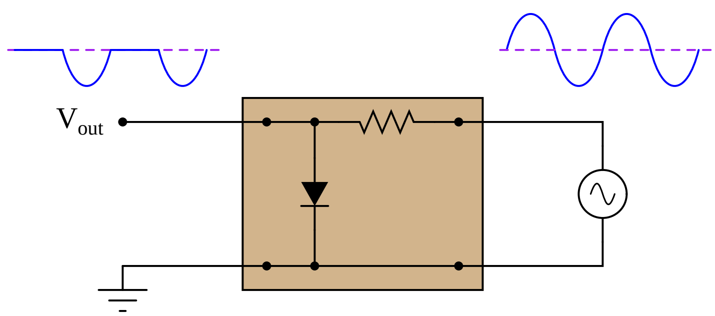
Some surge protectors use varistors, others use zener diodes, and others use more advanced technologies. I'll let you research designs and schematic diagrams on your own!

Answer 3

The diodes serve to protect the listener from very loud volumes, in the event of accidental connection to a large voltage source.

Review question: the purpose of the transformer is to increase the effective impedance of the headphones, from 8 Ω to a much larger value. Calculate this larger value, given a transformer turns ratio of 22:1.

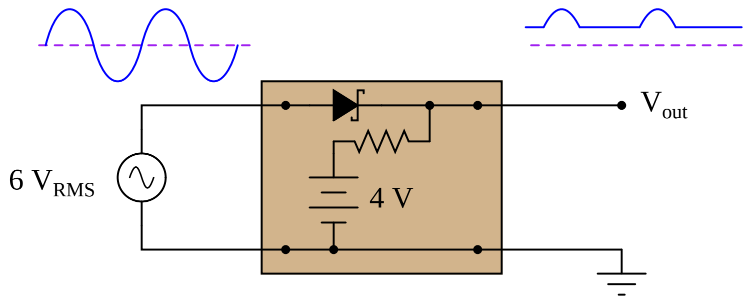
Answer 4



Note: the circuit shown here is not the only possible solution!

Follow-up question: the output waveform shown for this circuit is true only for an *ideal* diode, not a real diode. Explain what the output waveform would look like if a real diode were used, and recommend a diode model that closely approximates the ideal case for this application.

Answer 5

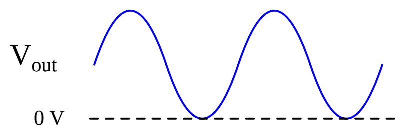


Follow-up question: explain why a *Schottky* diode is shown in this circuit rather than a regular silicon PN-junction diode. What characteristic(s) of Schottky diodes make them well suited for many clipper applications?

Answer 6

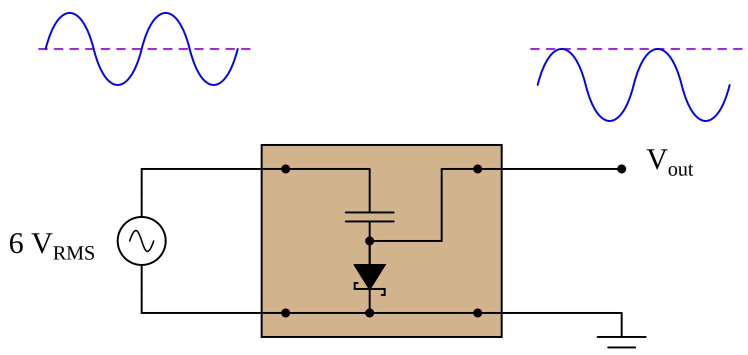
"Clamper" circuits provide just enough DC bias voltage to offset an AC signal so that almost its entire shape occurs either above or below ground potential.

Answer 7



Follow-up question: how does the clamper circuit "know" how much it needs to bias the AC voltage waveform so that it gets shifted just enough to eliminate reversals of polarity? Would this circuit function the same if the AC voltage were increased or decreased? Explain why.

Answer 8

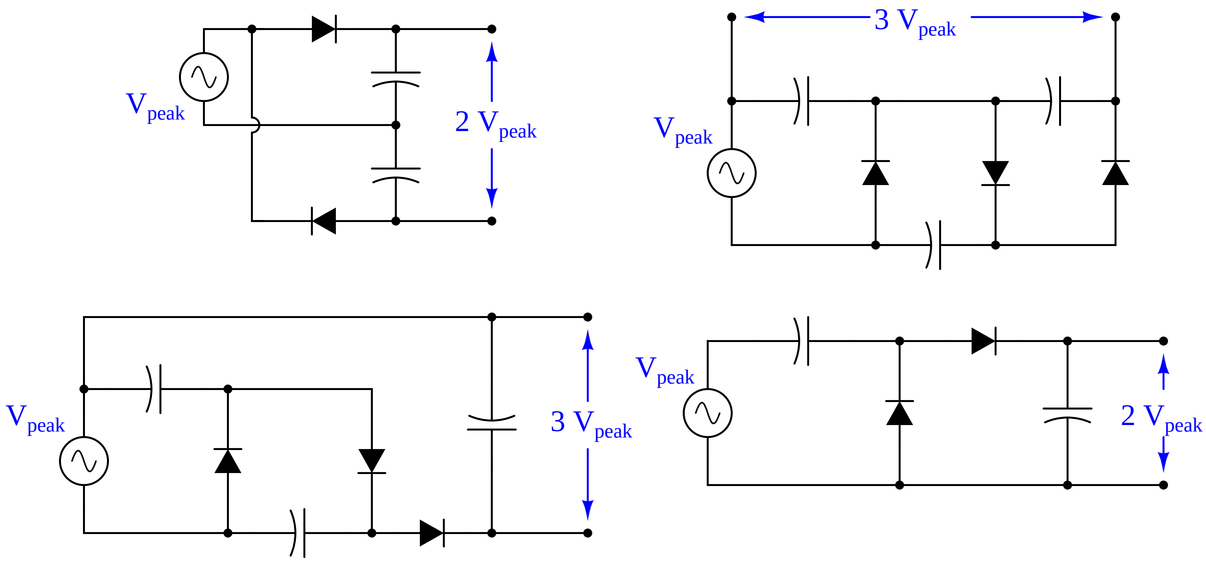


Answer 9

The diode's peak inverse voltage ("PIV") rating is insufficient. It needs to be about 85 volts or greater in order to withstand the demands of this circuit.

Follow-up question: suggest a part number for a diode capable of withstanding the reverse voltage generated by this circuit, and able to handle at least 1 amp of continuous current.

Answer 10



Answer 11

Once turned on, a thyristor tends to remain in the "on" state, and visa-versa.

Answer 12

Turn on: voltage drop across device must exceed a certain threshold voltage (the *breakover voltage*) before conduction occurs.

Turn off: current through the device must be brought to a minimum level before the device stops conducting (*low-current dropout*).

Answer 13

The positive feedback intrinsic to this circuit gives it hysteretic properties: once triggered "on," it tends to stay on. When "off," it tends to stay off (until triggered).

Answer 14

The smallest terminal (on top) is the gate. The identities of cathode and anode may be determined by connecting one test lead to the gate terminal, and touching the other test lead to either of the other terminals.

Answer 15

I'll let you research the answers to these questions!

Answer 16

A "TRIAC" functions as two reverse-parallel-connected SCR units, so as to be able to control AC and not just DC.

Follow-up question: draw the equivalent circuit for a TRIAC.

Answer 17

1. Applying a voltage pulse at the gate terminal
2. Exceeding the anode-to-cathode "breakover" voltage
3. Exceeding the "critical rate of rise" for anode-cathode voltage ($\frac{dv}{dt}$)

Answer 18

The SCR circuit's lamp will energize when the switch is actuated, and remain on after the switch is released. The TRIAC circuit's lamp will energize when the switch is actuated, and immediately de-energize when the switch is released.

Follow-up question: explain why these circuits do not behave identically. Aren't SCRs and TRIACs both thyristor (hysteretic) devices? Why doesn't the TRIAC remain in the "on" state after its triggering voltage is removed?

Answer 19

$$V_P \approx \frac{V_{BB} R_{B1}}{R_{B1} + R_{B2}} + 0.7$$

Follow-up question: how is the the *standoff ratio* defined for a UJT, and how might this equation be re-written to include it?

Answer 20

Unijunction transistors are hysteretic, like all thyristors. A positive pulse to the emitter terminal latches the UJT, and a negative pulse makes it "drop out".

Challenge question: what is the purpose of resistor R_3 in this circuit?

Answer 21

- F_1 protects the voltage source from damage
- R_1 and R_2 provide a divided sample of +V
- R_3 and D_1 provide a reference ("threshold") voltage
- Q_1 detects the overvoltage condition
- R_4 de-sensitizes the SCR gate
- SCR_1 clamps the output voltage

Answer 22

Once any one of the SCRs has been latched, the voltage available at the switches for triggering the other SCRs is substantially reduced. A normally-closed "reset" switch may be installed in series with the battery to reset all lamps back to the "off" state.

Challenge question: how could this circuit be modified to serve as a "first place" detector for runners competing on three different tracks? Draw a schematic diagram showing suitable sensors (instead of pushbutton switches) for detecting the passage of the three runners.

Answer 23

This circuit is an example of a *parallel capacitor, forced commutation* circuit. When one SCR fires, the capacitor is effectively connected in parallel with the other SCR, causing it to drop out due to low current.

Answer 24

The difference between these two circuits is a matter of switch currents. If you understand how a TRIAC works, the answer to this question should not be too difficult to figure out on your own.

Answer 25

Advantages

- Less DC drive current required
- No moving parts to wear
- Zero-crossing turn-off naturally provided by the TRIAC
- *Any others you can think of . . . ?*

Disadvantages

- "Off" state not as high-impedance as an electromechanical relay
- Susceptible to $\frac{dv}{dt}$-induced turn-on
- *Any others you can think of . . . ?*

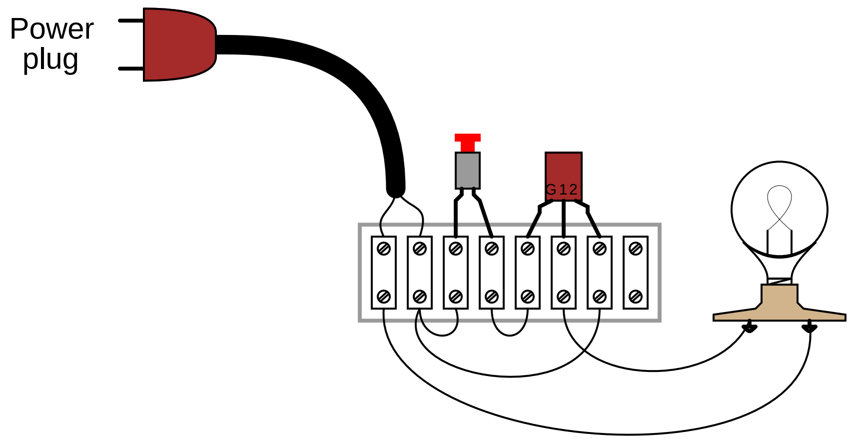
Follow-up question: what is *zero-crossing turn-off*, and what type of load might benefit most from this feature?

Answer 26

Too much triggering voltage is being applied to the TRIAC in this configuration. I'll let you determine how to re-wire the circuit to avoid this problem!

Answer 27

Terminals MT1 and MT2 on the TRIAC need to be reversed, like this:



Answer 28

The TRIAC's triggering is based on amplitude of the power source sine wave only. At minimum (adjustable) power, the TRIAC triggers exactly at the sine wave's peak, then latches on until the load current crosses zero. A shorter waveform duty cycle is simply not possible with this scheme because there is no way to trigger the TRIAC at a point past the sine wave peak.

Follow-up question #1: which direction must the student rotate the potentiometer shaft (CW or CCW) in order to *dim* the lamp, based on the pictorial diagram shown in the question?

Follow-up question #2: explain how the oscilloscope is being used by the student, with two probes, channel B inverted, and the "Add" function engaged. Why is this mode of usage important for this kind of voltage measurement?

Answer 29

E_C phase shift = -76.7^o

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

Answer 30

The TRIAC controls power to the primary winding of the step-down transformer. Afterward, that AC power is rectified to DC for charging purposes.

Answer 31

"Duty cycle" is a measure of a pulse waveform's *on* time versus its *total* time (period):

$$D = \frac{t_{on}}{t_{total}}$$

I'll let you figure out how to write an equation solving for pulse width (t_{on}) in terms of duty cycle and frequency.

Answer 32

Duty cycle $\approx$ 38%

Answer 33

Duty cycle $\approx$ 30%

Answer 34

When the transistor is on, is acts like a closed switch: passing full load current, but dropping little voltage. Thus, its "ON" power ($P = IE$) dissipation is minimal. Conversely, when the transistor is off, it acts like an open switch: passing no current at all. Thus, its "OFF" power dissipation ($P = IE$) is zero. The power dissipated by the load (the light bulb) is the time-averaged power dissipated between "ON" and "OFF" transistor cycles. Thus, load power is controlled without "wasting" power across the control device.

Answer 35

The motor would rotate at some speed less than full speed.

Follow-up question: explain how this general principle could be used to control the speed of an electric motor.

Answer 36

The greater the duty cycle, the more power delivered to the motor.

Follow-up question: how do you recommend a suitable oscillator *frequency* be determined for this motor control circuit? Describe how you might experiment with the circuit to determine a suitable frequency without performing any calculations.

Answer 37

Transistor power dissipation will increase if operating in its "linear" range of operation rather than being completely cut off or saturated. This decreases its service life as well as the energy efficiency of the circuit.

Answer 38

Duty cycle $\approx$ 42%
$P_{average} \approx 1.5$ W

Follow-up question: which oscilloscope setup parameters (vertical sensitivity, probe ratio, coupling, and timebase) are necessary for performing these calculations? Which parameters are unnecessary, and why?

Answer 39

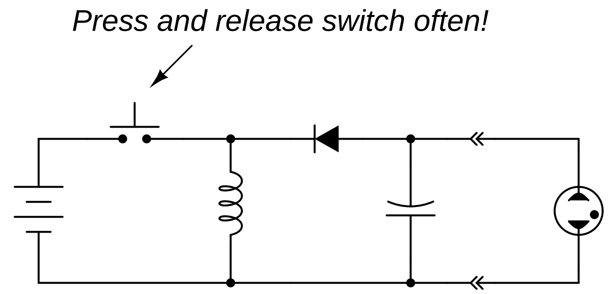
Duty cycle $\approx$ 71.4%
$P_{average} \approx 344$ W

Follow-up question: which oscilloscope setup parameters (vertical sensitivity, probe ratio, coupling, and timebase) are necessary for performing these calculations? Which parameters are unnecessary, and why?

Answer 40

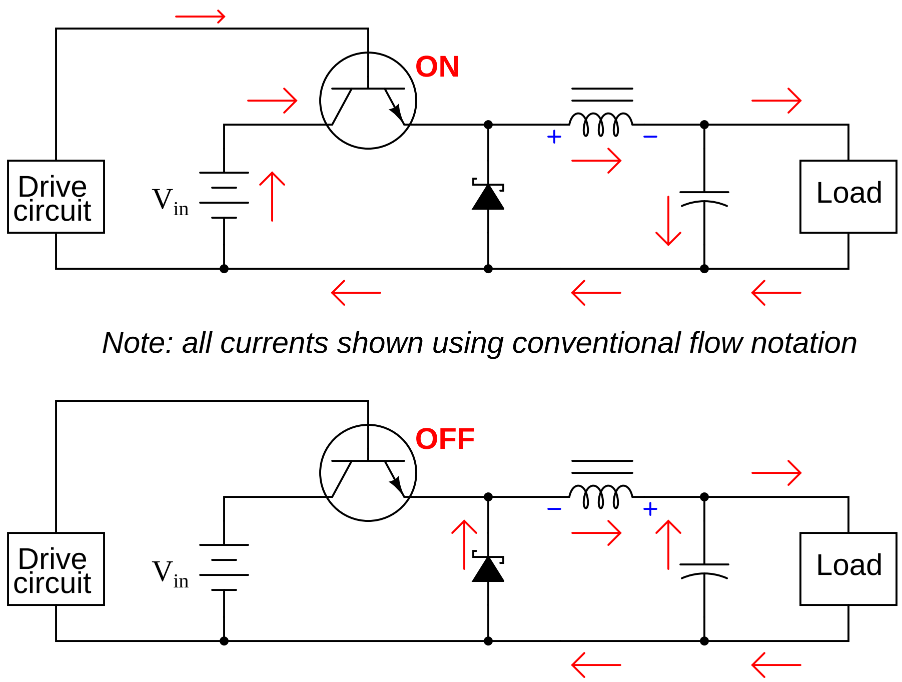
As in PWM, AC power control circuits using TRIAC and SCR devices modulate power by controlling the amount of *time* the load receives power from the source.

Answer 41



Follow-up question: how would you recommend we "automate" this circuit so that a person does not have to keep pressing and releasing the switch for it to generate a continuous DC output voltage?

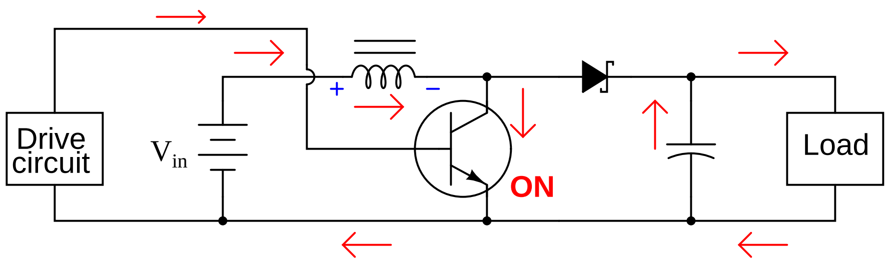
Answer 42



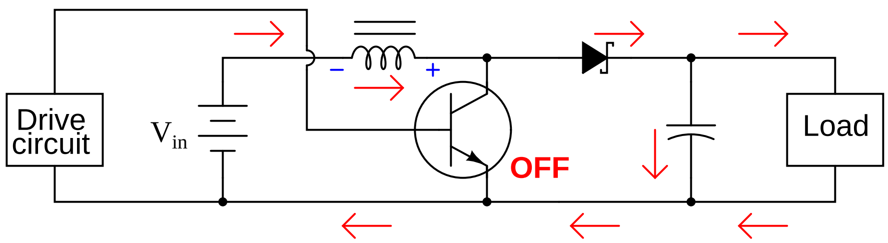
Follow-up question: how does the load voltage of this converter relate to the supply (battery) voltage? Does the load receive more or less voltage than that provided by the battery?

Challenge question: why do you suppose a Schottky diode is used in this circuit, as opposed to a regular (PN) rectifying diode?

Answer 43



Note: all currents shown using conventional flow notation



Follow-up question: how does the load voltage of this converter relate to the supply (battery) voltage? Does the load receive more or less voltage than that provided by the battery?

Challenge question: why do you suppose a Schottky diode is used in this circuit, as opposed to a regular (PN) rectifying diode?

Answer 44

The battery supplying the linear circuit must source 240 mA, while the battery supplying the switching circuit must only source an average current of 88.9 mA.

Follow-up question: calculate the power efficiency of the linear circuit, and comment on why it is so different from the switching circuit.

Answer 45

- $D = 0\%$; $V_{out} = 0$ volts
- $D = 25\%$; $V_{out} = 10$ volts
- $D = 50\%$; $V_{out} = 20$ volts
- $D = 75\%$; $V_{out} = 30$ volts
- $D = 100\%$; $V_{out} = 40$ volts

Answer 46

- $D = 0\%$; $V_{out} = 40$ volts
- $D = 25\%$; $V_{out} = 53.3$ volts
- $D = 50\%$; $V_{out} = 80$ volts
- $D = 75\%$; $V_{out} = 160$ volts
- $D = 100\%$; $V_{out} = 0$ volts

Answer 47

- $D = 0\%$; $V_{out} = 0$ volts
- $D = 25\%$; $V_{out} = 13.3$ volts
- $D = 50\%$; $V_{out} = 40$ volts
- $D = 75\%$; $V_{out} = 120$ volts
- $D = 100\%$; $V_{out} = 0$ volts

Answer 48

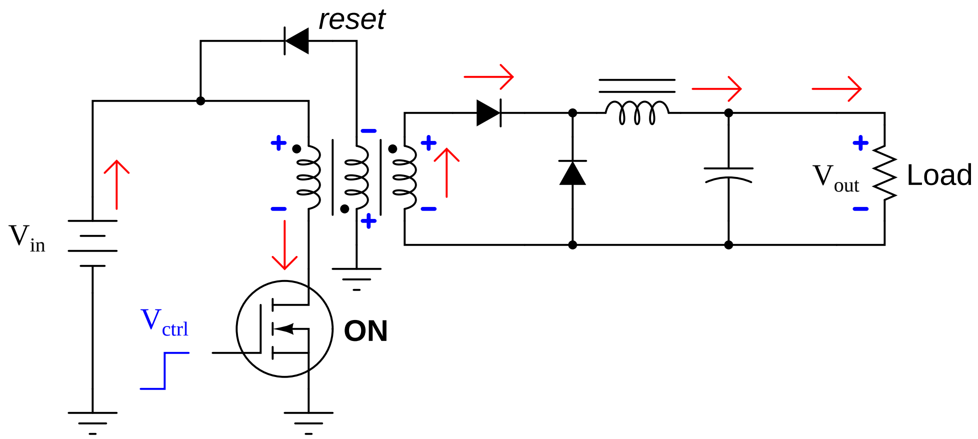
$$D = \frac{V_{out}}{V_{in}} \qquad \text{(Buck converter circuit)}$$

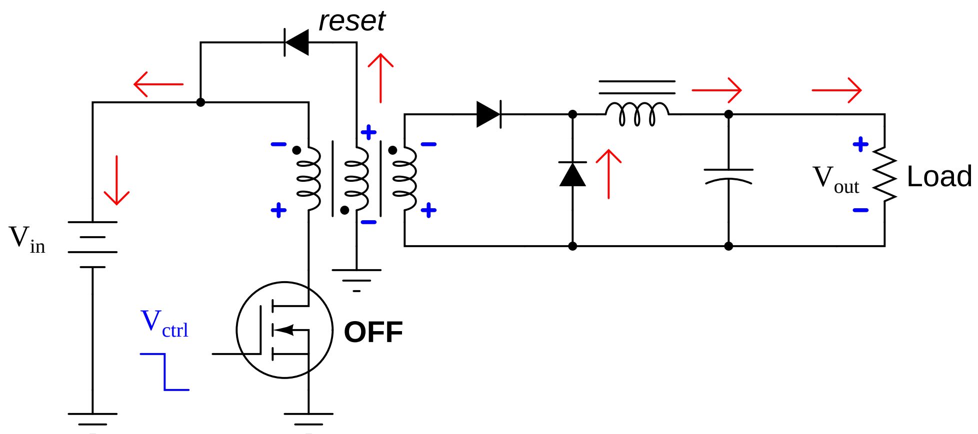
$$D = 1 - \left(\frac{V_{in}}{V_{out}}\right) \qquad \text{(Boost converter circuit)}$$

$$D = \frac{V_{out}}{V_{in} + V_{out}} \qquad \text{(Inverting or Cuk converter circuit)}$$

Answer 49

In the following schematics, conventional flow notation has been used to denote direction of currents:





The purpose of the reset winding is to rid the transformer core of stored energy during the off cycle. If this were not done, the transformer core's magnetic flux levels would reach saturation after just a few on/off cycles of the transistor.

Answer 50

I'll let you do all the research for this question!

Answer 51

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

Answer 52

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

Answer 53

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

Answer 54

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

Answer 55

- Diode D_1 fails open: *No output voltage at all.*
- Diode D_1 fails shorted: *Full AC signal at output (no clipping at all).*
- Resistor R_1 fails open: *No change (if diode is indeed ideal), but realistically there may not be much clipping if the receiving circuit has an extremely large input impedance.*
- Resistor R_1 fails shorted: *No output voltage at all.*

Answer 56

- Diode D_1 fails open: *Full AC signal at output (no clipping at all).*
- Diode D_1 fails shorted: *No output voltage at all.*
- Resistor R_1 fails open: *No output voltage at all.*
- Resistor R_1 fails shorted: *Normal operation if source impedance is substantial, otherwise diode and/or source may be damaged by direct short every half-cycle.*

Answer 57

- Diode D_1 fails open: *No effect on small signals, clipping of large signals will be incomplete (only one-half of the waveform will be clipped in amplitude).*
- Diode D_1 fails shorted: *No sound heard at headphones at all.*
- Transformer T_1 primary winding fails open: *No sound heard at headphones at all.*
- Resistor R_1 fails open: *No sound heard at headphones at all.*
- Solder bridge (short) past resistor R_1: *Volume (slightly) louder than usual.*
- Wiper fails to contact slide in potentiometer: *No sound heard at headphones at all.*

Answer 58

The diode might be failed open, but this is only one possibility.

Answer 59

- Switch contacts fail open: *Load never receives power.*
- Switch contacts fail shorted: *Load always receives power.*
- Resistor R_1 fails open: *Load never receives power.*
- Solder bridge (short) past resistor R_1: *Load energizes momentarily the first time the switch is actuated, then refuses to turn on after the LED inside the solid-state relay (SSR_1) becomes damaged.*
- Battery (V_1) dies: *Load never receives power.*

Answer 60

- Capacitor C_1 fails open: *Neither pushbutton switch has any effect on the LED.*
- Capacitor C_1 fails shorted: *Circuit behaves normally.*
- Resistor R_1 fails open: *LED always off, refuses to turn on.*
- Solder bridge (short) past resistor R_1: *LED always on, refuses to turn off.*
- Resistor R_2 fails open: *LED always on, refuses to turn off.*
- Solder bridge (short) past resistor R_2: *LED always off, refuses to turn on.*

Answer 61

- Potentiometer R_{pot} fails open: *Lamp remains off.*
- Capacitor C_1 fails shorted: *Lamp remains off.*
- Capacitor C_1 fails open: *Range of lamp brightness control extends from 100% to 50%, and any attempt to make it dimmer results in the lamp just turning all the way off.*
- DIAC fails open: *Lamp remains off.*
- TRIAC fails shorted: *Lamp remains on at 100% brightness.*

Answer 62

- Drive circuit fails with a constant "low" (0 volts) output signal: *Output voltage falls to zero after capacitor discharges.*
- Drive circuit fails with a constant "high" (+V) output signal: *Output voltage rises to become approximately equal to* V_{in}.
- Diode fails shorted: *Output voltage falls to zero, then transistor fails due to overheating.*
- Inductor fails open: *Output voltage falls to zero after capacitor discharges.*
- Capacitor fails shorted: *Output voltage falls to zero immediately.*

Answer 63

- Drive circuit fails with a constant "low" (0 volts) output signal: *Output voltage rises to become approximately equal to* V_{in}.
- Drive circuit fails with a constant "high" (+V) output signal: *Output voltage falls to zero after capacitor discharges.*
- Diode fails shorted: *Output voltage exhibits very large "ripple" as the voltage repeatedly falls to zero and spikes back up each drive cycle, transistor may fail due to overheating.*
- Inductor fails open: *Output voltage falls to zero after capacitor discharges.*
- Capacitor fails shorted: *Output voltage falls to zero immediately.*

Answer 64

Possible faults (not an exhaustive list)

- SCR failed shorted
- Zener diode failed shorted
- R_1 failed shorted
- R_2 failed open
- R_4 failed open (especially if SCR is a sensitive-gate type)
- UJT Q_1 failed shorted between base terminals

Answer 65

The output will be a square wave with a peak-to-peak voltage of approximately 1.4 volts.

Answer 66

The potentiometer adjusts the threshold at which the positive peak of the AC waveform is clipped.

Follow-up question: modify this circuit to function as a variable *negative* peak clipper instead.

Answer 67

This simple AM "detector" circuit is widely discussed in basic electronics textbooks and other technical literature. There is little I can say here that would expand on what is already written about these circuits. I leave it to you to do the research!

Answer 68

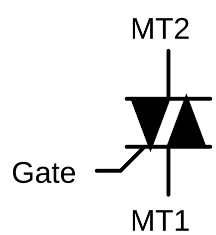
The DC output voltage will increase as the input signal frequency is increased. This lends itself to frequency measurement applications.

Answer 69

The constituent transistors of an SCR become driven heavily into saturation in its conductive state, with a bare minimum of drive (gate) current necessary.

Follow-up question: how does the internal operation of an SCR explain its very fast turn-on time, in addition to explaining its low conducting voltage drop?

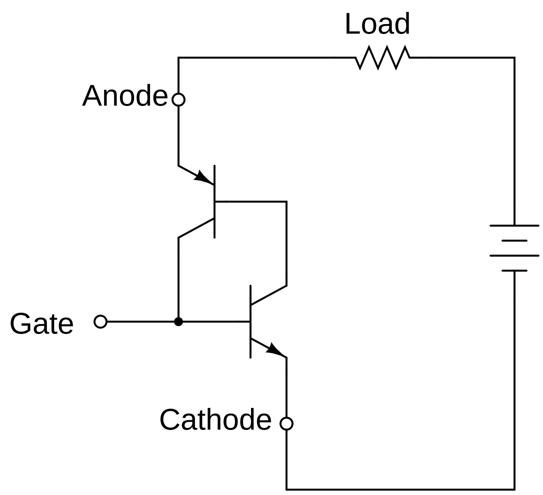
Answer 70



Answer 71

SCRs and TRIACs with "sensitive gates" resemble the idealized devices illustrated in textbooks. SCRs and TRIACs with "non-sensitive" gates are intentionally "desensitized" by the addition of an internal loading resistor connected to the gate terminal.

Follow-up question: where would this loading resistor be connected, in the following equivalent diagram for an SCR?



Answer 72

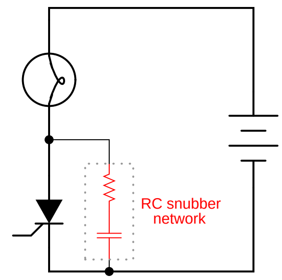
A "crowbar" circuit uses an SCR to clamp the output voltage of a DC power supply in the event of accidental overvoltage, in the same manner that a (literal) metal crowbar thrown across the terminals of a power supply would forcibly clamp the output voltage.

Answer 73

I'll let you determine the reason why SCRs cannot be used as audio amplification devices.

Answer 74

Parasitic (Miller-effect) capacitances inside the SCR's bipolar structure make the device vulnerable to voltage transients, large $\frac{dv}{dt}$ rates creating base currents large enough to initiate conduction. Snubber circuits are typically provided to mitigate these effects:



Answer 75

$V_P \approx 12.7$ volts

Answer 76

The UJT will remain in the nonconducting state as the potentiometer voltage increases from 0 volts, until it reaches V_P. At that voltage, the UJT turns on and stays on. To turn the UJT off, the potentiometer must be adjusted back down in voltage until the current through point **A** decreases to a certain "dropout" value.

Answer 77

Commutation is nothing more than a fancy word for "switching" (think of the *commutator* in a DC electric motor – its purpose being to *switch* polarity of voltage applied to the armature windings). In the context of thyristors, "commutation" refers to the issue of how to turn the device(s) off after they have been triggered on.

Follow-up question: in some circuits, commutation occurs naturally. In other circuits, special provisions must be made to force the thyristor(s) to turn off. Identify at least one example of a thyristor circuit with *natural commutation* and at least one example of a thyristor circuit using *forced commutation*.

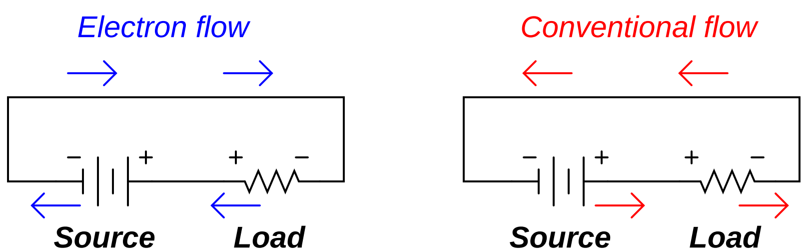
Answer 78

Remember that CR_1 only needs one pulse at its gate to turn (and latch) it on! C_2 and R_4 form a *passive differentiator* to condition the square wave signal from the UJT oscillator.

Follow-up question: how would you suggest we modify this circuit to make the time delay adjustable?

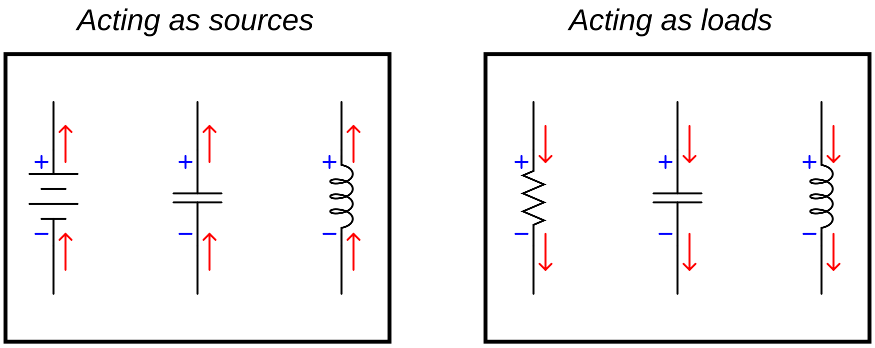
Answer 79

Here I show the answer in two different forms: current shown as *electron flow* (left) and current shown as *conventional flow* (right).



Whichever notation you choose to follow in your analysis of circuits, the understanding should be the same: the reason voltage polarities across the resistor and battery differ despite the same direction of current through both is the flow of power. The battery acts as a *source*, while the resistor acts as a *load*.

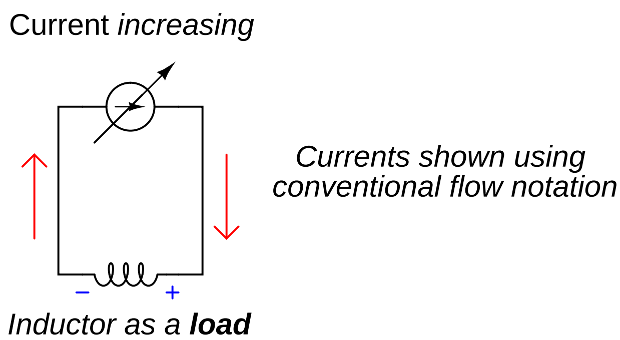
Answer 80



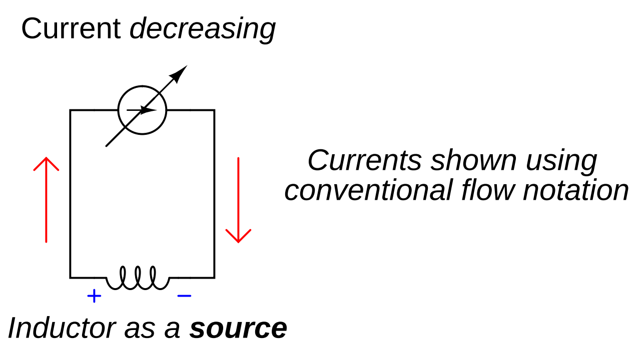
Follow-up question: what form does the stored energy take inside each type of reactive component? In other words, *how* does an inductor store energy, and *how* does a capacitor store energy?

Answer 81

As the applied current increases, the inductor acts as a load, accumulating additional energy from the current source. Acting as a load, the voltage dropped by the inductor will be in the same polarity as across a resistor.

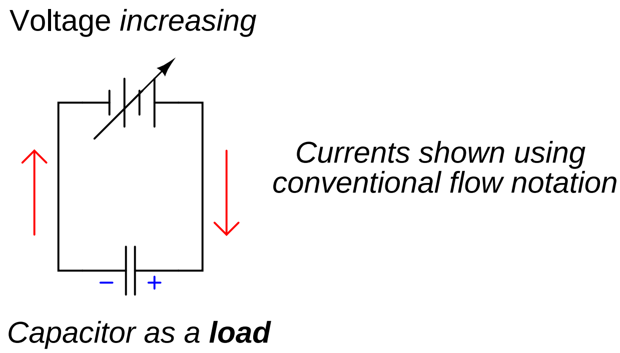


As the applied current decreases, the inductor acts as a source, releasing accumulated energy to the rest of the circuit, as though it were a current source itself of superior current. Acting as a source, the voltage dropped by the inductor will be in the same polarity as across a battery, powering a load.

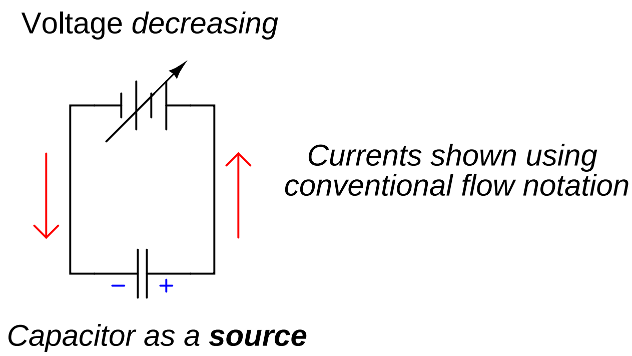


Answer 82

As the applied voltage increases, the capacitor acts as a load, accumulating additional energy from the voltage source. Acting as a load, the current going "through" the capacitor will be in the same direction as through a resistor.



As the applied voltage decreases, the capacitor acts as a source, releasing accumulated energy to the rest of the circuit, as though it were a voltage source itself of superior voltage. Acting as a source, the current going "through" the capacitor will be in the same direction as through a battery, powering a load.



Answer 83

There is a direct-proportional relationship between duty cycle and DC output voltage in this circuit, making it possible for a PWM signal to represent analog data.

Follow-up question #1: why is it important that the circuit generating the PWM signal for the integrator be able to both source *and* sink current?

Follow-up question #2: what would have to be done to reduce the ripple voltage at the integrator's output?

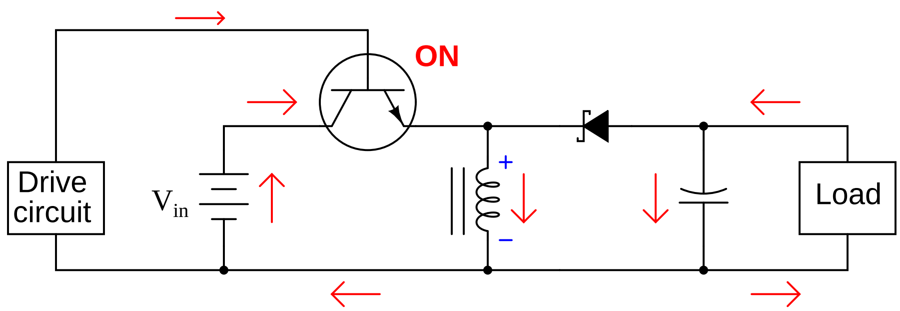
Answer 84

A *dynamotor* is a special type of electromechanical machine intended to convert one form of electrical power into another, using a common magnetic field and rotating element.

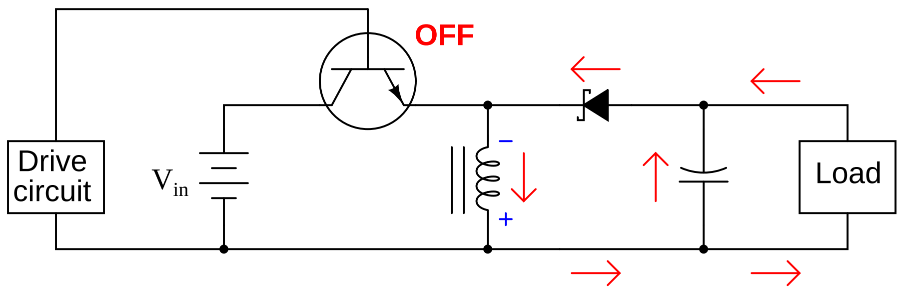
Answer 85

A "DC-DC converter" is a circuit that transforms a DC voltage either up or down, generally with an inverse transformation in current. Applications include supplying DC power to load devices where the main power source is DC, but of the wrong voltage.

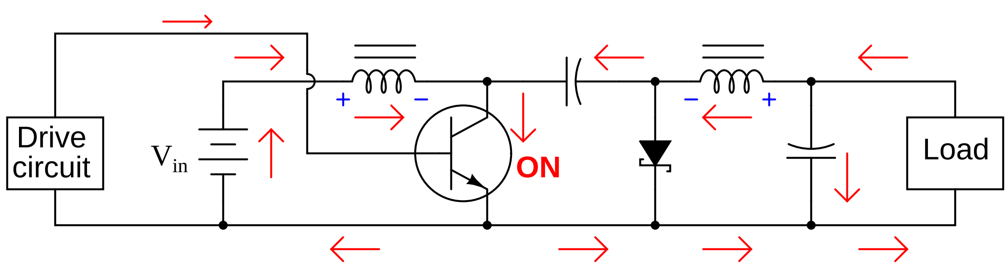
Answer 86



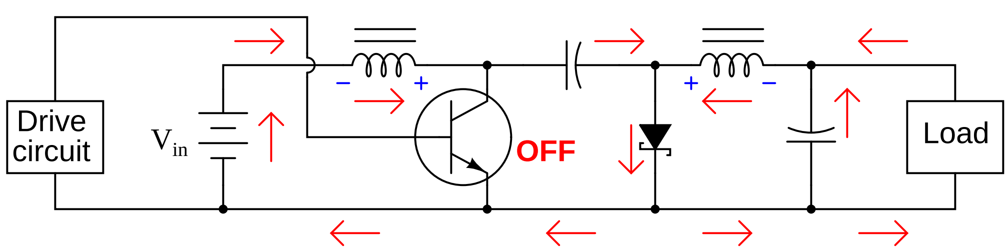
Note: all currents shown using conventional flow notation



Answer 87



Note: all currents shown using conventional flow notation



Follow-up question: how does the load voltage of this converter relate to the supply (battery) voltage? Does the load receive more or less voltage than that provided by the battery?

Answer 88

- $D = 0\%$; $V_{out} = 0$ volts
- $D = 25\%$; $V_{out} = 8.33$ volts
- $D = 50\%$; $V_{out} = 25$ volts
- $D = 75\%$; $V_{out} = 75$ volts
- $D = 100\%$; $V_{out} = 0$ volts

Answer 89

A *buck* regulator circuit functions in nearly the same manner as a transformer: stepping voltage down while stepping current up. Ideally, switching regulator circuits waste zero energy, unlike (resistive) linear regulator circuits.

Follow-up question: which type of linear regulator circuit does the traditional *zener diode voltage regulator* belong to, series or shunt?

Answer 90

A MOSFET in its enhanced mode will drop less voltage than a diode (even a Schottky diode) in this circuit, improving power efficiency.

Answer 91

The input current of a switching regulator is *inversely* proportional to the input voltage when powering a constant load, appearing as a *negative impedance* to the power source.

Answer 92

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!

Answer 93

While there are several different methods which could be used here to transform 12 volts into 24 volts, I will not reveal any of them here, lest I spoil the fun for you!

Notes 1

Ask your students to reveal their information sources used when researching varistors, and also if they were able to determine how these devices are constructed.

Notes 2

Ask students how a surge protector (or surge "suppressor") is similar in principle to *clipper* circuits used for small electronic signals.

Notes 3

My first encounter with this application of diodes came when I was quite young, soldering together a kit multimeter. I was very confused why the meter movement had two diodes connected to it in parallel like this. All I knew about diodes at the time was that they acted as one-way valves for electricity. I did not understand that they had a substantial forward voltage drop, which is the key to understanding how they work in applications such as this. While this may seem to be a rather unorthodox use of diodes, it is actually rather common.

Incidentally, I *highly* recommend that students build such an audio test set for their own experimental purposes. Even with no amplifier, this instrument is amazingly sensitive. An inexpensive 120 volt/6 volt step-down power transformer works well as an impedance-matching transformer, and is insulated enough to provide a good margin of safety (electrical isolation) for most applications. An old microwave over power transformer works even better (when used in a step-down configuration), giving several thousand volts worth of isolation between primary and secondary windings.

The circuit even works to detect DC signals and AC signals with frequencies beyond the audio range. By making and breaking contact with the test probe(s), "scratching" sounds will be produced if a signal of sufficient magnitude is present. With my cheap "Radio Shack" closed-cup headphones, I am able to reliably detect DC currents of less than 0.1 μA with my detector! Your mileage may vary, depending on how good your hearing is, and how sensitive your headphones are.

I have used my own audio detector many times in lieu of an oscilloscope to detect distortion in audio circuits (very rough assessments, mind you, not precision at all) and even as a detector of DC voltage (detecting the photovoltaic output voltage of a regular LED). It may be used as a sensitive "null" instrument in both AC and DC bridge circuits (again, DC detection requires you to make and break contact with the circuit, listening for "clicking" or "scratching" sounds in the headphones).

Another fun thing to do with this detector is connect it to an open coil of wire and "listen" for AC magnetic fields. Place such a coil near a working computer hard drive, and you can hear the read/write head servos in action!

If it isn't clear to you already, I am very enthusiastic about the potential of this circuit for student engagement and learning . . .

Notes 4

A good review of basic diode concepts here. Students should recognize the output waveform as being indicative of half-wave rectification, which may cause them to think of other circuit designs.

Notes 5

Ask your students whether they would classify this circuit as a *series* or a *shunt* clipper.

If your students are unfamiliar with Schottky diodes, this is an excellent opportunity to discuss them! Their low forward voltage drop and fast switching characteristics make them superior for most signal clipper and clamper circuits.

Notes 6

Ask your students to provide an example of a clamper circuit schematic.

Notes 7

Ask your students to replace the capacitor with a DC voltage source (oriented in the correct polarity, of course), and explain how the capacitor actually functions as a voltage bias in this clamper circuit.

Notes 8

Have multiple students share their thoughts as to how they designed the clamper circuit.

Notes 9

If students experience difficulty calculating the necessary PIV rating for this circuit's diode, ask them to analyze the peak output from the transformer's secondary winding *for each half-cycle of the AC waveform*, noting the voltage drops across all circuit components. Once a full-cycle voltage analysis is performed for all circuit components, the necessary diode rating should become obvious.

Though it may not be obvious at first reading, this question may actually serve as a lead-in for discussing voltage multiplier circuits. The fact that the diode experiences a reverse voltage *twice* that of the peak AC voltage is something we may exploit!

Another reliability factor most students won't recognize in this circuit is the "inrush" current experienced by the diode every time the circuit is powered up and the capacitor recharges. Certainly, the diode was not properly rated for the reverse voltage it was being subjected to, but this might not be the only form of abuse! If time permits, discuss this possibility as well.

Notes 10

Ask your students how they analyzed each of these voltage multiplier circuits, and to explain their technique(s) to the rest of the class during discussion.

Notes 11

The hysteretic action of thyristors is often referred to as *latching*. Ask your students to relate this term to the action of a thyristor. Why is "latching" an appropriate term for this behavior? Can your students think of any applications for such a device?

Notes 12

Although the answer may seem obvious to many, it is worthwhile to ask your students how the behavior of a Shockley diode compares to that of a normal (rectifying) diode. The fact that the Shockley diode is called a "diode" at all may have fooled some of your students into thinking that it behaves much like a normal diode.

Ask you students to explain how these two devices (Shockley diodes versus rectifying diodes) are similar. In what ways are they different?

Another good discussion question to bring up is the difference between a *Shockley* diode and a *Schottky* diode. Although the names are very similar, the two devices are definitely not!

Notes 13

Have students demonstrate the positive feedback "latching" action of this circuit by drawing directions of current on a diagram for the class to see (on the whiteboard, in view of everyone). Ask your students why the circuit "waits" until a triggering pulse to turn on, and why it "latches" on once triggered.

Notes 14

Ask your students how they know the gate terminal is the smallest one. Why would it be the smallest? Does it *have* to be the smallest terminal? Why? Also, ask them what continuity indication would distinguish cathode from anode in the continuity test described in the answer.

Notes 15

Let students explain (or perhaps even demonstrate) their answers. It is extremely important for students to realize that SCR's are *thyristors*, "latching" on and off with transient stimuli. They differ significantly from transistors in this regard.

Notes 16

A popular application for TRIACs is lamp dimmer controls, for line-powered (50 or 60 Hz) incandescent lamps. If time permits, discuss with your students how these lamp dimmer circuits control power to the lamp in a manner reminiscent of PWM (Pulse-Width Modulation).

Notes 17

Although gate triggering is by far the most common method of initiating conduction through SCRs and TRIACs, it is important that students realize it is not the only way. The other two methods, both involving voltage applied between the anode and cathode terminals (or MT1-MT2 terminals) of the device, are often *accidental* means of triggering.

Be sure to discuss with your students the reason *why* excessive $\frac{dv}{dt}$ can trigger a thyristor, based on an examination of inter-electrode capacitance within the transistors of a thyristor model.

Notes 18

This question addresses a very common misunderstanding that students have about TRIACs in AC circuits. Students often mistakenly think that TRIACs will latch AC power just like an SCR latches DC power, simply because the TRIAC is also a hysteretic device. However, this is not true!

One might be inclined to wonder, of what benefit is the TRIAC's hysteresis in an AC circuit, then? If latching is impossible in an AC circuit, then why have TRIACs at all? This is a very good question, and its answer lies in the operation of a TRIAC *within the timespan of an AC power cycle*, which is much faster than human eyes can see.

Notes 19

The standoff ratio is perhaps the most important UJT parameter, given the hysteretic switching function of this device. Writing the equation for trigger voltage (V_P) and understanding the definition for standoff ratio requires that students remember the voltage divider formula from their studies in DC circuits:

$$V_R = V_{total}\left(\frac{R}{R_{total}}\right)$$

This question provides a good opportunity to review the operation of voltage divider circuits, and this formula in particular.

Notes 20

Ask your students to identify the terminals on the UJT. The designations for each terminal may be surprising to your students, given the names of bipolar transistor terminals!

The challenge question may only be answered if one carefully considers the characteristics of an LED. Resistor R_3 helps overcome problems that might potentially arise due to the nonlinearities of the diode in its off state.

I got this circuit from the October 2003 issue of Electronics World magazine, in their regular "Circuit Ideas" section. The design is attributed to André de Guérin.

Notes 21

In this question, students must piece together their knowledge of both UJTs and SCRs to analyze the function of the circuit. Perhaps the most complex aspect of it is the divided voltage sensing, whereby the UJT senses only a fraction of the supply voltage in determining whether to trigger or not.

Notes 22

Discuss the operation of this circuit with your students in detail. It serves as an excellent practical example of SCR action, as well as a good review of general diode action. Ask them why an NC switch connected in series with the battery would serve to reset the SCRs.

A good question to challenge students' understanding of this circuit is to ask them how to "expand" it to include four, five, or six lamps instead of just three.

I found this circuit design in the October 2003 edition of Electronics World magazine. The original circuit, submitted to this periodical by M.J. Nicholas, appears on page 35 of the magazine in a slightly different form, with four lamp circuits instead of three, and using regular rectifying diodes instead of Schottky diodes as I have shown.

Notes 23

This method of switching load current between two thyristors is a common technique in power control circuits using SCRs as the switching devices. If students are confused about this circuit's operation, it will help them greatly to analyze the capacitor's voltage drop when SCR_1 is conducting, versus when SCR_2 is conducting.

Notes 24

A benefit of this circuit that is easy to miss is the TRIAC's ability to provide *zero crossing turn-off*. Discuss why this might be important when controlling power to inductive loads.

Notes 25

It should be noted that the label "solid-state relay" is not exclusively reserved for opto-TRIAC devices. Many different types of solid-state relays exist, including opto-BJT, opto-FET, and opto-SCR. Be sure to mention this to your students.

Notes 26

I've seen students do this a few times, with startling results!

Notes 27

This aspect of TRIACs is often omitted from texts on thyristor devices, but it is important for students to understand. Even though TRIACs are bilateral devices, it still *does* matter where the triggering voltage is applied (between Gate and MT1, versus Gate and MT2).

Notes 28

Some students find this concept difficult to grasp, so it may be necessary to discuss what the load power waveforms appear like at different power settings.

Notes 29

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

Notes 30

The interesting point of this circuit is that by controlling AC power with the TRIAC, DC power to the battery is subsequently controlled.

Ask your students to explain the purpose of each component in the circuit, and pose some troubleshooting questions for them to analyze. There are many possibilities for component failures stopping DC power from getting to the battery. Discuss the examples your students think of, and determine the relatively likelihood of each.

Notes 31

Duty cycle is a very important concept, as analog information may be conveyed through the variable duty cycle of an otherwise digital pulse waveform. Discuss this application with your students, if time permits.

Notes 32

This question challenges students to apply their knowledge of duty cycle to a measurement scenario.

Notes 33

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Notes 34

Students may have a hard time grasping how a light bulb may be *dimmed* by turning it on and off really fast. The key to understanding this concept is to realize that the transistor's switching time must be much faster than the time it takes for the light bulb's filament to fully heat or fully cool. The situation is analogous to throttling the speed of an automobile by rapidly "pumping" the accelerator pedal. If done slowly, the result is a varying car speed. If done rapidly enough, though, the car's mass averages the "ON"/"OFF" cycling of the pedal and results in a nearly steady speed.

This technique is very popular in industrial power control, and is gaining popularity as an audio amplification technique (known as *Class D*). The benefits of minimal wasted power by the control device are many.

Notes 35

Since the circuit in this question embodies a general power control principle, it would be good to contrast it against other forms of power control. Ask your students how they think this method of control compares to that of placing a variable resistance in series with the motor. Is the "switching" method more or less efficient?

Notes 36

As review, ask your students to identify what type of MOSFET this is (type of channel, and either depletion or enhancement mode), and what the proper oscillator signal amplitude should be to drive the MOSFET alternately between cutoff and saturation.

Notes 37

Review with your students what it means for a transistor to be in "cutoff" or in "saturation," if they are not familiar with these terms or if it has been a while since they have studied this. A clear understanding of this concept is crucial to their being able to understand the efficiency of PWM power control.

Notes 38

Calculating the duty cycle should be easy. Calculating load power dissipation requires some thought. If your students do not know how to calculate average power, suggest this thought experiment: calculating power dissipation at 0% duty cycle, at 100% duty cycle, and at 50% duty cycle. The relationship between duty cycle and average power dissipation is rather intuitive if one considers these conditions.

If a more rigorous approach is required to satisfy student queries, you may wish to pose another thought experiment: calculate the *energy* (in units of Joules) delivered to the load for a 50% duty cycle, recalling that Watts equals Joules per second. Average power, then, is calculated by dividing Joules by seconds over a period of one or more whole waveform cycles. From this, the linear relationship between duty cycle and average power dissipation should be clear.

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Notes 40

Discuss with your students the similarities and differences between these two forms of time-based power control. Of course, PWM is more sophisticated than naturally-commutated SCR and TRIAC control schemes, but it is also more complex and therefore possibly more prone to faults.

Notes 41

Ask your students to explain their solutions for "automating" the switch's action. Prepare yourself for some creative answers!

Notes 42

Ask your students why they think this circuit is called a *buck* converter. "Buck" usually refers to something that is in opposition. What is being opposed in this circuit?

Notes 43

Ask your students why they think this circuit is called a *boost* converter. "Boost" usually refers to something that is aiding something else. What is being aided in this circuit?

Notes 44

Explain to your students that switching power conversion circuits are very efficient: typically 85 to 95 percent! It should be rather obvious which battery will last longer, and why. This is precisely why switching regulator circuits (DC-DC converters with a feedback network to stabilize output voltage) are used in place of linear regulator circuits (zener diode based) in many battery-powered electronic applications.

In essence, switching converter circuits act like DC transformers, able to step voltage down (or up), with current inversely proportional. Of course, the Law of Energy Conservation holds for switching circuits just as it does for transformers, and students may find this Law the easiest way to perform supply/load current calculations knowing the supply and load voltages:

$$P_{out} \approx P_{in}$$

$$V_{in} I_{in} \approx V_{out} I_{out}$$

If time permits, you might want to show your students a datasheet for a power converter controller, showing them how integrated circuits exist to precisely control the switching of MOSFETs for power converter circuits just like this.

Notes 45

The calculations for this circuit should be very straightforward.

Note that the switching element in the schematic diagram is shown in generic form. It would never be a mechanical switch, but rather a transistor of some kind.

Notes 46

The calculations for this circuit should be straightforward, except for the last calculation with a duty cycle of $D = 100\%$. Here, students must take a close look at the circuit and not just follow the formula blindly.

Note that the switching element in the schematic diagram is shown in generic form. It would never be a mechanical switch, but rather a transistor of some kind.

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Notes 48

Given the equations for these converter circuit types solving for output voltage in terms of input voltage and duty cycle D, this question is nothing more than an exercise in algebraic manipulation.

Note to your students that all of these equations assume a condition of zero load on the converter circuit. When loads are present, of course, the output voltage will not be the same as what is predicted by these neat, simple formulae. Although these DC-DC power converter circuits are commonly referred to as "regulators," it is somewhat misleading to do so because it falsely implies a capacity for self-correction of output voltage. Only when coupled to a feedback control network are any of these converter circuits capable of actually *regulating* output voltage to a set value.

Notes 49

This question is a great review of the "dot convention" used in transformer schematic symbols.

Notes 50

While many "switching" power supply circuits will be too complex for beginning electronics students to fully understand, it will still be a useful exercise to analyze such a schematic and identify the major components (and functions).

Ask your students why "switching" power supplies are smaller and more efficient than "brute force" designs. Ask your students to note the type of transformer used in switching power supplies, and contrast its construction to that of line-frequency power transformers.

Notes 51

Any diodes will work for this, so long as the source frequency is not too high. I recommend students set the volts/division controls on both channels to the exact same range, so that the slope of the clipped wave near zero-crossing may seen to be exactly the same as the slope of the input sine wave at the same points. This makes it absolutely clear that the output waveform is nothing more than the input waveform with the tops and bottoms cut off.

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.

Notes 52

I have had good success using 12 volts DC for the supply voltage, an MCR8SN silicon-controlled rectifier, and a small brushless DC fan motor (80 mA running current) as the load. The MCR8SN is a "sensitive gate" SCR, which makes it easy to demonstrate static triggering (just *touch* the gate terminal with your finger to start the motor!). Some SCR's may be difficult to keep latched with low-current loads, so be sure to prototype your SCR/load combination before assigning part numbers to your students!

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Notes 53

Use a variable-voltage, regulated power supply to supply any amount of DC voltage below 30 volts. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

This circuit produces nice, sharp-edged square wave signals at the transistor collector terminals when resistors R_1 and R_4 are substantially smaller than the combined resistance of resistors R_2 and R_3 and the respective potentiometer section resistances. This way, R_{pot}, R_2, and R_3 dominate the capacitors' charging times, making calculation of duty cycle much more accurate. Component values I've used with success are 1 kΩ for R_1 and R_4, 10 kΩ for R_2 and R_3, 100 kΩ for R_{pot}, and 0.001 μF for C_1 and C_2. In my prototype circuit, I used 2N2222 bipolar transistors and an IRF510 power MOSFET.

Although small DC motors work well as demonstrative loads, their counter-EMF may wreak havoc with measurements of average load voltage. Purely resistive loads work best when comparing measured average load voltage against predicted average load voltage. Also, motors and other inductive loads may cause the MOSFET to switch incorrectly (or not switch at all!) unless a commutating diode is installed to limit the voltage induced by the collapsing magnetic field every time the transistor turns off.

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Notes 54

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

Notes 55

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

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Notes 58

Have your students figured out any other possibilities for the fault in this circuit? They do exist, and in fact may be more likely than a failed-open diode! Ask your students how and why they chose the answer they did, and be sure to have them explain their follow-up diagnostic procedures.

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Notes 64

Discuss with your students the initial troubleshooting steps described in the question. What strategy or strategies is the technician taking to isolate the problem?

Notes 65

Ask your students why the waveform will be *square* rather than *sinusoidal*. Is it a perfect square-wave? Why or why not?

Notes 66

Some students may ask what this mathematical statement means:

$$R_{load} >> R_{series}$$

Explain to them that the "double-chevron" symbol means "*much* greater than" (reversing the chevrons would mean "much less than," of course).

Notes 67

Ask your students to explain the purpose of each component in the "crystal" radio circuit, not just those components related to the clipping function.

Notes 68

Do not accept an answer from students along the lines of "frequency measurement." Ask them to provide some *practical* examples of systems where frequency measurement is important. If they have difficulty thinking of anything practical, suggest that the input (square wave) signal might come from a sensor detecting shaft rotation (one pulse per revolution), then ask them to think of possible applications for a circuit such as this.

Notes 69

The key to fully answering why an SCR drives itself so hard during conduction is found in the principle of *positive feedback*. Discuss this principle with your students if they have not already studied it. If they have already studied it, use this question as an opportunity for review.

Notes 70

Ask your students where they found this information. Was it from a textbook, a datasheet, or some other source?

Notes 71

Ask your students why a thyristor such as an SCR or a TRIAC would need to be "de-sensitized" by the addition of a loading resistor? What is wrong with having a "sensitive" thyristor in a circuit?

Notes 72

Discuss with your students whether or not they think a crowbar circuit is the sort of mechanism that sees regular use, or whether it is seldom activated.

Notes 73

Believe it or not, I was once approached by an enthusiastic student with this very question!

Notes 74

The expression $\frac{dv}{dt}$ is, of course, a calculus term meaning rate-of-change of voltage over time. An important review concept for this question is the "Ohm's Law" formula for a capacitance:

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

Only by understanding the effects of a rapidly changing voltage on a capacitance are students able to comprehend why large rates of $\frac{dv}{dt}$ could cause trouble for an SCR.

Notes 75

Nothing special here, just practice calculating the trigger voltage. Note to your students that the symbol for the intrinsic standoff ratio (η) is the Greek letter "eta," which also happens to be used to symbolize efficiency.

Notes 76

Ask your students to describe how hysteresis is exhibited by the UJT in this scenario.

Notes 77

An important feature of all thyristors is that they *latch* in the "on" state once having been triggered. This point needs to be emphasized multiple times for some students to grasp it, as they are accustomed to thinking in terms of transistors which do not latch.

Notes 78

Knowing that the UJT forms an oscillator, it is tempting to think that the load will turn on and off repeatedly. The first sentence in the answer explains why this will not happen, though.

I got the basic idea for this circuit from the second edition of Electronics for Industrial Electricians, by Stephen L. Herman.

Notes 79

This type of distinction is very important in the study of physics as well, where one must determine whether a mechanical system is *doing work* or whether *work is being done on it*. A clear understanding of the relationship between voltage polarity and current direction for sources and loads is very important for students to have before they study reactive devices such as inductors and capacitors!

Notes 80

Although the answer may seem a bit too easy – nay, even obvious – the point here is to get students to correlate the behavior of capacitors and inductors in terms of components they already understand very well. Then, they may correctly associate direction of current with polarity of voltage drop according to the direction of energy flow (source versus load) the reactive component is subjected to.

Notes 81

Relating the polarity of voltage across an inductor to a change of applied current over time is a complex concept for many students. Since it involves rates of change over time, it is an excellent opportunity to introduce calculus concepts ($\frac{d}{dt}$).

Vitally important to students' conceptual understanding of an inductor exposed to increasing or decreasing currents is the distinction between an electrical energy *source* versus a *load*. Students need to think "battery" and "resistor," respectively when determining the relationship between direction of current and voltage drop. The complicated aspect of inductors (and capacitors!) is that they may switch character in an instant, from being a source of energy to being a load, and visa-versa. The relationship is not fixed as it is for resistors, which are always energy *loads*.

Notes 82

Relating the direction of current in a capacitor to a change of applied voltage over time is a complex concept for many students. Since it involves rates of change over time, it is an excellent opportunity to introduce calculus concepts ($\frac{d}{dt}$).

Vitally important to students' conceptual understanding of a capacitor exposed to increasing or decreasing voltages is the distinction between an electrical energy *source* versus a *load*. Students need to think "battery" and "resistor," respectively when determining the relationship between direction of current and voltage drop. The complicated aspect of capacitors (and inductors!) is that they may switch character in an instant, from being a source of energy to being a load, and visa-versa. The relationship is not fixed as it is for resistors, which are always energy *loads*.

Notes 83

Although it should not be difficult for students to discern the relationship between duty cycle and DC output voltage, the application of this relationship to data communication might be difficult for some students to grasp, especially on their own. Further elaboration on your part may be necessary.

An excellent example of this principle applied is the generation of an analog voltage by a 1-bit digital circuit. This technique is useful in microcontroller systems where output ports may be scarce, provided that ripple voltage (or slow response) is not a problem.

Notes 84

The answer here is purposely vague, as I want students to research the details themselves.

Notes 85

In many cases, DC-DC converters find use in large systems that were not designed well (i.e. with proper DC voltages provided by a common AC-DC supply circuit). However, converter circuits do have more legitimate uses, including applications where *isolation* is required between two DC circuits. Ask your students what "electrical isolation" is any why it might be important.

Notes 86

Ask your students why they think this circuit is called an *inverting* converter.

Although it may not be evident from viewing the circuit schematic, this converter circuit is capable of stepping voltage up *or* down, making it quite versatile.

Notes 87

The "strange" name of this circuit comes from the last name of the engineer who invented it! For more information, consult the writings of Rudy Severns on the general topic of switch-mode power conversion circuits.

Notes 88

The calculations for this circuit should be straightforward, except for the last calculation with a duty cycle of $D = 100\%$. Here, students must take a close look at the circuit and not just follow the formula blindly.

Note that the switching element in the schematic diagram is shown in generic form. It would never be a mechanical switch, but rather a transistor of some kind.

Astute students will note that there is no difference between the standard *inverting* converter circuit and the *Cuk* design, as far as output voltage calculations are concerned. This, however, does not mean the two circuits are equivalent in all ways! One definite advantage of the Cuk converter over the standard inverting converter is that the Cuk's input current never goes to zero during the switch's "off" cycle. This makes the Cuk circuit a "quieter" load as seen from the power source. Both inverting and buck converter circuits create a lot of electrical noise on the supply side if their inputs are unfiltered!

Notes 89

In the process of analyzing switching regulator functionality, it is easy for students to overlook the purpose for why they exist at all. Discuss the importance of power conversion efficiency, especially for electronic applications that are battery powered.

An important point to emphasize in this question is that most of the switching "regulator" circuits first shown to students are not actually regulators at all, but merely *converters*. A switching converter circuit does not become a regulator circuit until a feedback control is added. Such controls are usually too complex to introduce at the very beginning, so they are typically omitted for simplicity's sake. However, students should realize the difference between a switching *regulator* circuit and a mere switching *converter* circuit, lest they believe the converter to be capable of more than it is.

Notes 90

It might not be obvious to some students why less voltage drop (across the MOSFET versus across the diode) has an impact on conversion efficiency. Remind them that power equals voltage times current, and that for any given current, a reduced voltage drop means reduced power dissipation. For the free-wheeling current path, less power dissipation means less power wasted, and less power that needs to be supplied by the source (for the same load power), hence greater efficiency.

Notes 91

"Negative impedance" and "negative resistance" are phrases that may not be addressed very often in a basic electronics curriculum, but they have important consequences. If students experience difficulty understanding what the meaning of "negative" impedance is, remind them of this mathematical definition for impedance:

$$Z = \frac{dV}{dI}$$

One of the unintended (and counter-intuitive) consequences of a circuit element with negative impedance can be *oscillation*, especially when the input power circuit happens to contain substantial inductance.

Notes 92

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.

Notes 93

Students may be inclined to give easy answers to this problem ("use a DC-DC converter!"), but the purpose of it is for students to explore solutions at the *component level*. Even if they do not yet understand how the circuitry works, they should be able to find complete solutions in their research, or at least enough schematics for sections of the conversion process for them to engineer a complete solution.

Remind your students that this is a powerful spotlight they're going to have to power! Their conversion system may have to handle hundreds of watts.