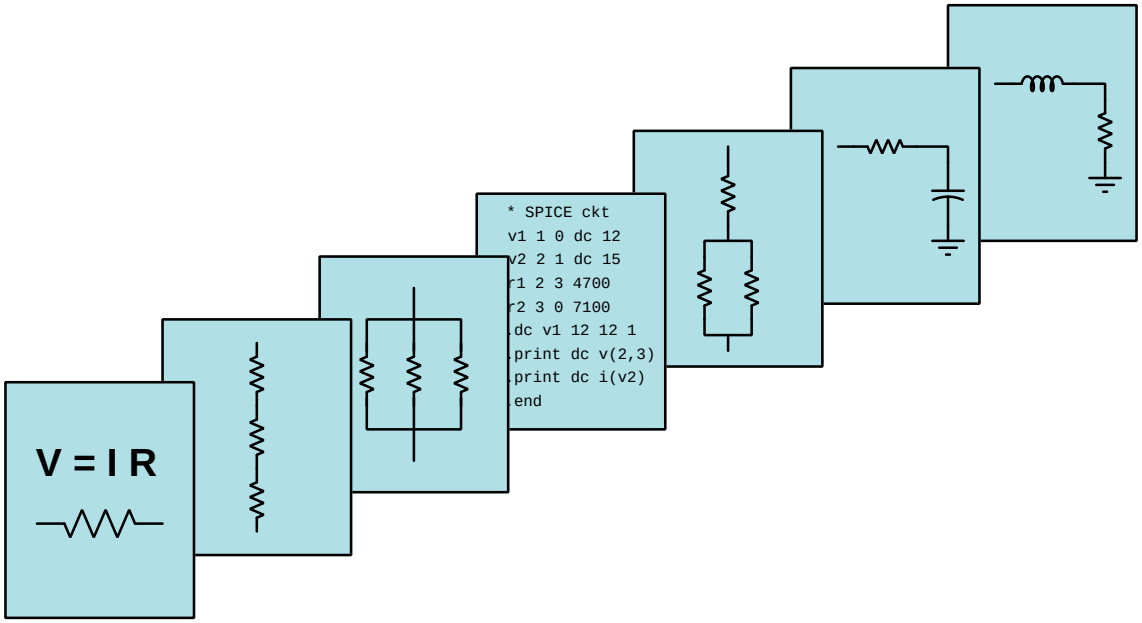
Modular Electronics Learning (ModEL) project



DC-AC Power Conversion

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Contents

1 Introduction **3**
- 1.1 Recommendations for students . . . 3
- 1.2 Challenging concepts related to DC-AC power conversion . . . 5
- 1.3 Recommendations for instructors . . . 6

2 Case Tutorial **7**
- 2.1 Example: inverter circuits from the Bright/Royer 1957 patent . . . 8
- 2.2 Example: inverter using a 555 timer . . . 11
- 2.3 Example: inverter using NOT gates . . . 13

3 Tutorial **17**
- 3.1 DC versus AC . . . 17
- 3.2 BJT and FET review . . . 19
- 3.3 Oscillator circuits . . . 24
- 3.4 Thyristor converters . . . 27
- 3.5 Three-phase converter circuits . . . 28
- 3.6 Converter output waveforms . . . 29

4 Historical References **33**
- 4.1 Thyratron inverter patent . . . 34

5 Animations **37**
- 5.1 Three-phase converter transistor switching sequence . . . 38
- 5.2 Animation of an NPN BJT turning on . . . 65
- 5.3 Animation of an E-type MOSFET turning on . . . 80

6 Questions **93**
- 6.1 Conceptual reasoning . . . 97
  - 6.1.1 Reading outline and reflections . . . 98
  - 6.1.2 Foundational concepts . . . 99
  - 6.1.3 Bright/Royer self-excited inverter circuits . . . 102
  - 6.1.4 Bright/Royer externally-excited inverter circuits . . . 103
  - 6.1.5 555-based inverter circuit . . . 104
  - 6.1.6 Early three-phase inverter design . . . 105

6.1.7 Voltmeter discrepancy . . . 106
6.2 Quantitative reasoning . . . 107
6.2.1 Miscellaneous physical constants . . . 108
6.2.2 Introduction to spreadsheets . . . 109
6.2.3 Converter efficiency . . . 112
6.2.4 Modified duty cycle . . . 113
6.3 Diagnostic reasoning . . . 115
6.3.1 Tracing fault current . . . 116
6.3.2 Faults in a VFD circuit . . . 117

A Problem-Solving Strategies **119**

B Instructional philosophy **121**
B.1 First principles of learning . . . 122
B.2 Proven strategies for instructors . . . 123
B.3 Proven strategies for students . . . 125
B.4 Design of these learning modules . . . 126

C Tools used **129**

D Creative Commons License **133**

E References **141**

F Version history **143**

Index **145**

Chapter 1

Introduction

1.1 Recommendations for students

Some electrical power sources naturally output *direct current* (DC), while some loads and other power-handling electrical components only function on *alternating current* (AC). In such cases, a device must go between the DC source and the AC circuit/load to convert DC to AC. These are generally known as DC-AC converters, or specifically *inverters*.

In the early days of electrical power systems, power conversion was performed by rotating machinery: an electric motor with its shaft coupled to an electrical generator. Such *motor-generator* sets used technology available at the time, and were remarkably effective. So long as the power and speeds of the two machines were well-matched, motor-generator sets could be used for almost any type of power conversion: from DC to AC (e.g. DC motor coupled to an AC generator), from AC to DC, from DC to DC at different voltages/currents, and from AC to AC at different voltages/currents and/or frequencies. Of course, these machines were large, heavy, relatively inefficient, and required regular maintenance due to their moving (wearing) components.

The modern counterpart to a motor-generator power conversion set is a solid-state power conversion circuit, of which DC-AC inverters is but one type. This module will focus on the details of solid-state DC-AC power conversion.

Important concepts related to DC-AC power conversion include **AC** versus **DC**, **transformers**, **rectification**, **oscillators**, **MOSFET behavior**, **BJT behavior**, **logic gates**, **thyristor behavior**, **comparators**, **fundamental frequency**, **harmonic frequency**, **superposition** of waveforms, and **pulse-width modulation**.

Here are some good questions to ask of yourself while studying this subject:

- How might an experiment be designed and conducted to prove the existence of harmonic frequencies within a non-sinusoidal waveform? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to measure the duty cycle of a pulse waveform? What hypothesis (i.e. prediction) might you pose for that experiment, and what

result(s) would either support or disprove that hypothesis?

- How might an experiment be designed and conducted to measure the energy conversion efficiency of a DC-to-AC converter circuit? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- Why was AC historically preferred over DC for transmission of electrical power?
- What were some legacy methods of converting AC into DC power?
- Why are common *oscillator* circuits unsuitable for power conversion?
- What conditions are necessary to turn on an E-type MOSFET?
- What conditions are necessary to turn on a BJT?
- How does an "H-bridge" circuit act to convert DC into AC?
- What advantages are there to using thyristors instead of transistors for DC-AC conversion?
- What disadvantages are there to using thyristors instead of transistors for DC-AC conversion?
- Why do harmonic frequencies exist in the output of DC-AC converter circuits?
- Why are harmonic frequencies problematic in AC power systems?
- Do rotary converter (motor-generator sets) produce harmonic frequencies like switching circuits do?
- How may sinusoidal waveshapes be "synthesized" using discrete on/off switching devices such as transistors?
- How does an astable multivibrator circuit function?

1.2 Challenging concepts related to DC-AC power conversion

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Necessary conditions for BJT operation** – bipolar junction transistors require a base current in the proper direction to inject minority carriers into the base layer (i.e. PNP transistors require hole injection from emitter to base, and so the emitter must be made positive and the base made negative, relative to each other; NPN transistors require electron injection from emitter to base, and so the emitter must be negative and the base positive.), and the collector-to-emitter voltage must be of the correct polarity (i.e. so that collector terminal current goes in the same direction as base terminal current, either *out* or *in*). Both currents join at the emitter terminal, making the emitter current the sum of the base and collector currents.

- **Necessary conditions for FET operation** – field effect transistors work on the principle of a transverse electric field affecting the conductivity of a homogenously-doped channel. For insulated-gate FETs (i.e. MOSFETs), the electric field exists across a thin layer of dielectric between the gate terminal and the modulated channel. When that applied gate-channel voltage is of such a polarity as to attract majority charge-carriers into the channel (e.g. electrons into an N-type channel, holes into a P-type channel) then the channel becomes more conductive.

- **Hysteresis** – whenever a component or system tends to remain in its last state, we refer to that lagging tendency as *hysteresis*. There are many physical manifestations of hysteresis including *magnetic hysteresis* (where a magnetic material tends to remain magnetized after the magnetizing influence is removed), *thyristor devices* (electronic devices that tend to remain "on" even after the triggering stimulus is removed), and physical mechanisms having *friction* (where the mechanism's position tends to stay put after the influencing force is removed).

- **Forced commutation** – thyristor-based DC-to-AC converters require a means to force "on" thyristors to the "off" state when the time comes to alternate the AC output (every half-cycle). The use of capacitors as energy-storage devices to facilitate this forced commutation is not necessarily easy to understand, but careful step-by-step qualitative analysis (i.e. sketching current directions, voltage polarities, etc) of these circuits at different points in time is helpful.

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

  Assessment – Students show how quantitative results were obtained by the author in the Tutorial chapter's examples.

  Assessment – Students present their "Conceptual Toolbox" Theory Journal entries listing important concepts applied in the Tutorial text(s). A "Conceptual Toolbox" serves as inspiration when solving problems, each concept suggesting a potential problem-solving action. Challenge students to collaboratively generate a Conceptual Toolbox for the day's topic during the class session and then use it when solving problems together, thus fostering the habit of reasoning from principles rather than recalling procedures!

- **Outcome** – Apply the concept of energy efficiency to DC-AC power conversion circuits

  Assessment – Calculate DC input power necessary for a converter circuit given energy efficiency and power output parameters; e.g. pose problems in the form of the "Converter efficiency" Quantitative Reasoning question.

- **Outcome** – Identify the function of various components and sections of complex circuits

  Assessment – Explain the purpose of individual components within the schematic diagram of a DC-AC converter circuit; e.g. pose problems in the form of the "Bright/Royer self-excited inverter circuits" and "Bright/Royer externally-excited inverter circuits" and "555-based inverter circuit" Conceptual Reasoning questions.

- **Outcome** – Independent research

  Assessment – Locate DC-AC converter ("inverter") datasheets and properly interpret some of the information contained in those documents including maximum continuous power output, maximum peak power output, DC voltage input, efficiency, etc.

Chapter 2

Case Tutorial

The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: inverter circuits from the Bright/Royer 1957 patent

Richard Bright and George Royer patented several circuit designs using what was then a new electronic device: the bipolar junction transistor. Their patent (US Patent 2,783,384, "Electrical Inverter Circuits" granted 26 February 1957) shows schematic diagrams for several DC-AC inverters.

Figures 1, 4, and 5 show self-excited[1] inverter circuits where the frequency of the AC output depends largely on the magnitude of the DC source voltage(s). Figures 6, 7, and 8 show externally-excited inverter circuits relying on an independent oscillator to drive the power transistors on and off.

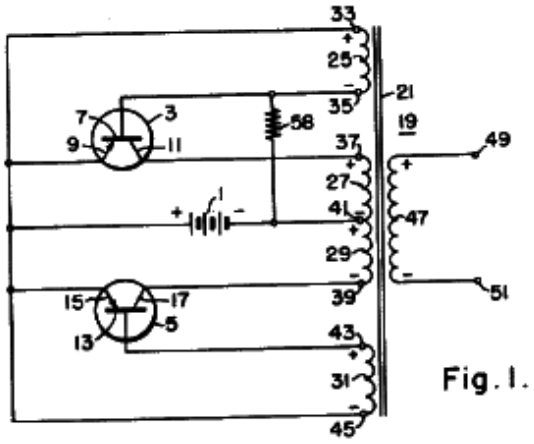
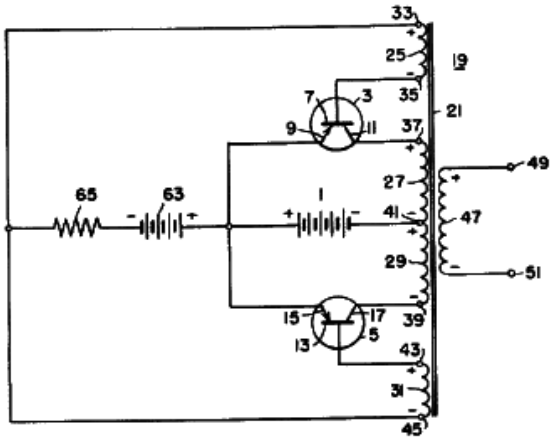


Fig. 1.

Fig. 4.



[1] These circuits are essentially high-powered oscillators, with the transistors performing the dual roles of oscillation and power amplification for the AC load.

Fig.5.

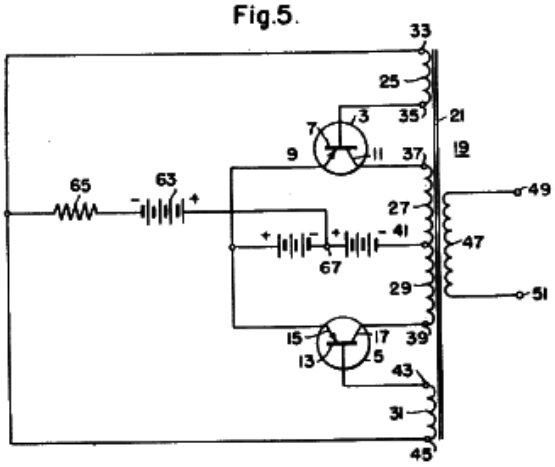


Fig.6.

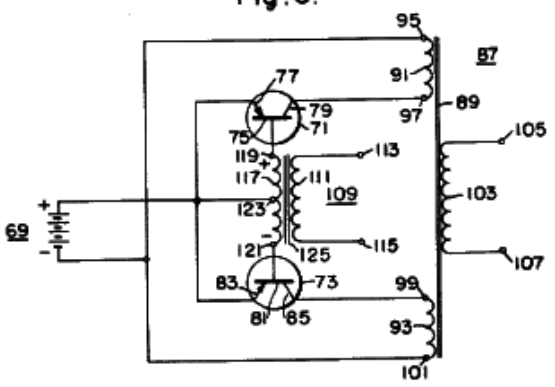


Fig.7.

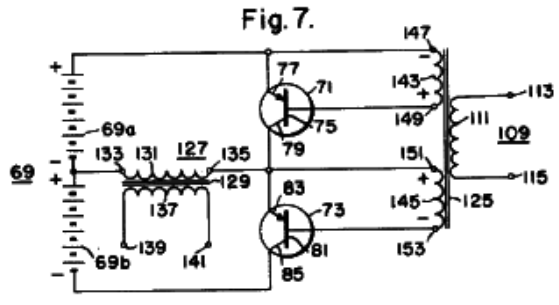
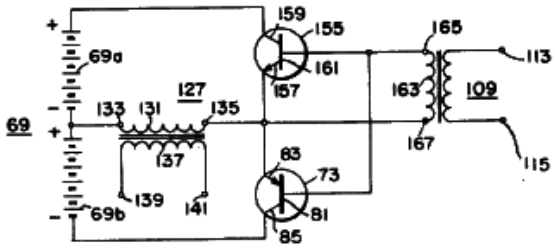


Fig. 8.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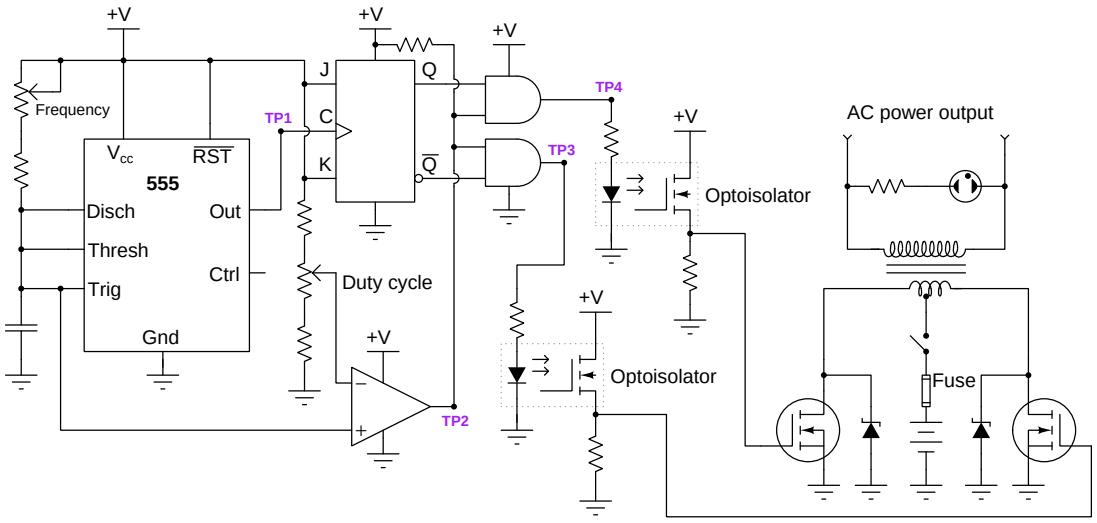
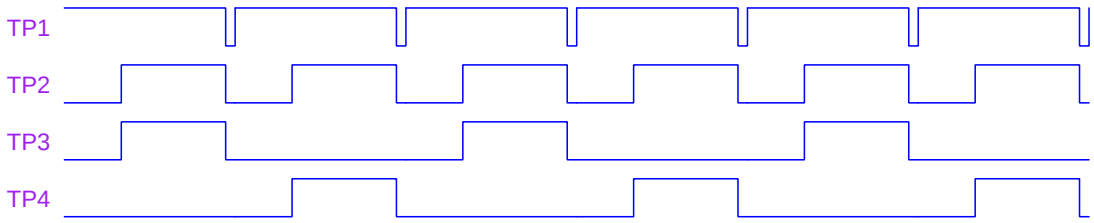
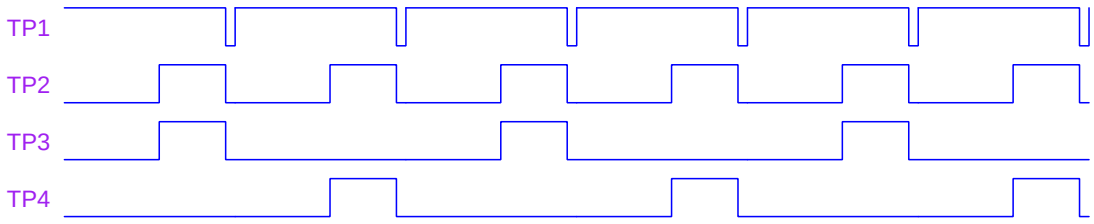
2.2 Example: inverter using a 555 timer



Duty cycle $> 50\%$:

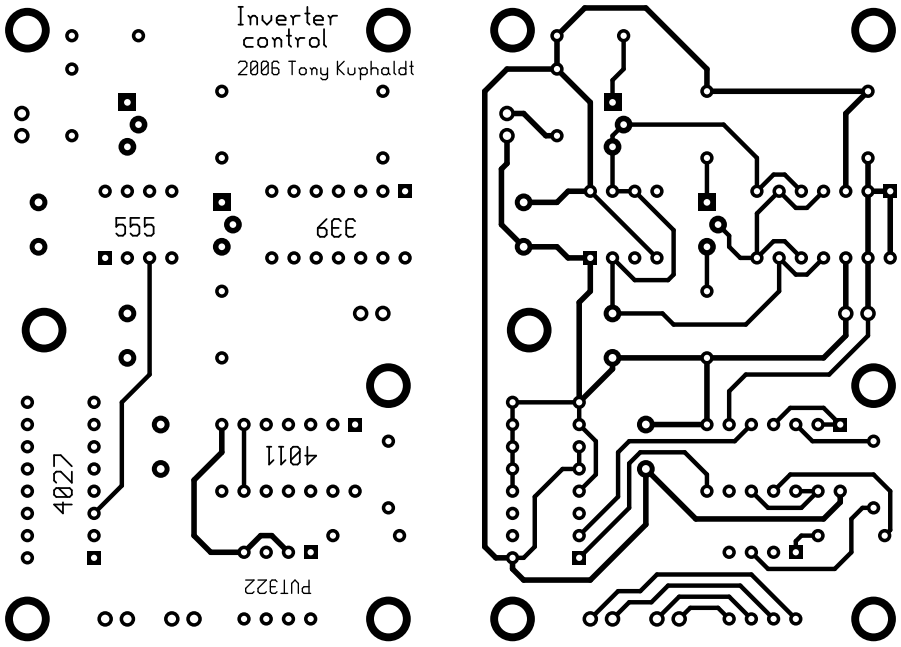


Duty cycle $< 50\%$:

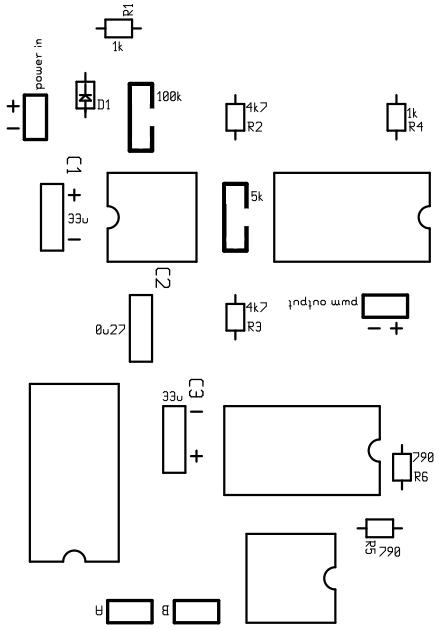


The AC output of this inverter is a "modified sine wave" which is really just a square wave with reduced duty cycle during each half-cycle.

Front-copper and rear-copper PCB layers for the control circuitry shown here:

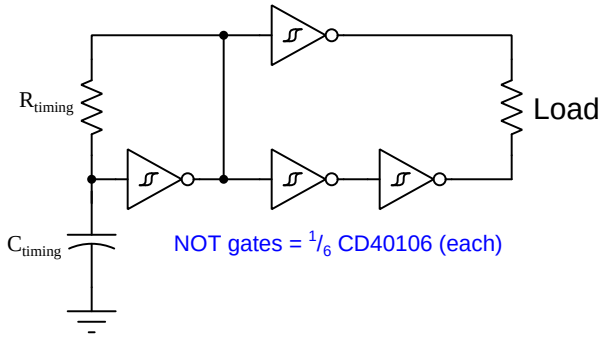


Front-silkscreen layer shown here:



2.3 Example: inverter using NOT gates

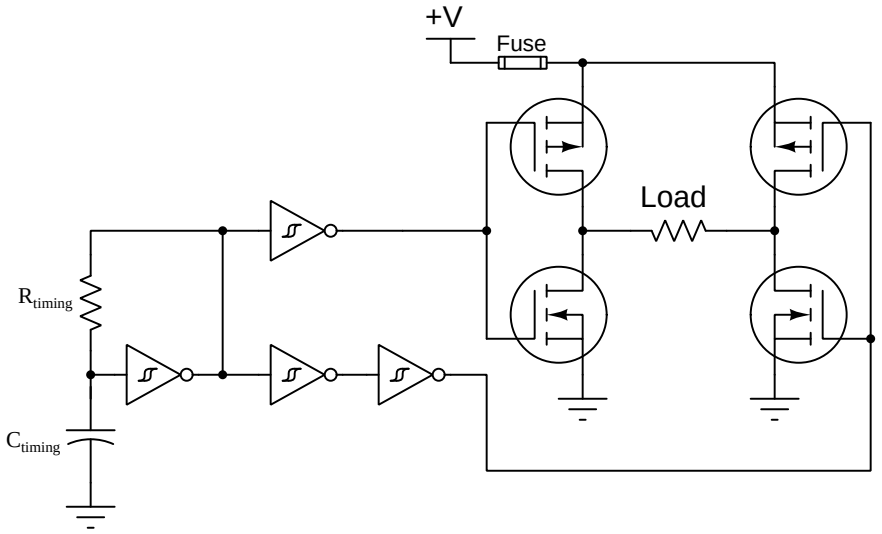
This proof-of-concept inverter uses a Schmitt-trigger NOT gate in conjunction with a resistor and a capacitor to form a simple relaxation oscillator. The remaining NOT gates simply "buffer" the oscillator's square-wave output signal so that the oscillator does not bear the burden of powering the load, that burden borne by the buffering NOT gates instead:



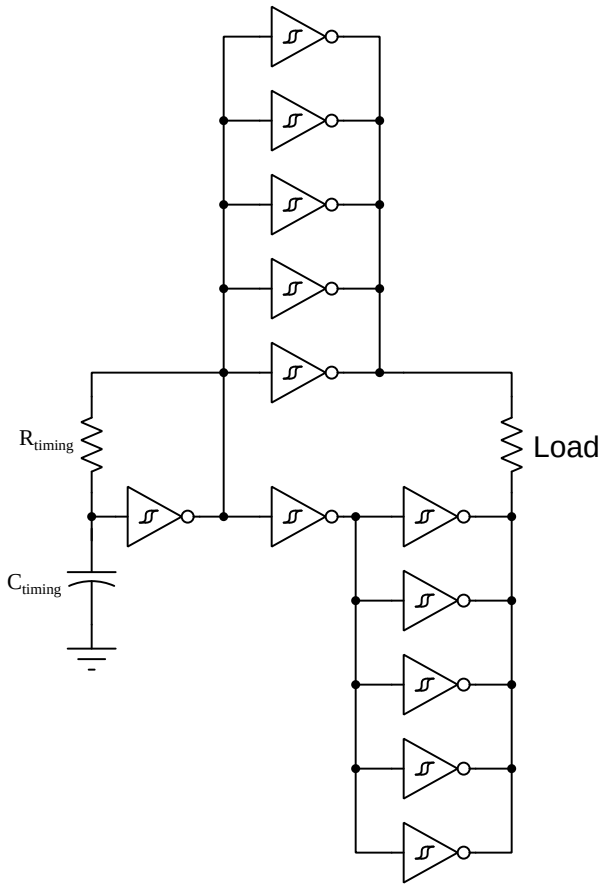
Those buffering NOT gates need not be Schmitt trigger in nature, but since NOT gates usually come in IC packages of six it makes sense to use them anyway rather than to let the other five Schmitt trigger gates in the CD40106 IC go unused.

Frequency is set by the combination of R_{timing} and C_{timing}. Load voltage will truly be alternating (AC) in nature, as one side will be "low" as the other is driven "high", then those logical states will reverse to reverse the load's voltage polarity. Load current is limited by the current sourcing and sinking capabilities of the NOT gates, which in the case of the CD40106 is in the order of several milliAmperes.

For higher load current applications, this circuit could be connected to an H-bridge like such:



Another method of achieving more load current is to gang multiple NOT gates together in parallel like so:



Since these typically come packaged six per DIP integrated circuit, it should be easy to gang together at least a few on each side of the load resistor. The example shown here makes full use of the NOT gates contained within two CD40106 ICs, but bear in mind even with all these NOT gates the load current capability will not be nearly as great as if using an H-bridge circuit with power MOSFETs.

Chapter 3

Tutorial

3.1 DC versus AC

Direct current (DC) is electricity with a constant direction and polarity, such as that output by a chemical battery or a solar cell. *Alternating current* (AC) is electricity whose direction and polarity periodically reverse, such as that output by an alternator.

Electric power "grid" networks largely use AC for multiple[1] reasons:

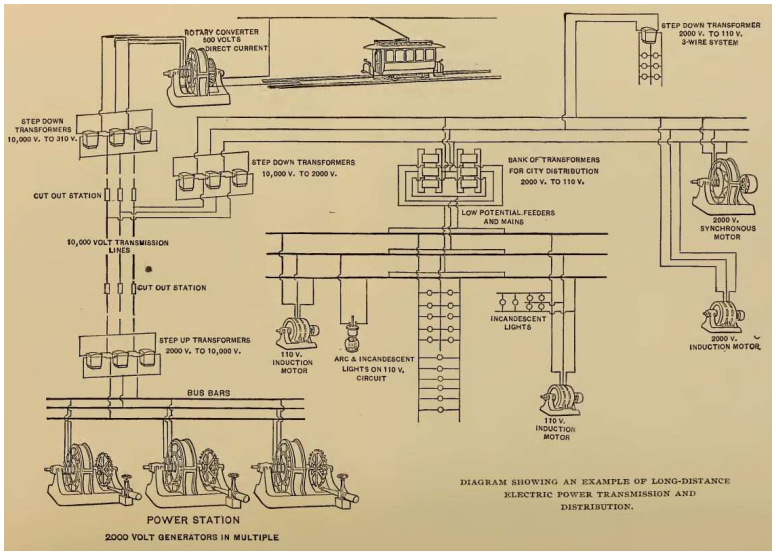
- AC permits the use of *transformers*, which allow us to "step" voltage and current to levels suitable for economic long-distance transmission (high V, low I) as well as points of customer use (low V, high I).
- AC generators and AC motors have no need for sliding-contact electrical terminals as is the case with DC, making them simpler and more reliable.

However, there are some electrical devices that are inherently DC, necessitating conversion either to or from AC when used within an otherwise AC power system. One such device is a photovoltaic solar panel used for generating electricity from sunlight. These panels use PN semiconductor junctions, naturally outputting DC when struck by light. In order to include such panels as sources in an AC power grid, the DC output of each panel must be converted into AC at the proper voltage, frequency, and phase. Another example of an inherently DC electrical source is a chemical battery. If included in an AC power system as an emergency source during power outages, this too requires some means of converting DC into AC suitable for the grid.

The problem of DC-AC conversion is not new, although the solutions have evolved dramatically over the years. In the 19th century, prior to the advent of truly *electronic* devices such as vacuum tubes and semiconductor components such as transistors, the most practical means of DC-AC conversion was to mechanically couple a motor to a generator. A DC motor spinning an AC generator would accomplish DC-AC conversion; an AC motor spinning a DC generator would do the opposite.

[1] Some interesting advantages of AC over DC had historical significance, but are not so important now. One example is electrolytic decomposition of early wire insulation, which is a greater problem for DC than for AC due to DC's constant polarity.

In the following illustration we see a simplified schematic diagram of an electric power system dating from the year 1895[2]. In this diagram we see AC generators driven by water turbines at Niagara Falls, sending electric power to various loads. One of those loads is an electrically-driven streetcar trolley which at the time was only practical to propel using *DC* electric traction motors. A motor-generator device called a *rotary converter* translated the 310 Volt three-phase AC power into 500 Volt DC power for the trolley system:



Of course, this is an example of AC-to-DC conversion rather than DC-to-AC conversion, but the fundamental principle of a motor-generator apparatus works either way.

Converting between DC and AC using rotating machinery is inefficient due to resistive and magnetic[3] energy dissipation in the motor/generator mechanisms, and these machines were rather large, heavy, and maintenance-intensive as well. Suffice it to say, electromechanical DC/AC conversion is a dead technology. What has replaced this legacy technology for DC/AC conversion is circuits using transistors and other semiconductor devices to periodically "steer" electric currents in different directions. Converting AC into DC is called *rectification*, and it requires nothing more than *diodes* to construct a rectifier circuit. Converting DC into AC, however, is a much more complicated matter.

[2]The source for this historical illustration is *Cassier's Magazine*, which was an engineering periodical published in the late 1800's and early 1900's out of London, England. The Smithsonian Institute maintains online archives of *Cassier's* spanning many years, and it is a treasure-trove for those interested in the history of mechanical, electrical, chemical, and civil engineering.

[3]This mostly takes the form of energy dissipation from magnetic *hysteresis*. As you alternate the magnetic field direction within a ferromagnetic material, the magnetic domains within that material must reverse polarity, and in so doing there is some energy converted into heat. Materials with a narrow B-H curve (i.e. magnetically "soft" materials) exhibit the lowest hysteretic losses, and alloys engineered to optimize that curve have been developed for the purpose of reducing these losses. However, those losses cannot be fully eliminated, which is one reason why rotating electrical machinery and transformers alike cannot be 100% efficient.

3.2 BJT and FET review

In order to properly understand how modern DC-to-AC converter circuits work, we must be familiar with the operation of both bipolar junction transistors (BJTs) and field-effect transistors (FETs).

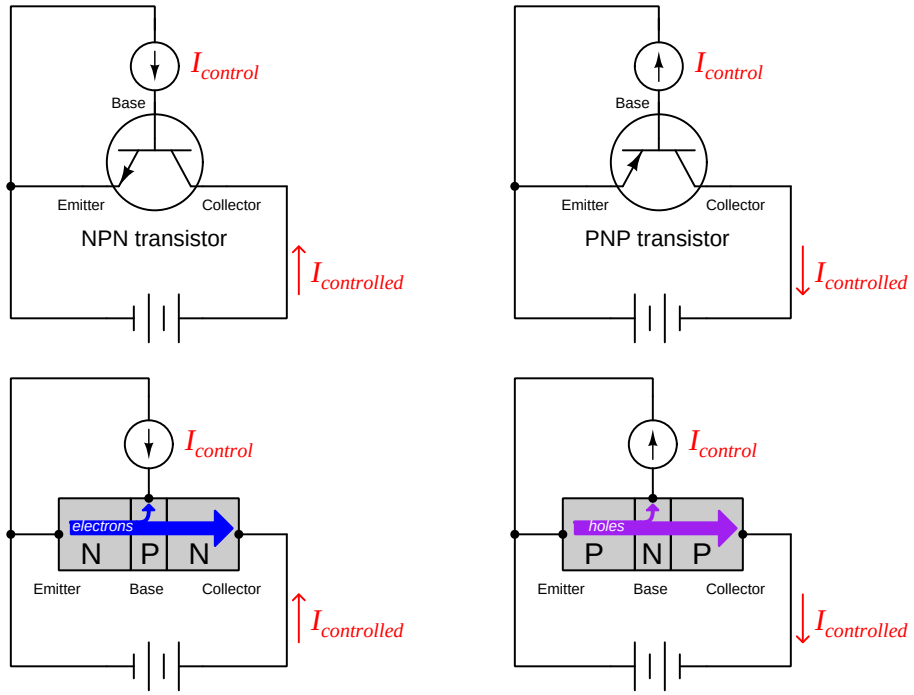
Transistors are semiconductor devices allowing one electrical signal to control another. Specifically, transistors work by allowing a relatively weak electrical signal to control the electrical conductivity of a solid material, and this modulated conductivity permits or denies passage of a much stronger electrical signal. This is the basic principle of *amplification*: where a smaller signal exerts control over a larger signal. Two major types of transistors dominate modern electronic circuits, *bipolar junction transistors* (BJTs) and *field-effect transistors* (FETs). Each has its own unique principle of operation[4], and although these principles differ markedly, both types of transistors perform similar functions within similar circuits.

Bipolar junction transistors function on the basis of *charge carrier injection*, where a weak electrical signal injects charge carriers into a region of semiconducting material previously lacking plentiful carriers. This injection of foreign charge carriers turns a formerly non-conductive material into a conductive material, allowing the transistor to pass a stronger (i.e. amplified) signal.

Field-effect transistors function on the basis of *channel width modulation*, where the effective width of an electrically conductive channel (i.e. pathway) varies with the application of an electric field from a weak voltage signal. This channel may be "pinched off" or "turned on" by this controlling voltage signal, allowing the transistor to conduct a stronger (i.e. amplified) signal.

[4]Most functional characteristics of transistors may be deduced from a proper understanding of these operating principles. Important behaviors such as the transistor's default state (i.e. whether or not it conducts current in the absence of a "driving" signal), as well as the necessary drive signal types to turn the transistor on (or off) also logically follow from these principles. When first learning about transistors, try to follow the logic connecting each transistor's operating principles with its functional characteristics. Avoid making the common mistake of merely committing facts to memory, devoid of understanding.

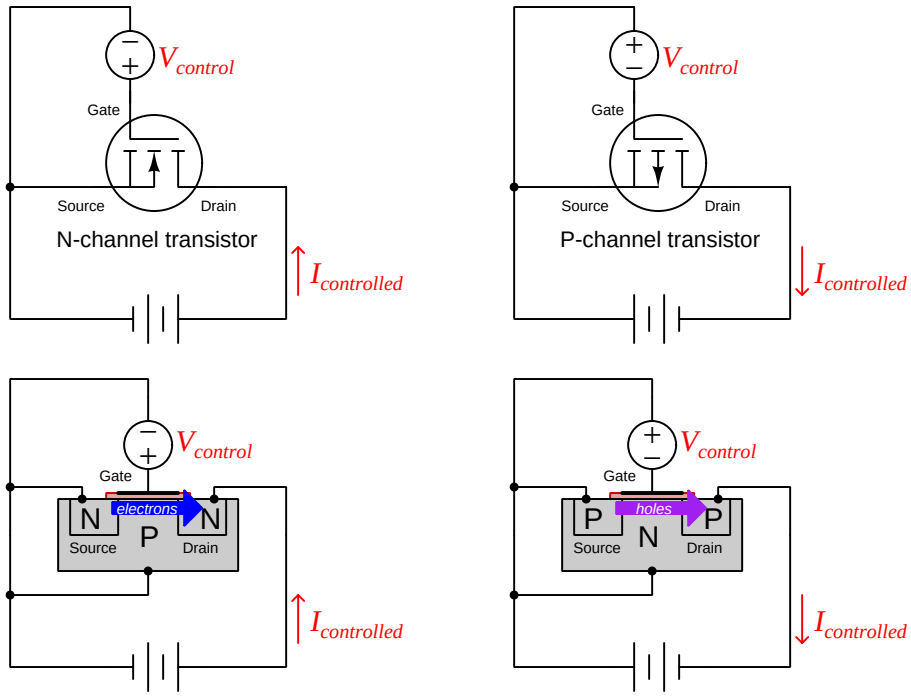
Bipolar junction transistors consist of a three-layer "sandwich" of differently-doped semiconductor materials, denoted either NPN or PNP. These three layers form two dissimilar "PN" junctions, hence the name *bipolar*. The middle layer (called the *base*) acts as a controlled-conductivity bridge between the other two layers (called the *emitter* and *collector*) conducting the controlled current. When unstimulated, base-emitter and base-collector depletion regions together prohibit current between collector and emitter. However, if an external source forward-biases the base-emitter junction to collapse that depletion region, charge carriers will be "emitted" by the emitter into the extremely thin base layer where most of them coast through the other side of the base and become "injected" into the depletion region of the base-collector junction, thus making the transistor conductive from end to end. Bipolar junction transistors are *minority-carrier* devices because the majority-type charge carriers emitted by the emitter layer are "minority" type once they enter the base (e.g. holes emitted from a P-type emitter, being injected in the N-type base).



The key to turning on a BJT is to forward-bias the base-emitter junction in order to initiate this charge-injection process. Without this injection of charge carriers into the depleted base-collector region, the transistor defaults to its "off" state because there is no continuous region of charge carriers naturally stretching from emitter to collector.

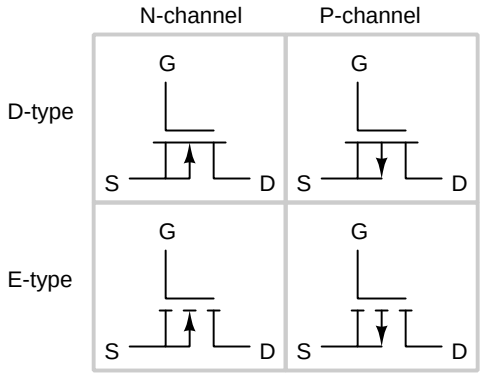
Field-effect transistors consist of a channel formed of one type of semiconductor material (i.e. either P-type or N-type) that is either flanked or interrupted by a region of the opposite doping type. An electric field applied transverse to this channel affects the quantities and types of charge carriers residing within the channel. Like bipolar junction transistors which exist in NPN and PNP forms, field-effect transistors may be manufactured with either N-type channels or P-type channels. However, unlike BJTs, there are several distinct design variations for FETs: *junction* FETs and two different forms of *insulated-gate* FETs (commonly called *MOSFETs* for their metal-oxide-semiconductor construction). For the sake of simplicity, we will show an *enhancement-mode* MOSFET in the following illustration because it behaves most similarly to a BJT.

Instead of emitter, base, and collector terminals, FETs have *source*, *gate*, and *drain* terminals. The controlled current flows between drain and source, while the gate terminal provides a point to apply the controlling voltage signal. Field-effect transistors are *majority-carrier* devices because the charge carriers leaving the source to pass through the channel (e.g. holes through a P-type channel, electrons through an N-type channel) are native to that channel's doping, never traversing a region of opposite doping:

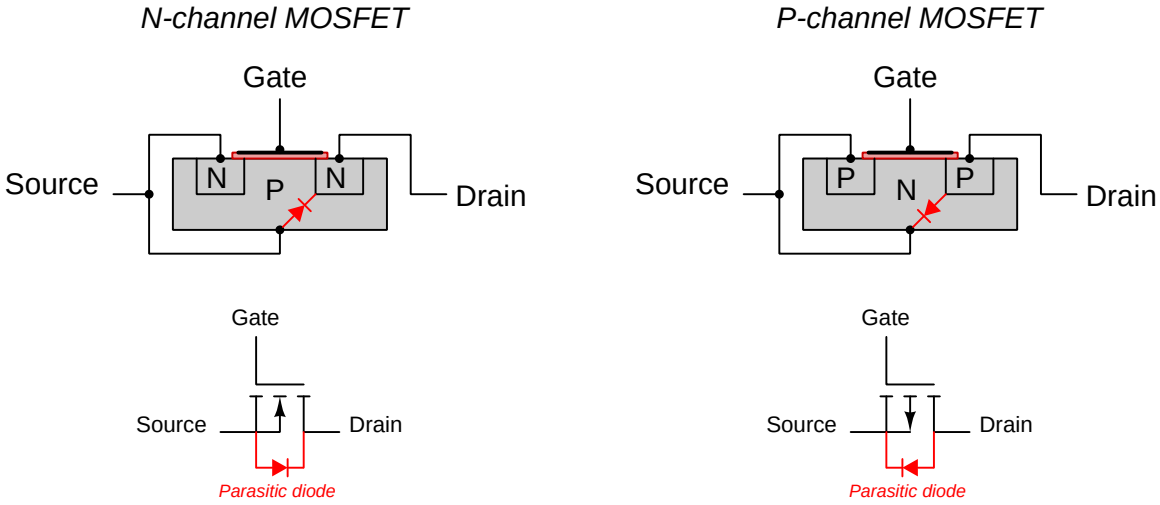


The key to turning on a FET is to electrostatically attract more majority carriers into the channel by giving the gate terminal a polarity opposite the channel type. Reversing this polarity forces the FET to turn off. Different forms of FET (JFET, depletion-mode, enhancement-mode) possess different natural states. JFETs are normally-on devices which may only be turned off (i.e. depleted). D-type MOSFETs are normally-half-on devices which may be turned on more (i.e. enhanced) or turned off more (i.e. depleted). E-type MOSFETs – the type shown above – are normally-off devices which may only be turned on (i.e. enhanced) similar to the behavior of a BJT.

Although the MOSFET is fundamentally a four-terminal device, they are often constructed with the substrate and source terminals connected by wire, which means the controlling voltage must be impressed between the gate and source terminals:



An interesting consequence of this internal connection is that it results in a single PN diode-like parasitic junction connected between the source and drain terminals:



When the source and drain terminals are properly biased[5], this parasitic diode will be reverse-biased and have no effect on the transistor's operation. However, if source-drain polarity ever reverses, this diode will become forward-biased and short past the transistor's channel!

[5]The arrow inside of a MOSFET symbol actually shows you which way this parasitic diode points! For any PN junction the tip of the arrowhead points toward the "N" side and the wide end of the arrowhead is on the "P" side. Note how the wide end of the N-channel MOSFET's arrow connects to the source terminal, as does the anode of the parasitic diode; likewise the tip of the P-channel MOSFET's arrowhead connects to the source terminal, as does the cathode of the parasitic diode. Your task in deciding how to connect any MOSFET into a circuit is to keep this parasitic diode reverse-biased so that the transistor will not be bypassed by it.

Field-effect transistor (FET) and bipolar junction transistor (BJT) behavior differs in several important ways:

Characteristic	**FET**	**BJT**
Charge carrier type	Majority	Minority
Principle of operation	Effective width of a continuous channel modulated by voltage	Charge carriers injected into a depleted region
Drive signal	Voltage only (no DC current)	Voltage and current both necessary
Switching time limit	RC time constant of gate capacitance and drive resistance	Stored charges in base waiting to be swept out
Temperature effect	Greater temperature increases channel resistance	Greater temperature decreases effective resistance
Resting status	Normally-on and normally-off types	Normally-off (only)
Gain	Transconductance $g = \frac{\Delta I_{DS}}{\Delta V_{GS}}$	Beta ratio $\beta = \frac{I_C}{I_B}$
Current regulation	Depletion region "pinch" effect intensifies with increasing V_{DS}	Rate of charge injection into base sets a maximum limit on I_C

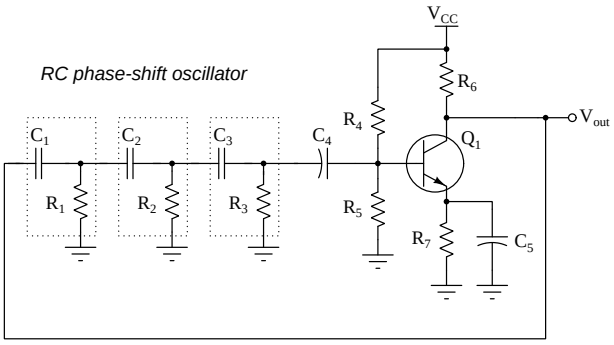
Generally speaking, FETs are capable of switching on and off faster[6] than BJTs, and FETs generally offer less resistance[7] to the controlled current when fully turned on than BJTs which means FETs generally have higher current ratings than comparable BJTs. However, comparable BJTs generally have higher voltage ratings than FETs. Perhaps the starkest contrast between the two transistor technologies is their drive requirements: FETs never require a constant current at their gate terminals, whereas BJTs *do* require base current to continuously activate.

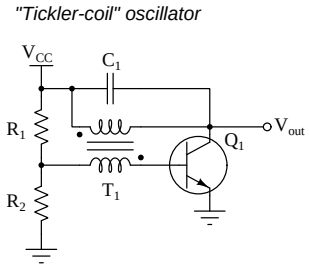
[6] The natural resistive-capacitive time delay of an FET's gate may be minimized through external circuit design, but the stored charge within a BJT's base region is largely a function of a transistor's internal construction.

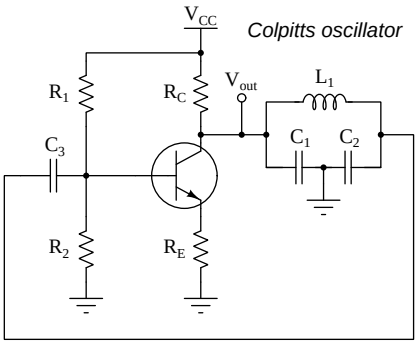
[7] Charge carriers crossing the base-emitter junction of a BJT require an energy investment to do so, and much of this energy later dissipates in the form of heat. No such intrinsic barrier exists within a FET, which means conductance is limited only by charge carrier density and channel area.

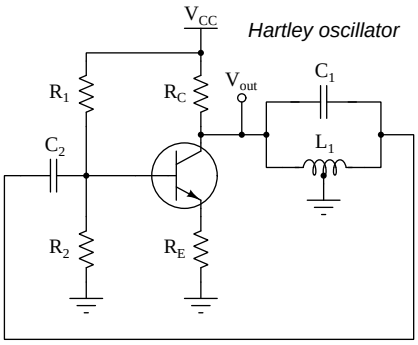
3.3 Oscillator circuits

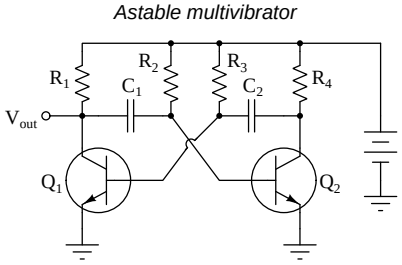
A class of electronic circuits called *oscillators* converts DC electrical energy into oscillating (AC) signals, but most oscillator designs cannot output enough energy for the types of loads common to electrical power systems. Connecting a heavy load to the V_{out} terminals of an oscillator circuit will likely kill the oscillations, or at least cause the frequency and/or amplitude to shift. Oscillator circuits are therefore better-suited for applications such as audio tone generation, radio wave transmission, and digital clock pulse generators.

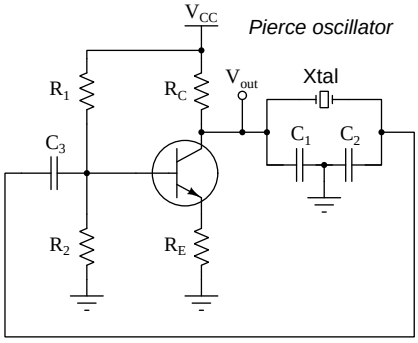






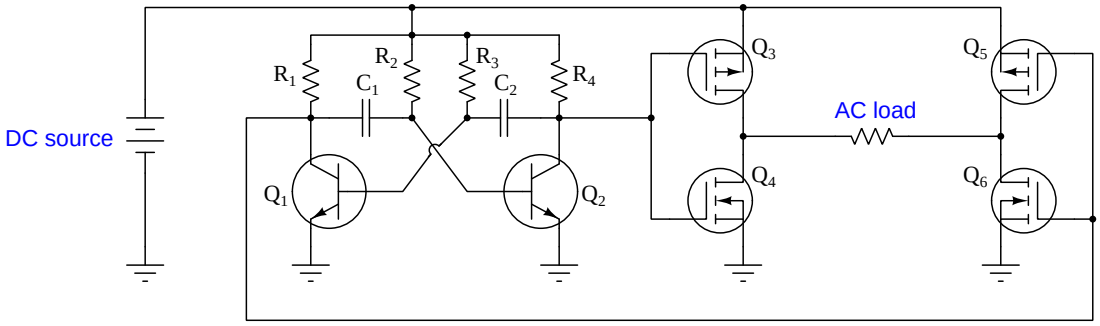






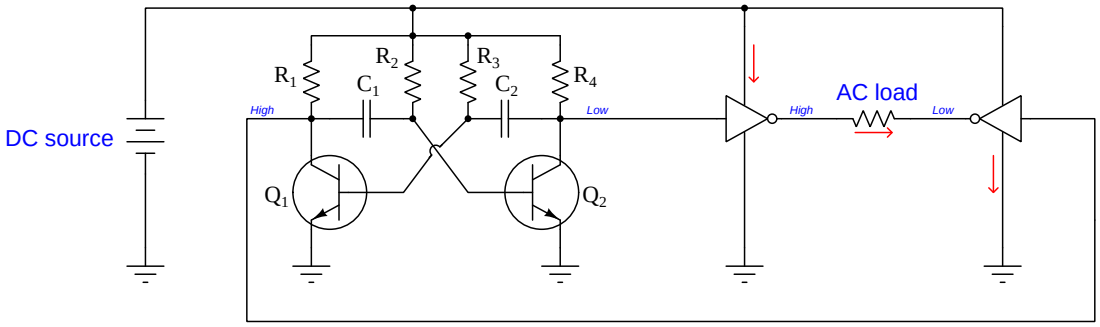
One way to boost the power-handling capability of an oscillator circuit is to connect its output to a set of power transistors. For our example circuits we will use the astable multivibrator oscillator design to send pulse signals triggering dedicated power transistors. The gain of the power transistors effectively shield the oscillator circuit from any effects of load changes, allowing its AC amplitude and frequency to remain unaffected by loading.

One such inverter circuit is shown in the following diagram, the astable multivibrator's dual output signals alternately driving pairs of MOSFET power transistors:

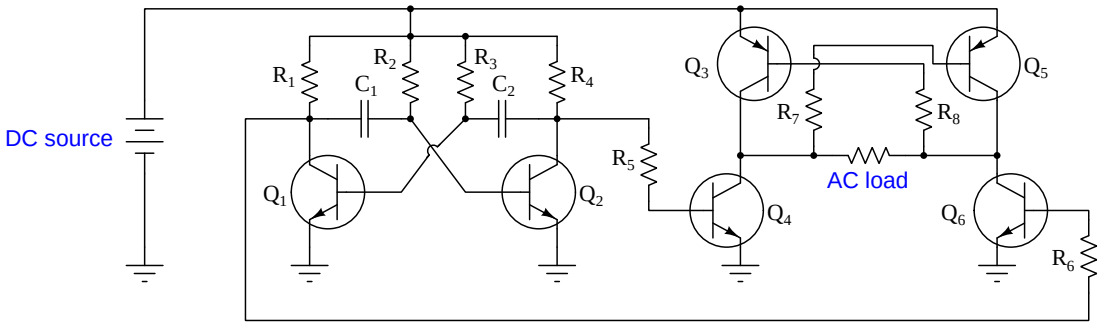


As the multivibrator oscillates, the pulse signals at the collector terminals of Q_1 and Q_2 will be complementary square waves: when V_{CE1} is "high", V_{CE2} will be "low", and vice-versa. These alternating pulse signals trigger the MOSFET gates in complementary fashion as well: when V_{CE1} is "high" and V_{CE2} is "low", MOSFETs Q_3 and Q_6 will be turned on while Q_4 and Q_5 remain off. This sends DC current through the AC load from left to right. That load current direction reverses when the multivibrator enters the second half of its cycle (V_{CE2} "high" and V_{CE1} "low").

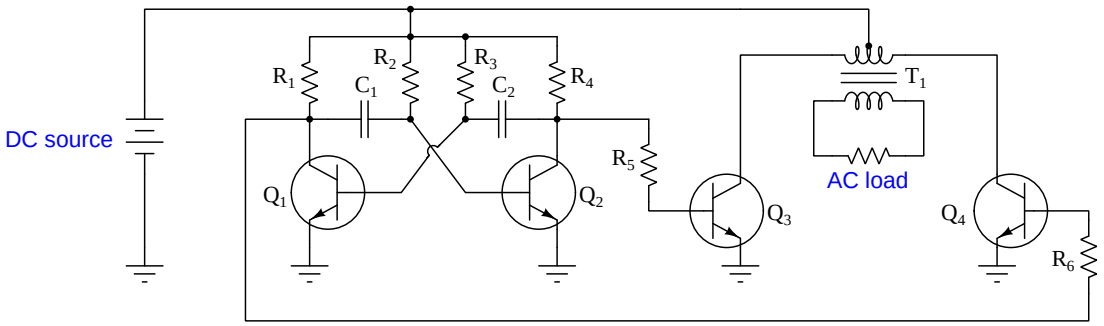
One way to model the MOSFET "H-bridge" network is to consider each totem-pole transistor pair as a heavy-duty version of a CMOS logic inverter (NOT) gate. As the multivibrator drives these two NOT gates, the load experiences true alternating current. This next diagram shows the MOSFET pairs as NOT gates, with "high" and "low" logic levels and current directions shown for the condition where V_{CE1} is in a "high" state:



A bipolar transistor variation on this same *H-bridge* circuit design works by having the multivibrator signals trigger the two sinking (NPN) transistors while the two sourcing (PNP) transistors activate when their respective base terminals find a path to ground through one of the "on" NPN transistors:



Another power-stage design for this inverter circuit replaces two of the power transistors with a transformer having a center-tapped winding:



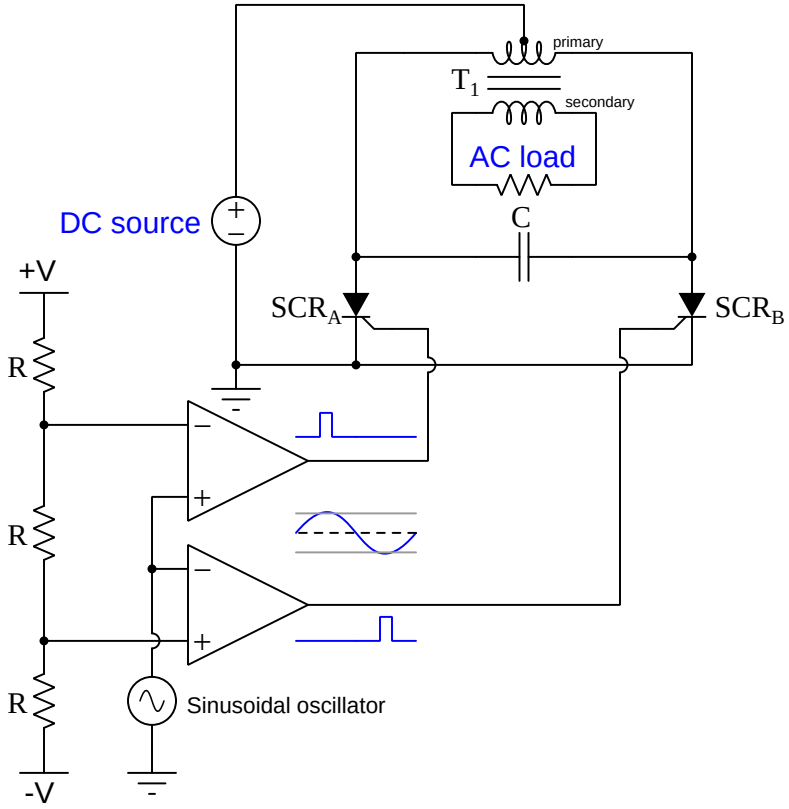
The transformer-based design, while adding bulk and expense to the circuit, enjoys the advantages of electrical isolation[8] between the AC load and driving circuits as well as the ability to output AC voltages significantly greater than or less than the DC source voltage by exploiting the transformer's turns ratio.

Other possibilities exist on this same theme. For example, we could replace the astable multivibrator circuit with a more sophisticated oscillator, perhaps one based on operational amplifiers. We may also consider power-switching devices other than BJT or MOSFET transistors. Both changes are evident in the circuit shown next.

[8] For example, with the AC load isolated by the transformer, we have the freedom to ground one terminal of it to form definite "neutral" and "hot" conductors. This is not possible in either MOSFET or BJT "H-bridge" power stages because the connection to circuit ground alternates with each half-cycle.

3.4 Thyristor converters

Silicon-Controlled Rectifiers (SCRs) are a viable alternative to transistors, and with their *thyristor* behavior (internal positive feedback causing them to latch "on" once triggered and latch "off" once current is halted through them), their power dissipation in the "on" state will be less than for most types of transistors. However, SCRs must be *forced* out of conduction because thyristors do not naturally turn off like a power transistor when their gate signal is removed. A common method of forced thyristor commutation uses the stored energy within a capacitor to force one SCR to commutate when the other is triggered:



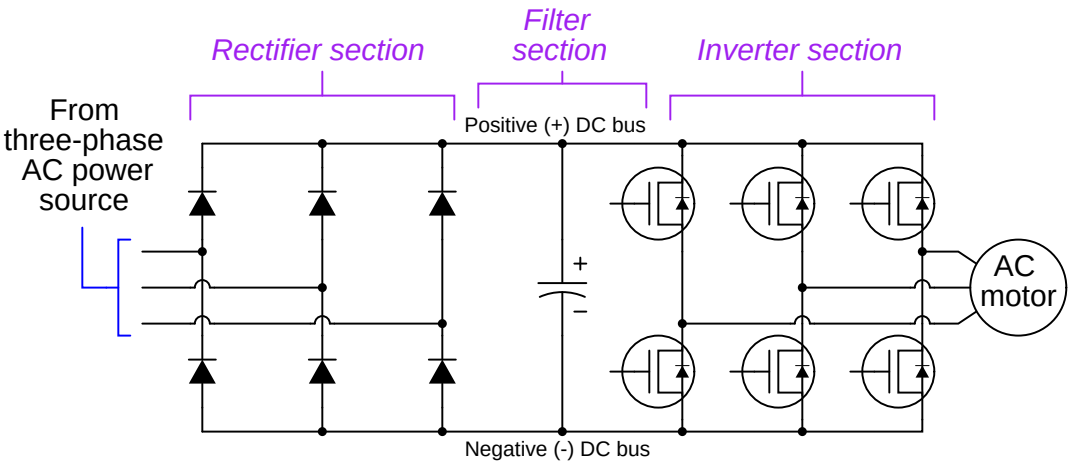
A thought experiment reveals how this forced commutation works. Imagine SCR_A conducting and SCR_B non-conducting, energizing *only* the left-half of the transformer winding. In this condition, capacitor C drops the primary winding's full voltage, positive on right and negative on left. Once the lower comparator generates a "high" pulse signal, SCR_B turns on and causes the capacitor (now acting as a voltage source) to deliver a surge of current from left to right. This surge diverts the primary winding's current through the capacitor and down to ground through SCR_B while impressing a reverse bias across SCR_A (+ on cathode and − on anode). The surge of current through SCR_B secures it in the "on" state while the reverse bias across SCR_A forces it off. Current through the left-half of the primary winding decays to zero as the capacitor accumulates a voltage (+ on left, − on right), while current begins to flow through the right-half of the primary winding.

This state persists until the upper comparator triggers SCR_A, at which point the opposite occurs turning SCR_A back on and forcing SCR_B off. At each reversal, the transformer's secondary winding experiences a change in magnetic flux direction, causing the output voltage to alternate polarity. Note how the triggering pulses need only be brief, as the SCRs' latching behavior generates full square-wave AC for the load even if the duty cycle values of these pulses are low.

3.5 Three-phase converter circuits

The control of three-phase AC loads, particularly induction-type AC electric motors, is a very important application of electric power conversion in modern industry. A converter circuit able to create three-phase AC at any desired frequency is necessary for controlling the speed of AC induction motors, these motors based on the principle of a rotating magnetic field produced by stator windings when energized by out-of-phase AC currents.

A very common form of three-phase AC converter circuit is shown below, typically part of a device called a *Variable Frequency motor Drive*, or *VFD*:



In this circuit we see electric power supplied by a three-phase AC source on the left, rectified into DC by a 6-pulse bridge rectifier, filtered by a capacitor, and then DC converted into AC by another 6-pulse circuit on the right except this final "inverter" network uses transistors instead of diodes. These six transistors must be pulsed on and off by some electronic control circuit not shown in this power circuit diagram, in a sequence appropriate to the creation of three-phase AC.

Three of these transistors on top serve to "source" current to the motor conductors, while the three bottom transistors serve to "sink" current from the motor conductors. Never are the sourcing and sinking transistors of any one motor conductor simultaneously conducting, as that would present a direct short-circuit across the DC "bus". Instead, what we typically find at any instant in time is one upper transistor sourcing current to a single motor conductor while two lower transistors sink current from the other two motor conductors, or vice-versa.

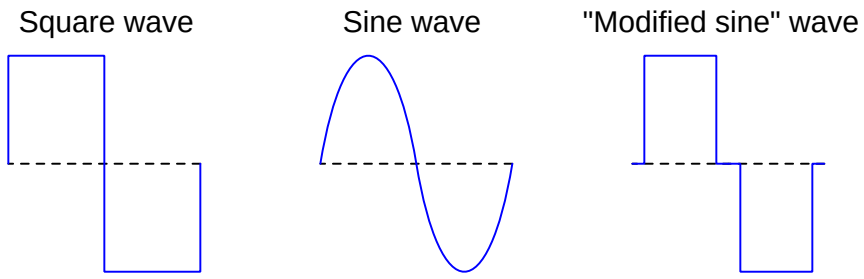
To see a flip-book animation of this converter circuit in action, refer to page 38 located in section 5.1.

3.6 Converter output waveforms

So far all the DC-AC converter circuits shown produce square-wave AC output voltage, though this may not be desirable for many types of AC loads. Square waves are rich in *harmonic*[9] frequencies, and these harmonics often create a range of problems including:

- Excessive coupling of electrical "noise" to adjacent conductors, because the relatively high frequencies of these harmonics constitute high $\frac{dV}{dt}$ voltage rates-of-change and high $\frac{dI}{dt}$ current rates-of-change, resulting in greater noise currents coupled by inter-conductor capacitance and greater noise voltages coupled by mutual inductance (respectively).
- Overheating of transformer cores due to greater levels of *eddy currents* induced in the iron.
- Overheating of AC electric motors due to the "jerking" motion of the rotating magnetic field produced in the motor by square-wave AC.
- Overpowering of AC loads if the square wave has the same peak value as the normal sine wave, given that RMS is equal to peak for a square wave but only equal to $\frac{1}{\sqrt{2}}$ peak for a true sine wave.

A compromise solution between square-wave output and true sine-wave output is a *modified-* or *pseudo-*sine wave which is a square-edged pulse waveform having equivalent RMS value to a sine wave of the same peak amplitude:

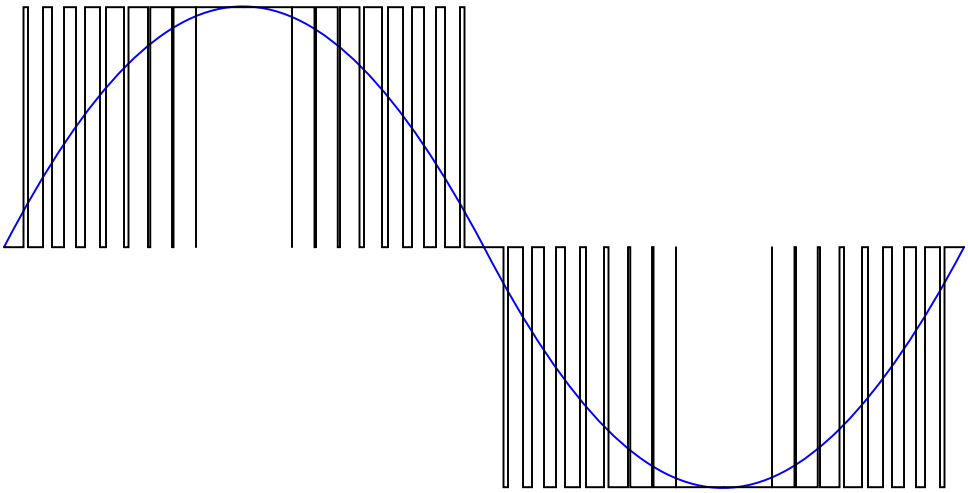


Driving a transistor power stage with a true sine-wave signal is impractical at high power levels because that would result in the power transistors operating in partial-on states rather than fully-on and fully-off where they are most energy-efficient. Therefore, the "modified sine" signal waveshape is a reasonable compromise because it exhibits less harmonic content than a pure square wave but enjoys the same switching efficiency as a square wave. It should be noted, though, that a "modified sine" waveform is not an option for a power stage using thyristors, because of the way we must "commutate" one thyristor by turning the other on: we cannot have both thyristors off at any time. Such square-wave variations require a *transistor*-based output stage.

[9] Any non-sinusoidal waveform is mathematically equivalent to a series of sinusoids at different frequencies, amplitudes, and phase angles. Sinusoidal frequencies that are integer-multiples of the waveform's fundamental (base) frequency are called *harmonics*. Square waves consist of an infinite series of odd-numbered harmonics.

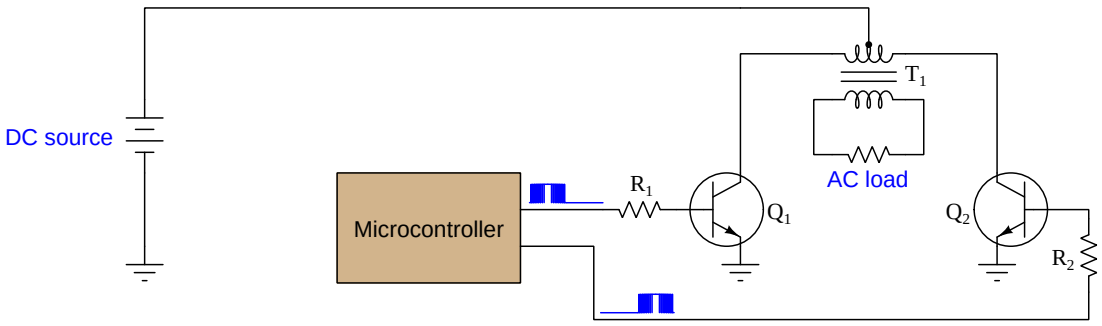
One way to more closely approach the ideal of a sine-wave output from a DC-AC converter circuit is to use *pulse-width modulation*, rapidly turning the power stage transistors on and off in such a way that the average power conveyed to the load follows a sinusoidal curve.

The equivalence between a rapidly-varied pulse-width modulation (PWM) waveform and a sine wave is shown in the following illustration:



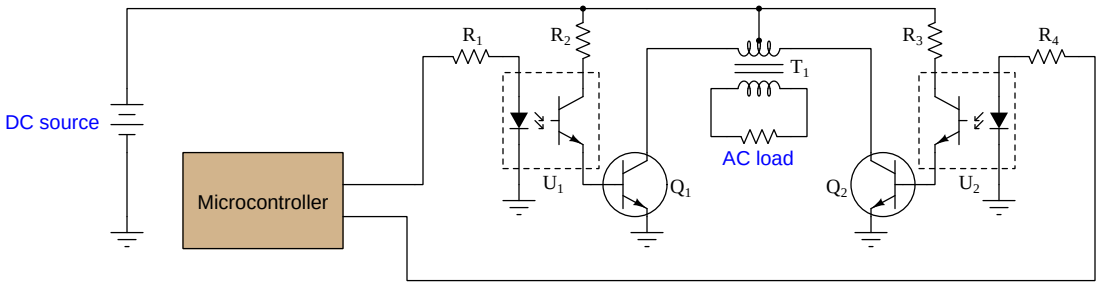
This concept of rapid PWM transistor switching allows the drive to "carve" any arbitrary waveform out of the DC source voltage. Virtually any frequency may be synthesized (up to a maximum limited by the frequency of the PWM pulsing), and any voltage (up to a maximum peak established by the DC source voltage).

Typically we would use a microcontroller or some other programmable digital device to generate the complex PWM patterns necessary to drive the power transistors:



Incorporating PWM into the power transistor drive signals gives us one more useful feature, and that is a means to also control the amplitude of the AC output. Instead of the PWM duty cycle varying from 0% to 100% with every half-cycle of the desired sine waveshape, we may program the microcontroller to vary from 0% to some lesser amount in order to effectively output less than full AC voltage. Control over both the frequency and amplitude of the DC-AC converter's output is very important if we wish to synchronize with an existing AC power grid. Control over both parameters is also important when using such an inverter to drive an AC motor to variable speeds, since we must reduce voltage as we reduce frequency to avoid over-heating the motor at low speeds[10].

An additional feature often seen in power-converter circuitry is *optical isolation* between the signal source (i.e. comparator or microcontroller) and the power-handling components (e.g. transistors). This often takes the form of an *optocoupler* which is a light-emitting diode and photo-sensitive switching component housed in a common integrated circuit (IC) package:



Power transistors Q_1 and Q_2 receive their base current signals through the respective optocoupler transistors, and those transistors in turn are optically triggered by light from the LEDs. This electrically isolates the microcontroller from the power components, which is useful in the event a power transistor were to fail in such a way that it may impose dangerously high voltages to the pins of the microcontroller. In such a fault event, the microcontroller would be spared damage from the power transistor failure.

Some power electronic devices – notably some high-voltage SCRs – may be *directly* triggered by light. Called Light-Activated SCRs (LASCRs), these power devices come equipped with a receiving port designed to interface to a fiber-optic cable, so that pulses of light transmitted through that cable from some controlling device may trigger the SCR while enjoying the full electrical isolation afforded by the non-conducting glass fiber.

[10] This concept is known as the Volts-per-Hertz (V/Hz) ratio, and is a standard feature of all variable-frequency AC motor drives (VFDs).

Chapter 4

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

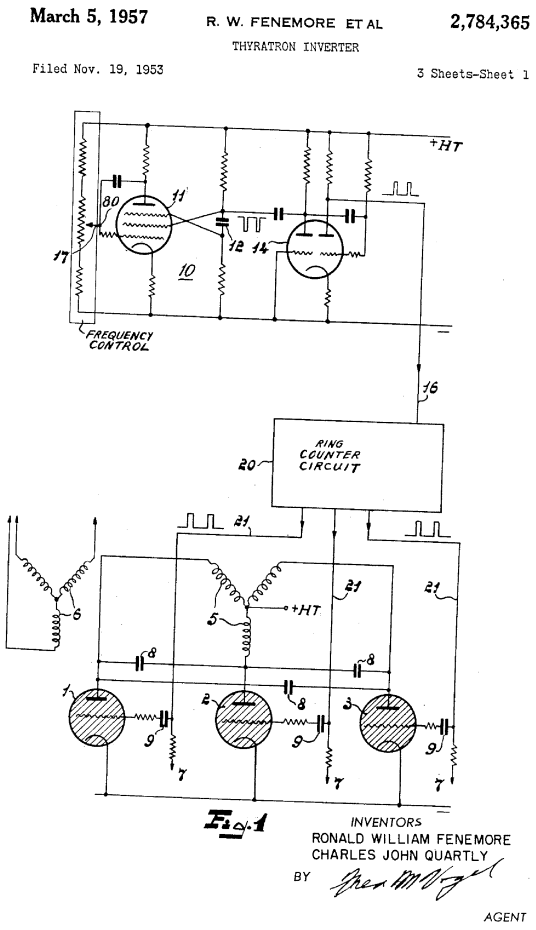
> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

4.1 Thyratron inverter patent

A predecessor to the solid-state thyristor was the gaseous-tube *thyratron*, similar in construction to a vacuum tube except with a low-pressure gas fill rather than a hard vacuum. The ionization effect of the filling gas provided a similar hysteresis effect for the thyratron tube as the interconnected-transistor structure provides hysteresis for a thyristor: once triggered, a thyratron tube would continue to conduct electricity until something *commutated* it.

The following diagram comes from a United States patent (number 2,784,365 granted 5 March 1957) submitted by inventors Ronald William Fenemore and Charles John Quartly of England, illustrating a circuit designed to invert DC into three-phase AC:



Three thyratron tubes near the bottom of the diagram handle the power switching, each one dedicated to a phase of a Wye-connected transformer primary. The positive pole of the DC supply (+HT) connects to the center of the transformer primary Wye, while the negative pole connects to

the cathodes of all three thyratron tubes. A *ring counter* circuit sends triggering pulses to the grid electrodes of the thyratron tubes, equivalent to the gate terminals of three SCRs.

Like SCRs, thyratrons are impractical to commutate via a negative pulse applied to the gate (grid) terminal, and instead must be commutated by other means. In this case, the conducting tube is commutated by firing another tube, and the key to the success of this scheme is the three capacitors (labeled 8 on the diagram). The inventors describe how this works, which could have easily described how a capacitor-commutated SCR circuit would function if SCRs were invented at the time:

> Three capacitors 8 are connected in a ring or delta between the anodes of the thyratrons 1, 2, 3 and operate in such manner as to extinguish automatically one thyratron when the next thyratron is fired. For example, if tube 2 is conducting at a particular instant and tube 3 is then fired by a pulse, the anode of the latter tube will drop in potential due to the current taken. This potential drop will be passed momentarily to the anode of tube 2 and will be sufficient to extinguish tube 2 in the absence of a firing pulse. The anode drop will also be communicated to tube 1, but ineffectively, since tube 1 will already be in the extinguished condition.

Chapter 5

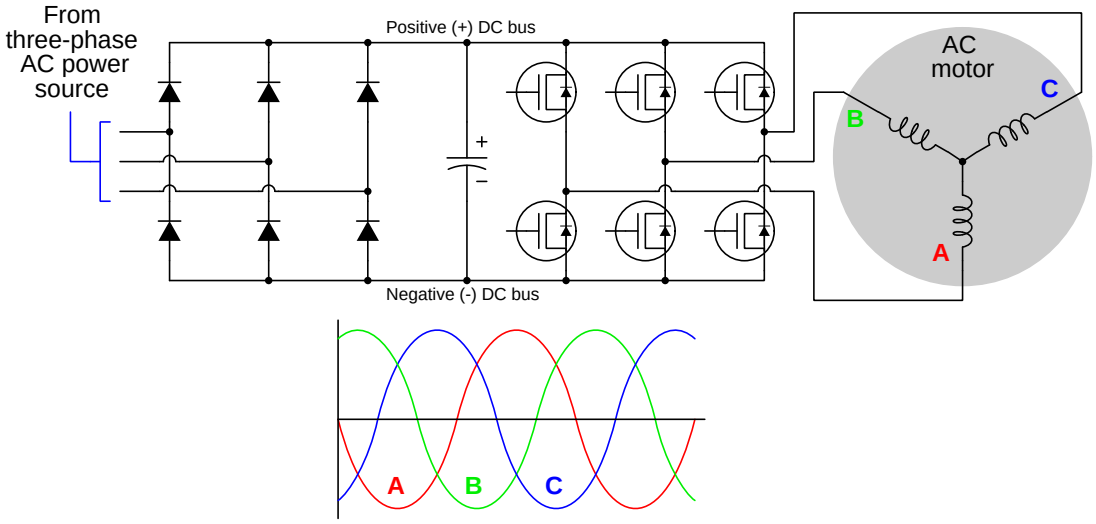
Animations

Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a "flip-book" animation where a set of pages in the document show successive frames of a simple animation. Such "flip-book" animations are designed to be viewed by paging forward (and/or back) with the document-reading software application, watching it frame-by-frame. Unlike video which may be difficult to pause at certain moments, "flip-book" animations lend themselves very well to individual frame viewing.

5.1 Three-phase converter transistor switching sequence

The following animation shows how the "rotating" magnetic field of a three-phase AC induction motor is produced by the interaction of three stator winding sets energized with different phases (A, B, and C) of a three-phase AC power source. A red arrow shows the direction of the *resultant* magnetic field created by the interaction of the three winding sets.

A VFD's power circuitry consists of a *rectifier* section to convert AC into DC, a *filter* section to "smooth" the DC so that it is more steady than it would be otherwise emerging from the rectifier, and finally an *inverter* section where the filtered DC is converted into three-phase AC at the desired voltage and frequency. In this animation we show the inverter stage's six transistors turning on and off as necessary to create the rotating magnetic field vector in the motor, but what we do not show is the high-speed pulsing of those transistors within each of their "on" periods necessary to synthesize a *sinusoidal* output current.


From
three-phase
AC power
source
Positive (+) DC bus
Negative (-) DC bus
+
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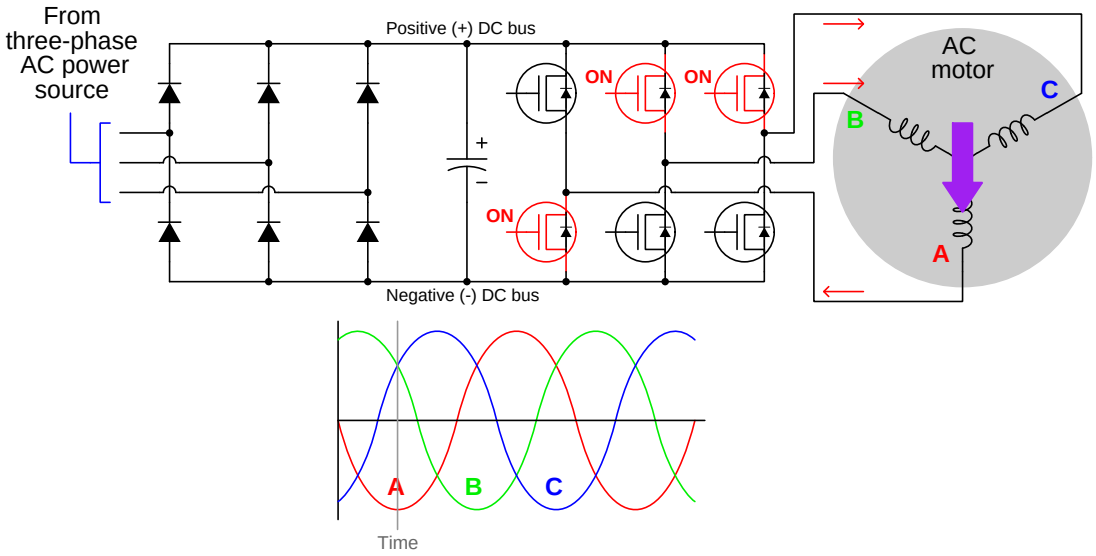
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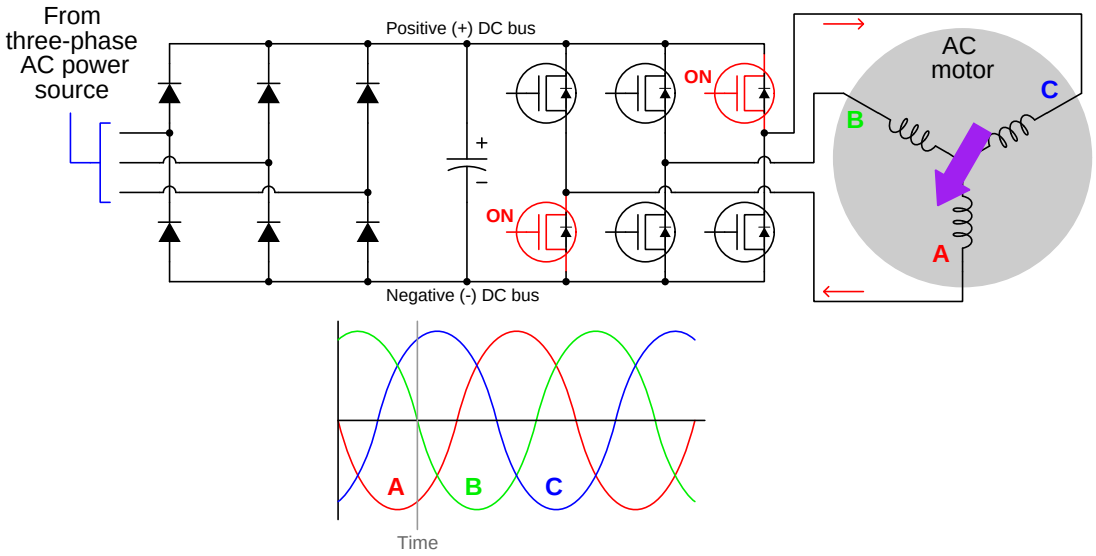
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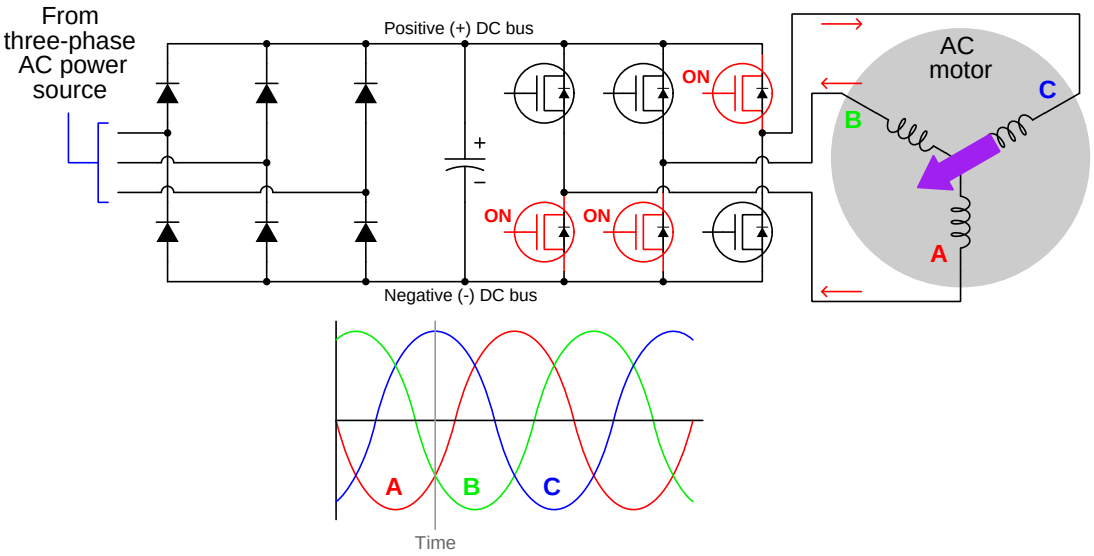
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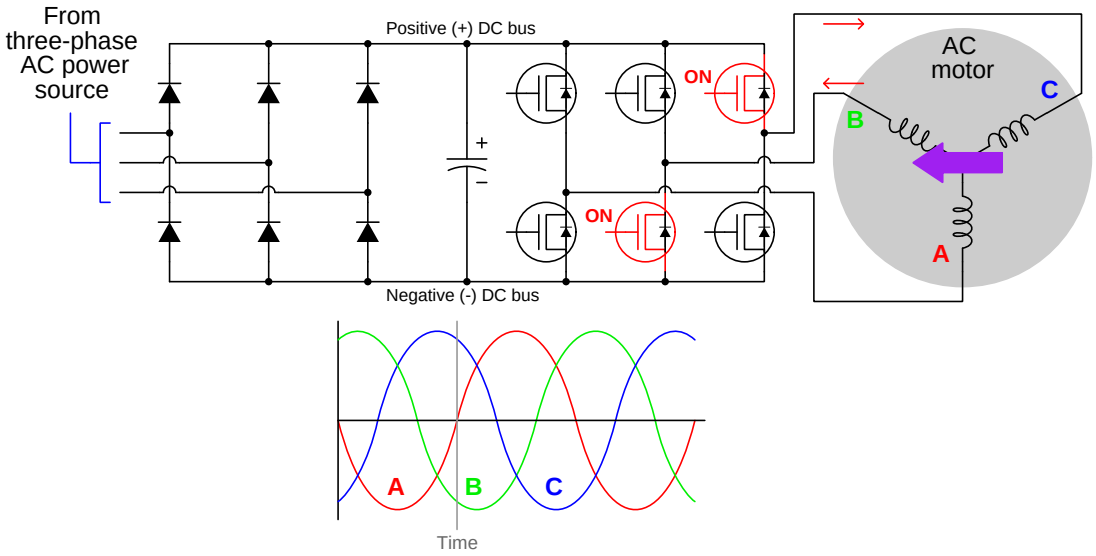
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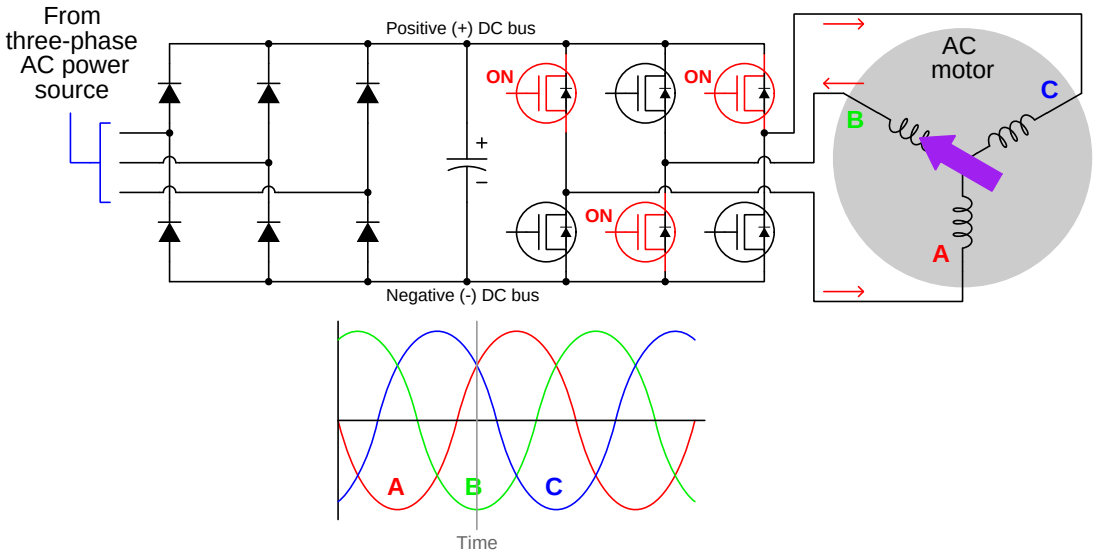
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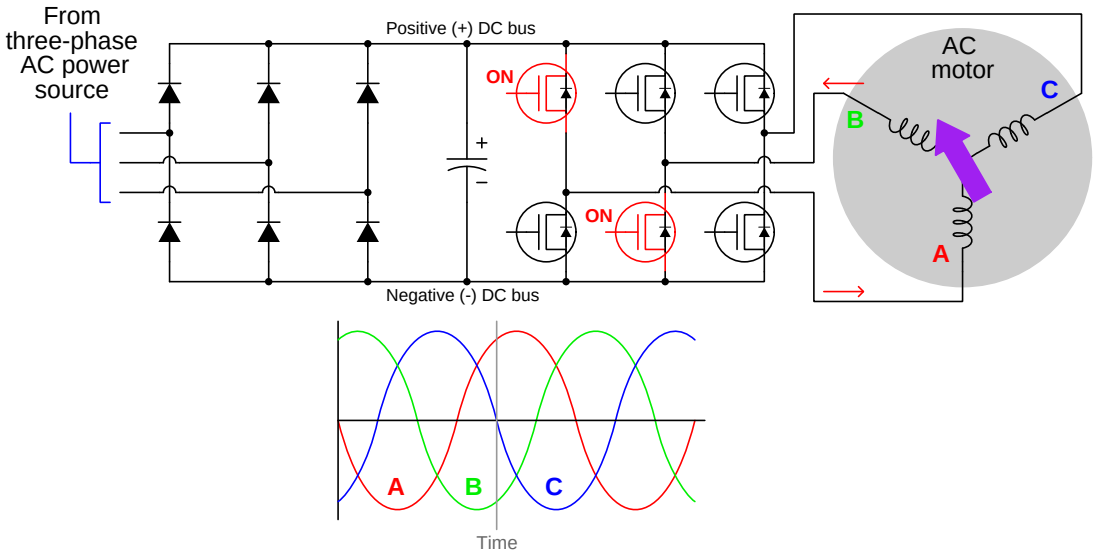
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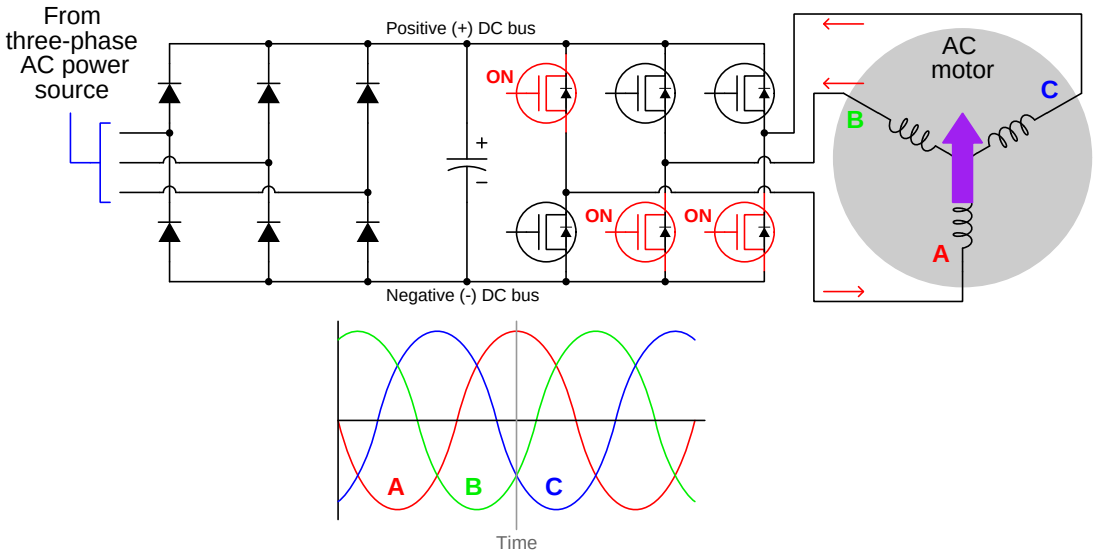
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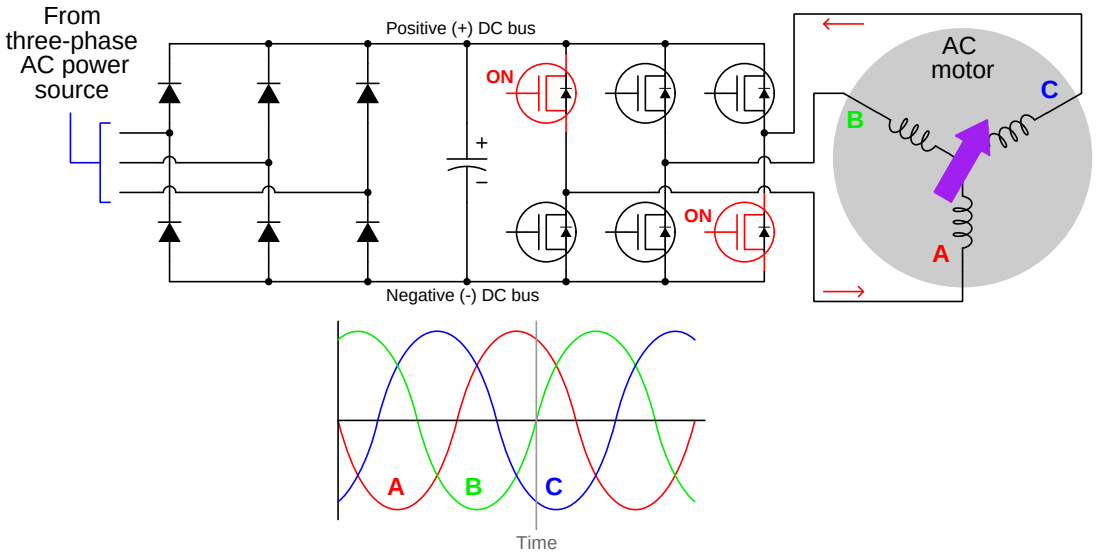
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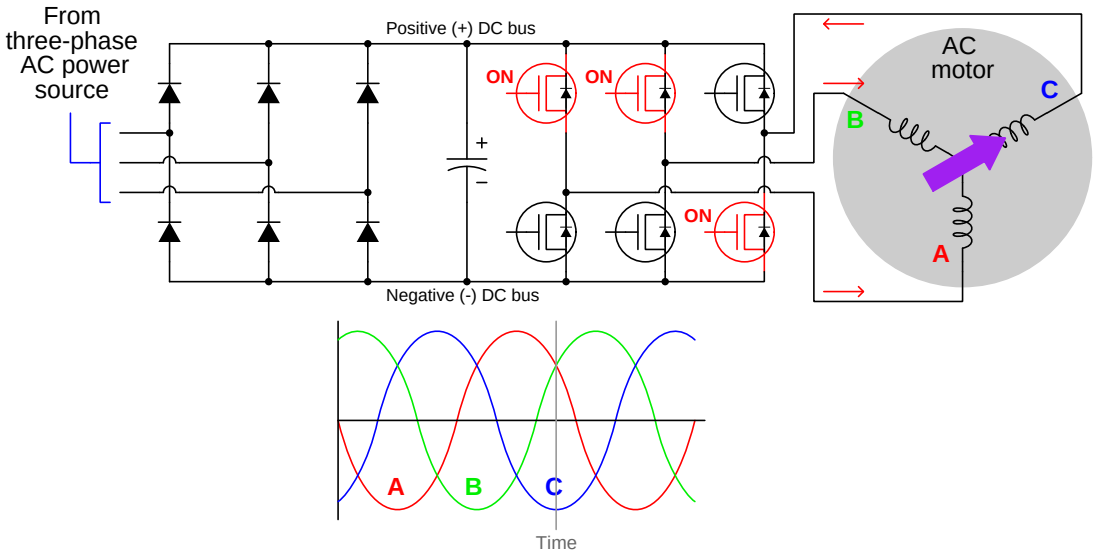
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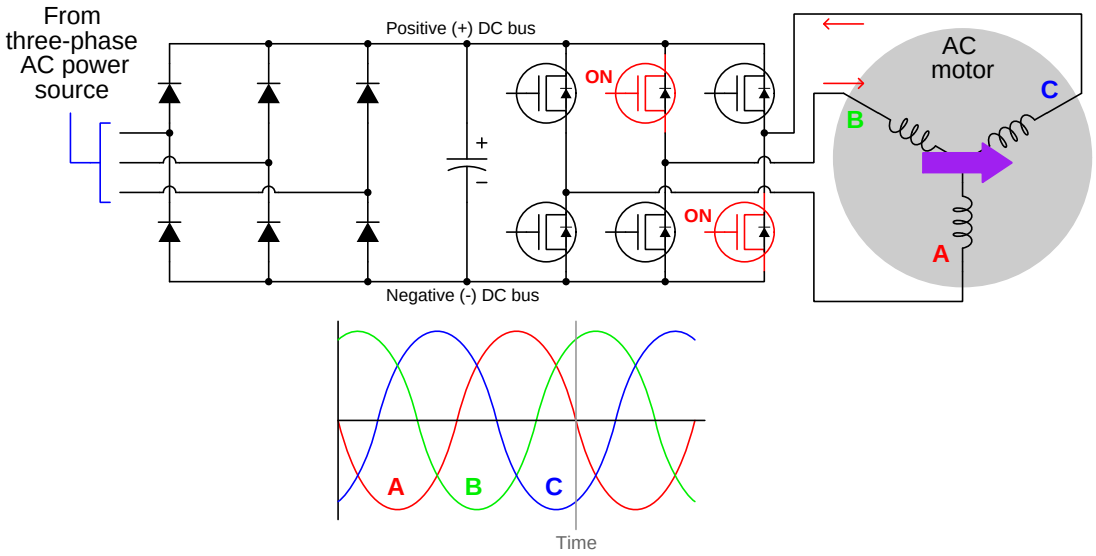
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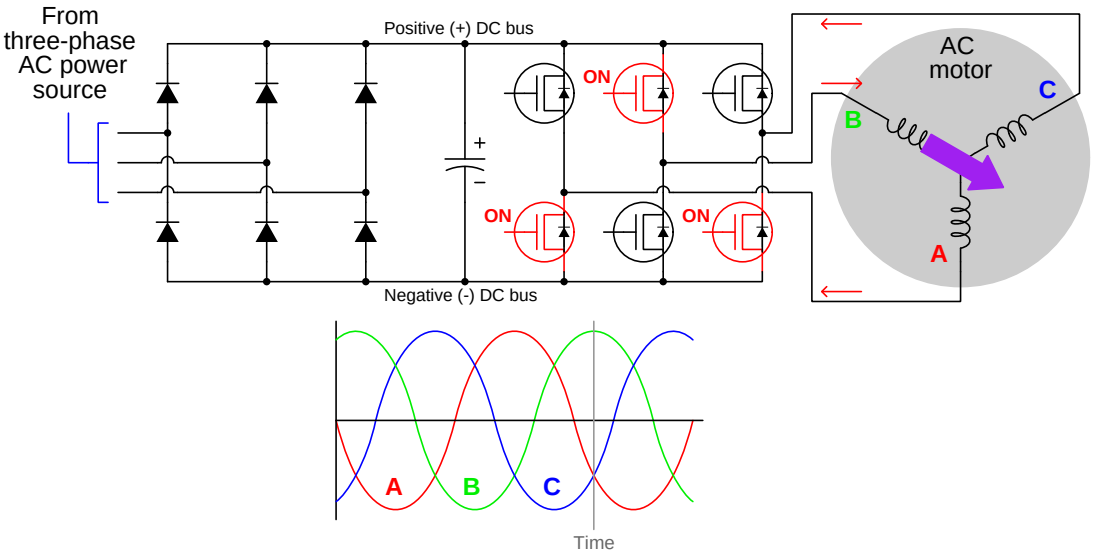
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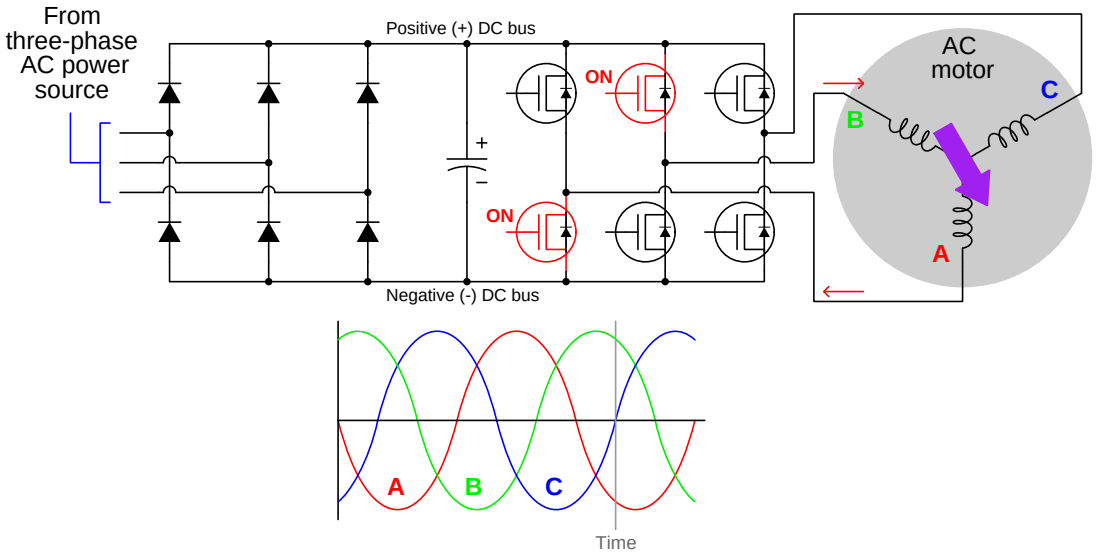
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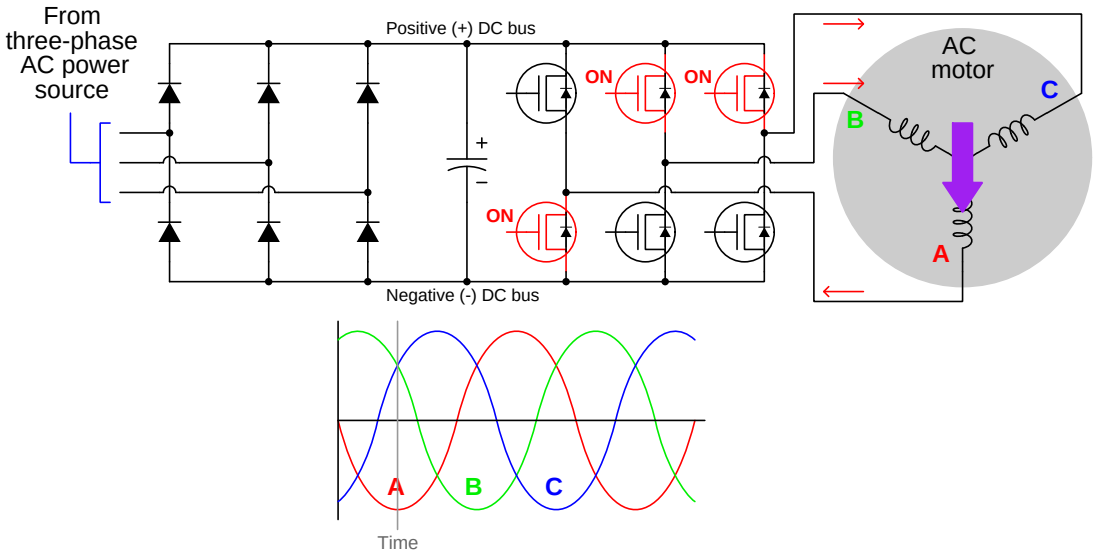
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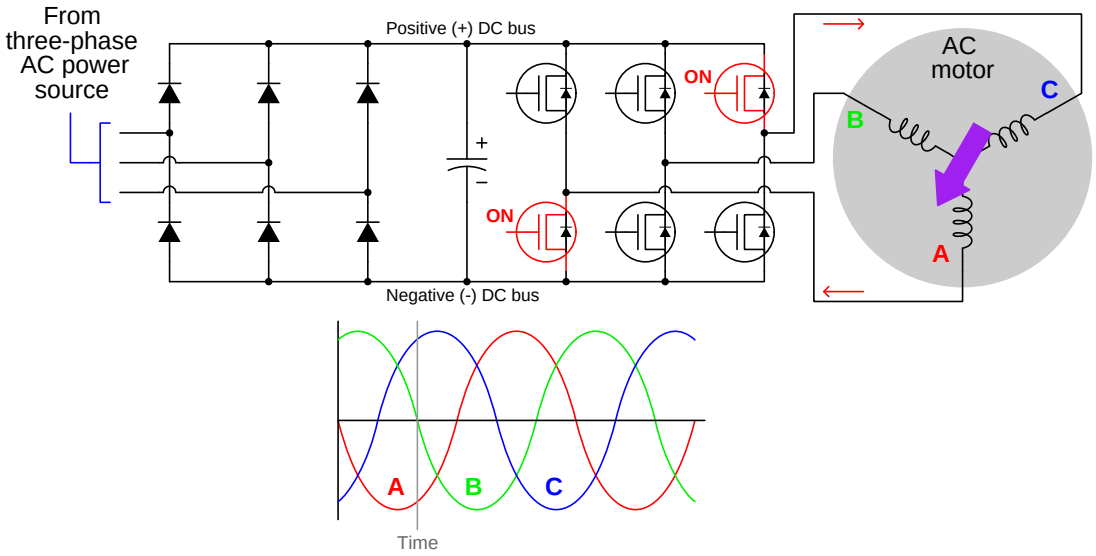
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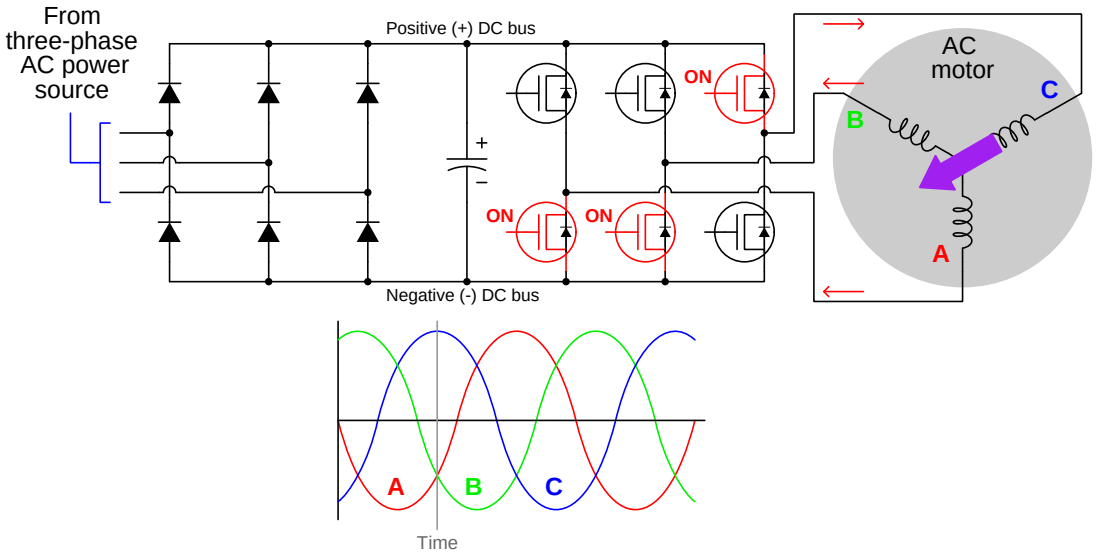
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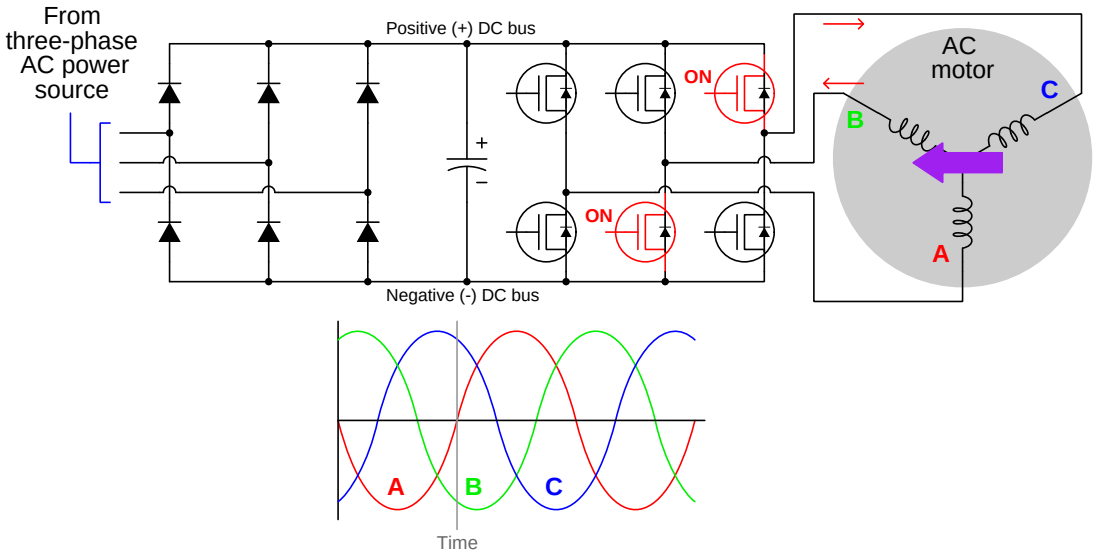
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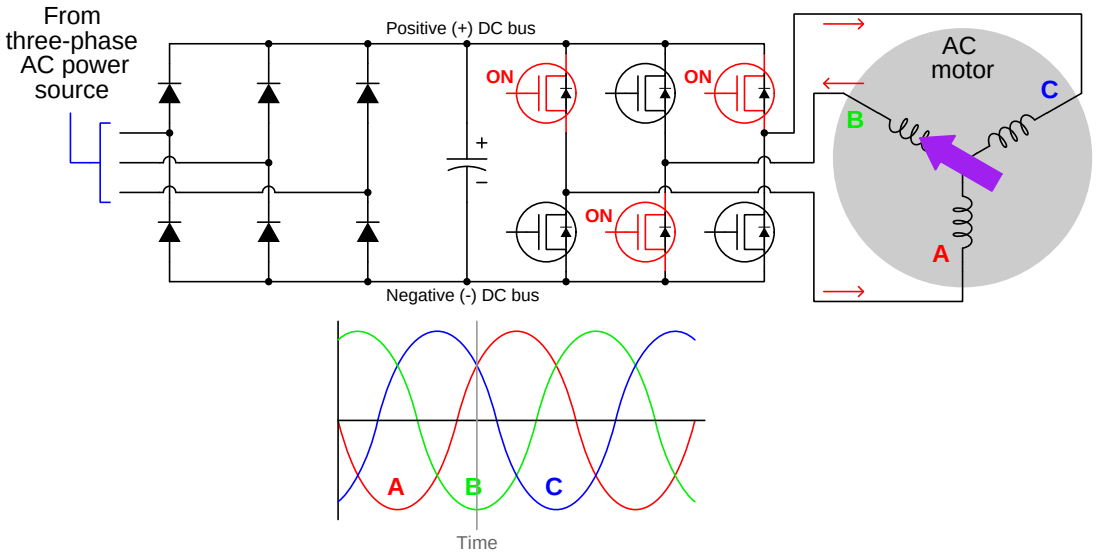
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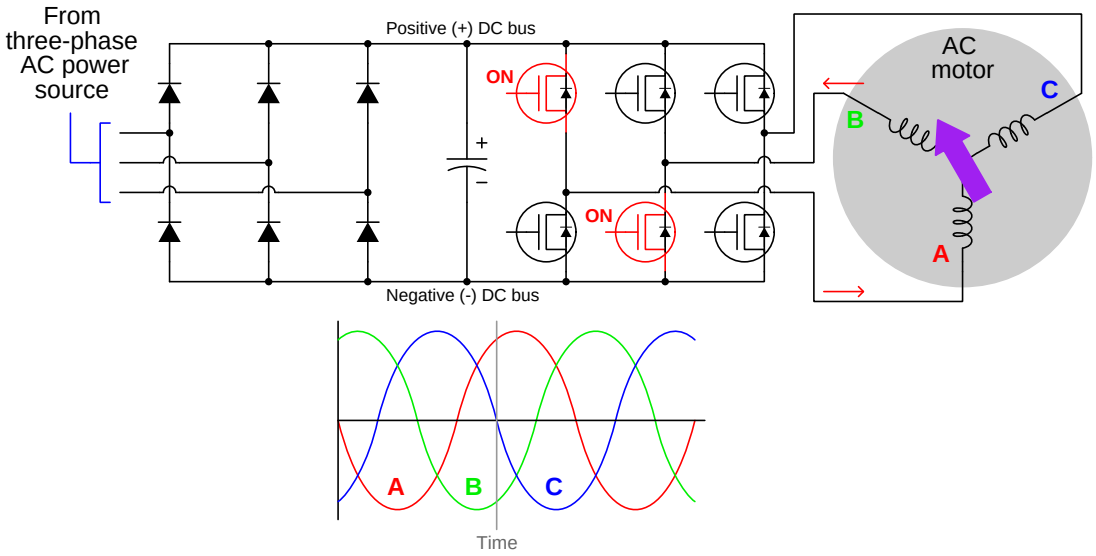
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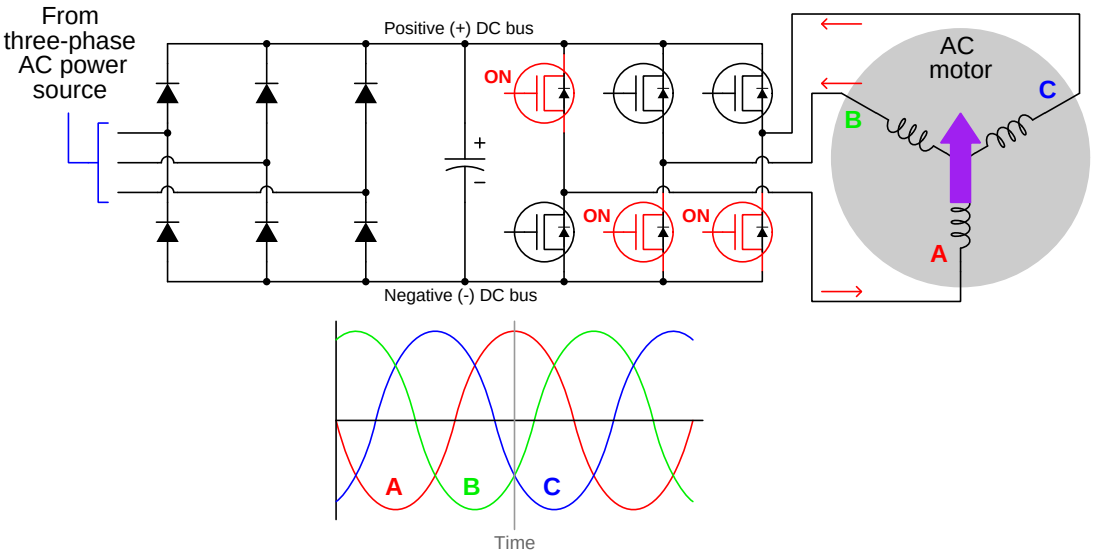
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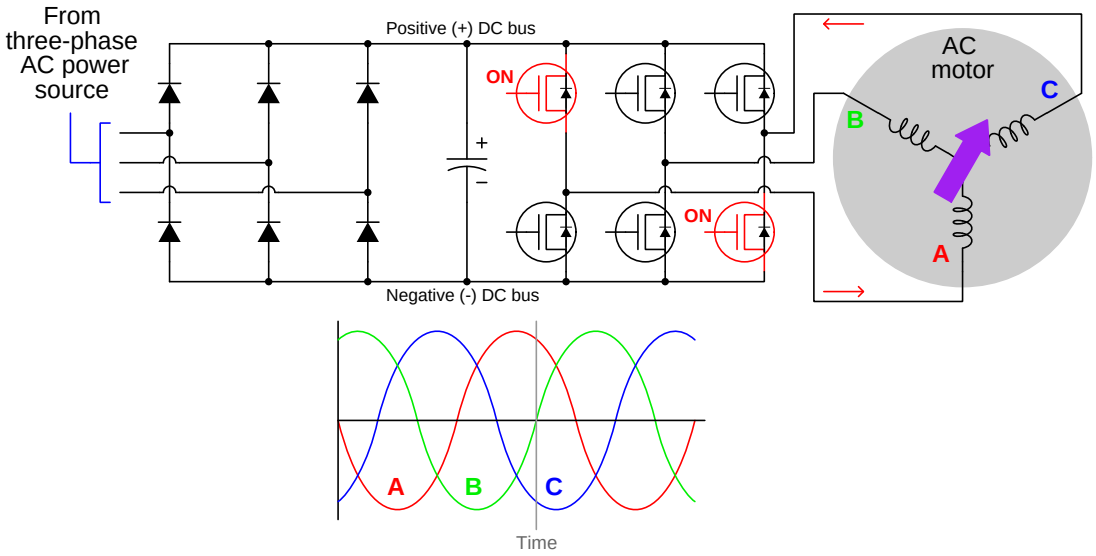
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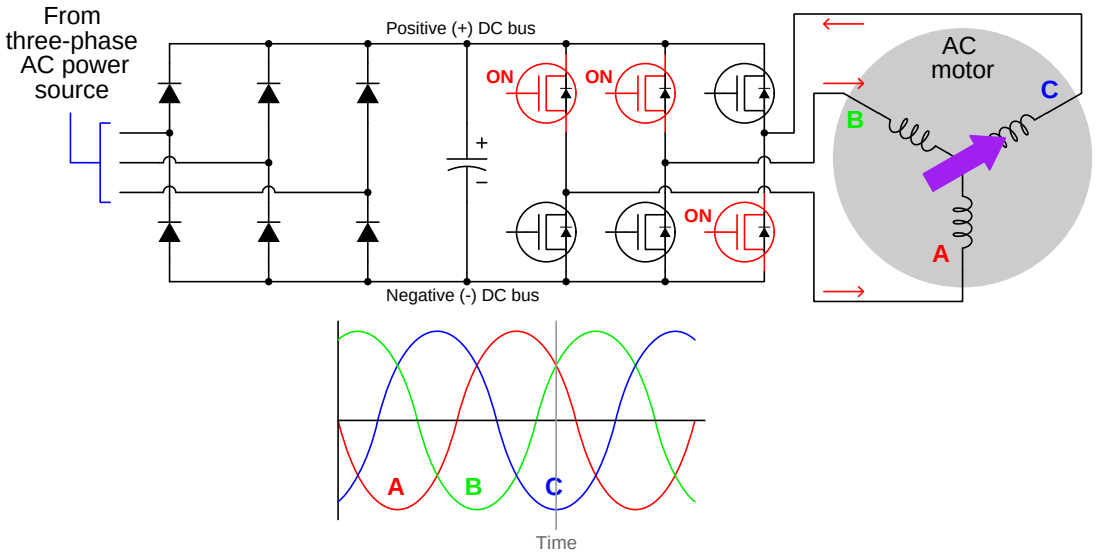
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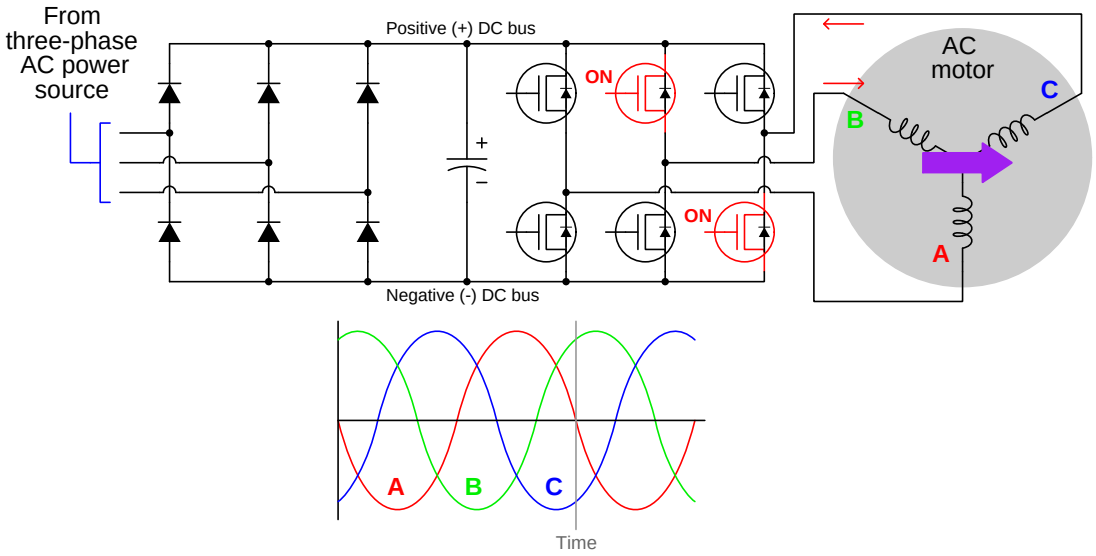
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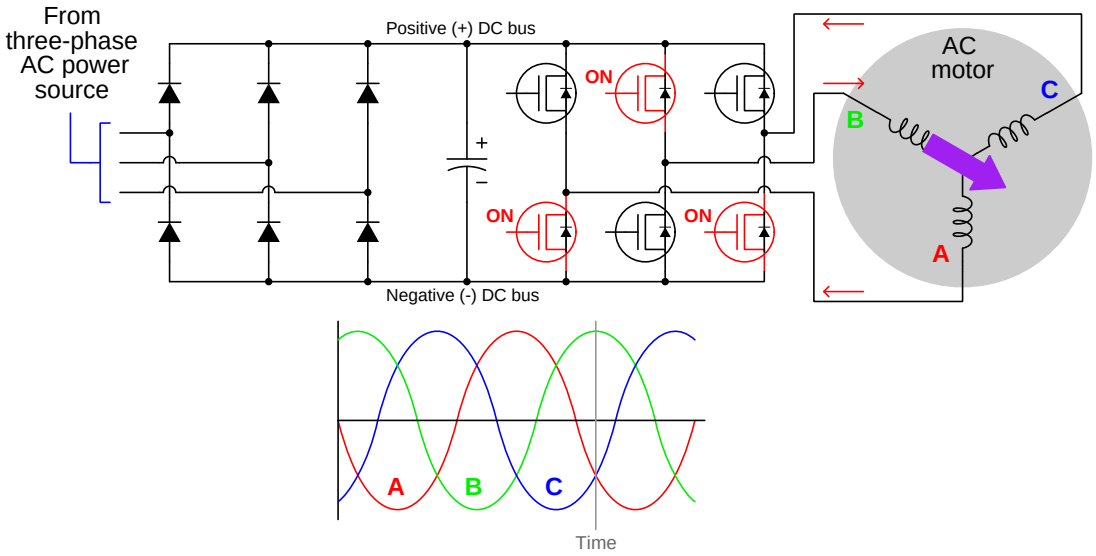
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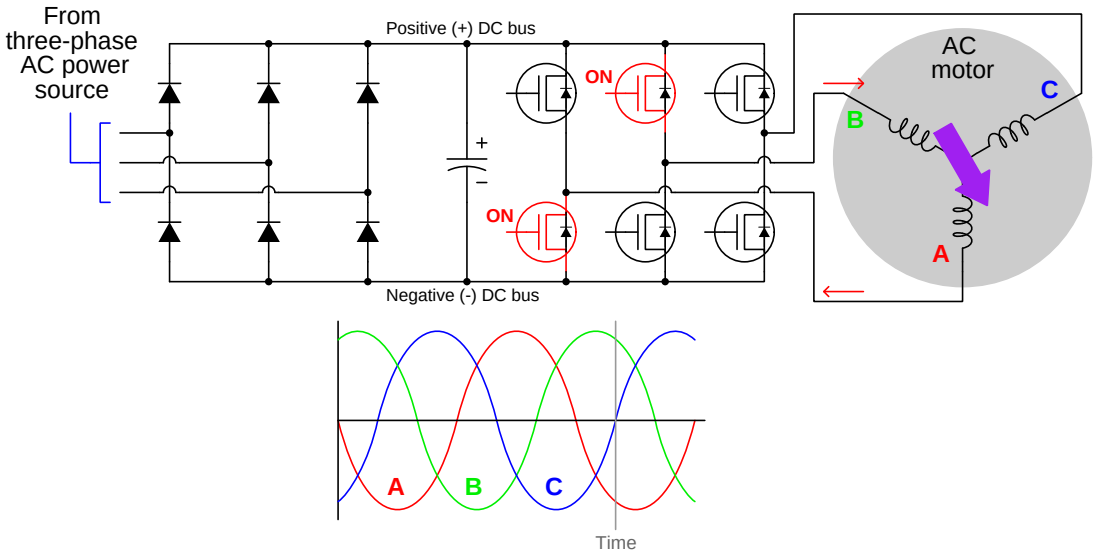
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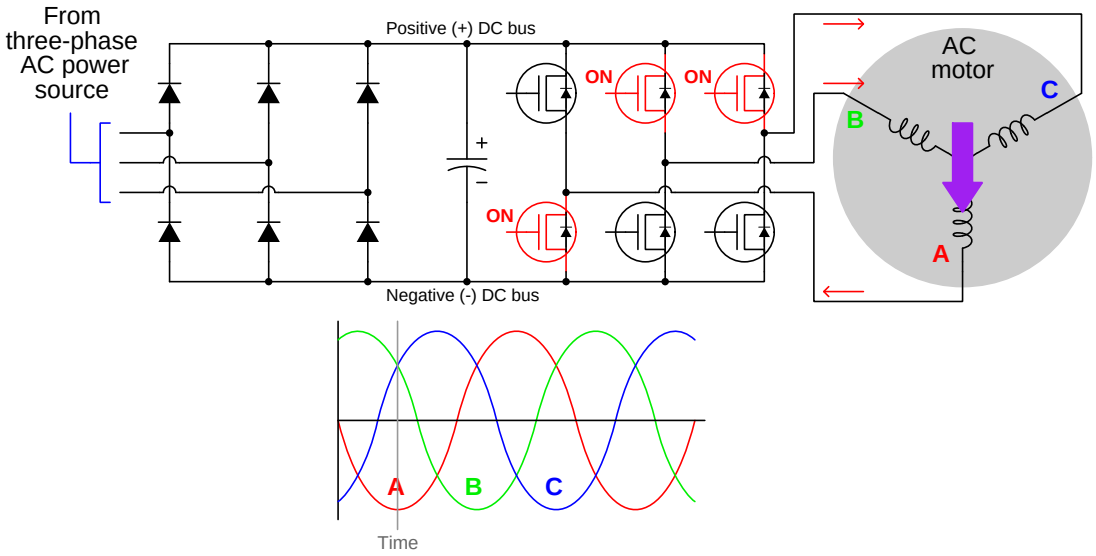
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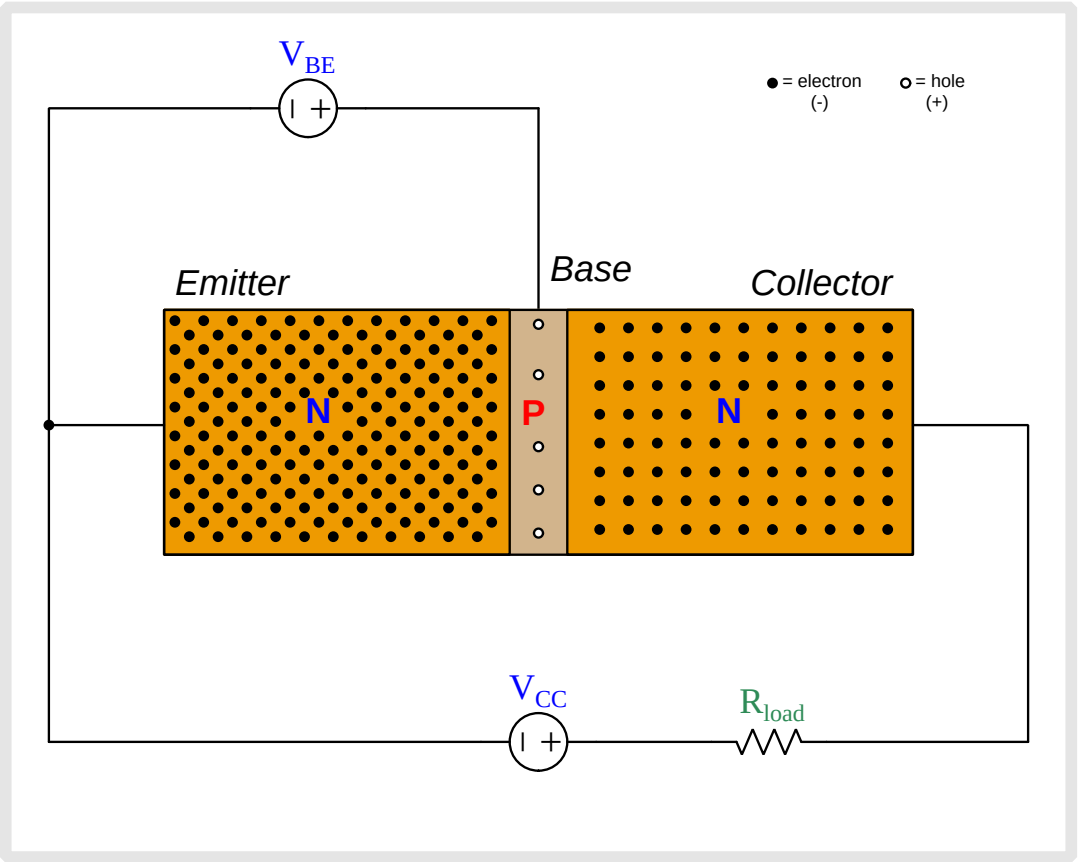
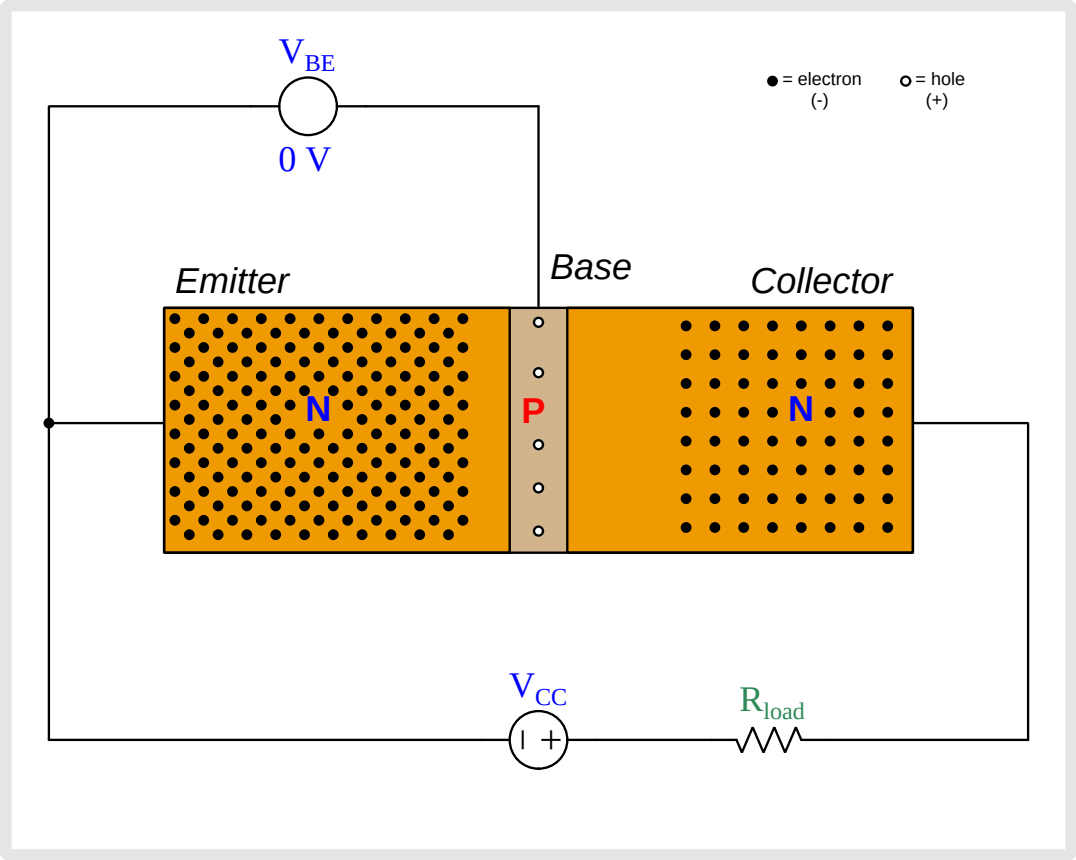
5.2 Animation of an NPN BJT turning on

Bipolar junction transistors are naturally "off" devices, having no continuous channel of conductive semiconductor material joining emitter and collector terminals. Instead the NPN or PNP sandwich interrupts that path with two series-opposed PN junctions. However, when the base-emitter PN junction is forward-biased by an external source, majority charge carriers from the emitter region are drawn into the thin and lightly-doped base region where some of them travel out the base but most carry past into the depletion region of the base-collector PN junction to be swept into the collector region. For an NPN transistor this means electrons from the N-type emitter region will be injected into the P-type base region (as "minority" type carriers there) before most of them get swept into the N-type collector region.

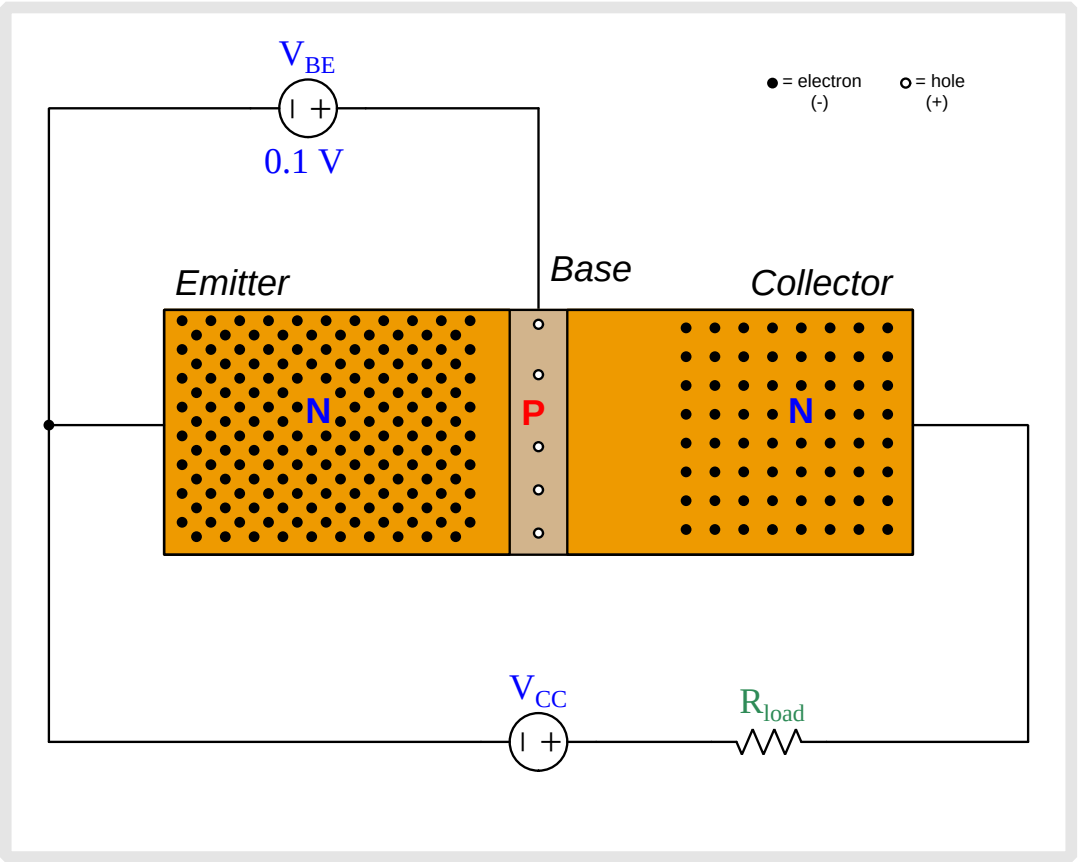


Above we see an NPN bipolar junction transistor connected to two sources. V_{BE} applies a controlling voltage between the base and emitter. V_{CC} is the voltage source which will drive current through the load resistor once the transistor begins to conduct.

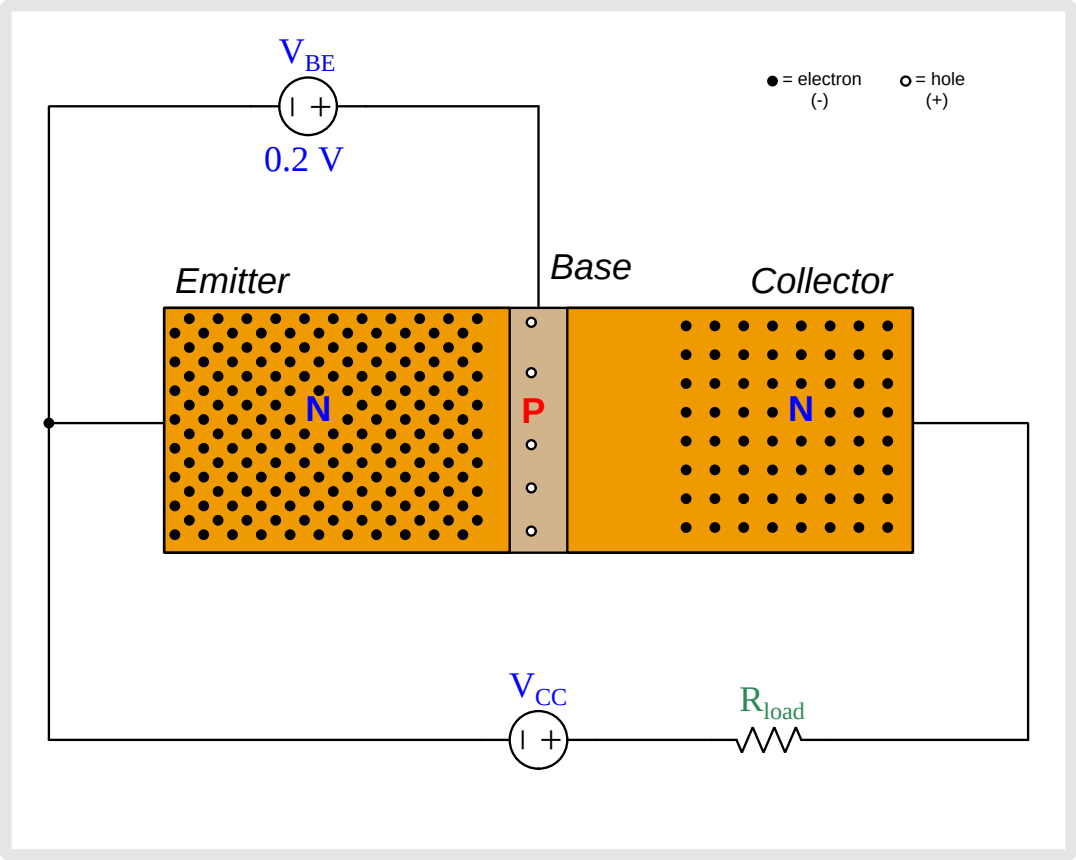
The N-doped emitter region is heavily doped and therefore contains many free electrons (negatively-charged) as mobile charge carriers. The collector region is also doped as an N-type semiconductor but the dopant concentration is less than that of the emitter. The P-doped base region is the least-doped of them all with just a few holes (positively-charged) as mobile charge carriers. Note that when load current begins to flow, its direction will be shown in *conventional flow notation* which is the same direction in which holes move but is opposite to the direction free electrons move.



Note the depletion regions shown as areas with no free charge carriers, the base-collector depletion region being wider than the base-emitter depletion region due to the applied reverse-bias potential of V_{CC}.



As we begin to apply a base-to-emitter voltage with the base positive and emitter negative, that applied potential difference drives the emitter and base regions' respective charge carriers toward each other, collapsing the base-emitter depletion region.



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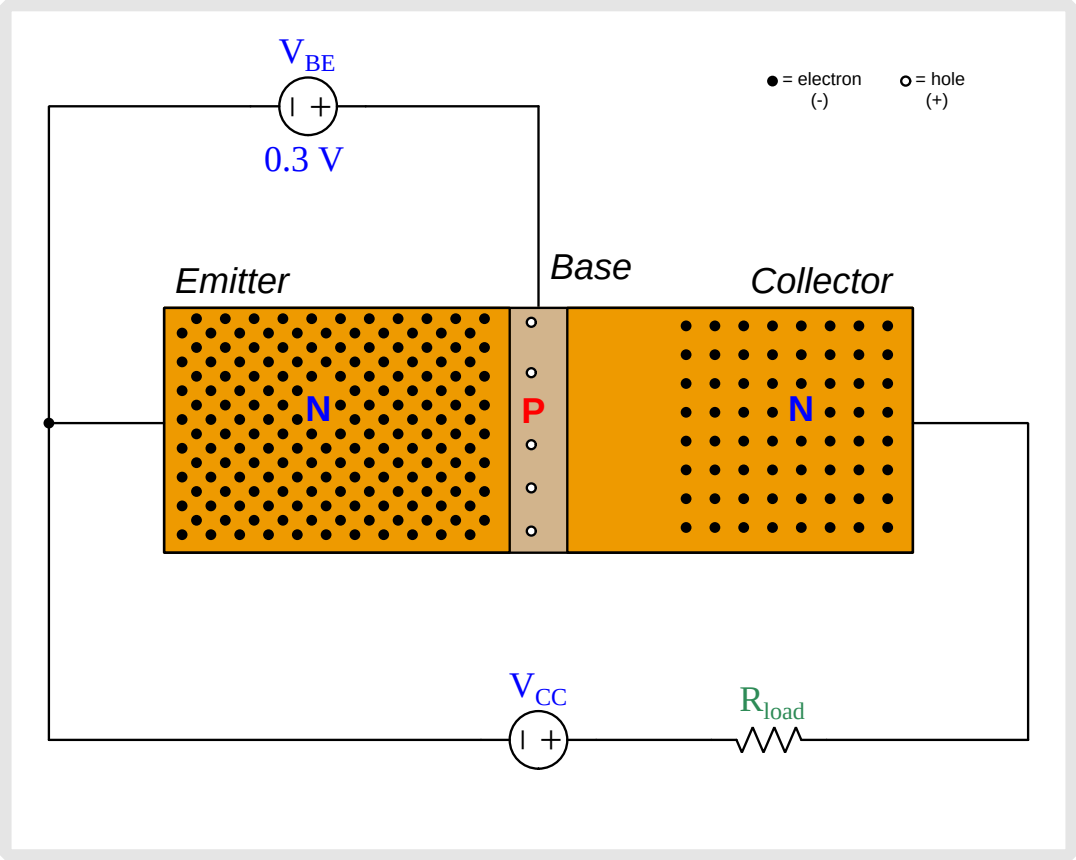

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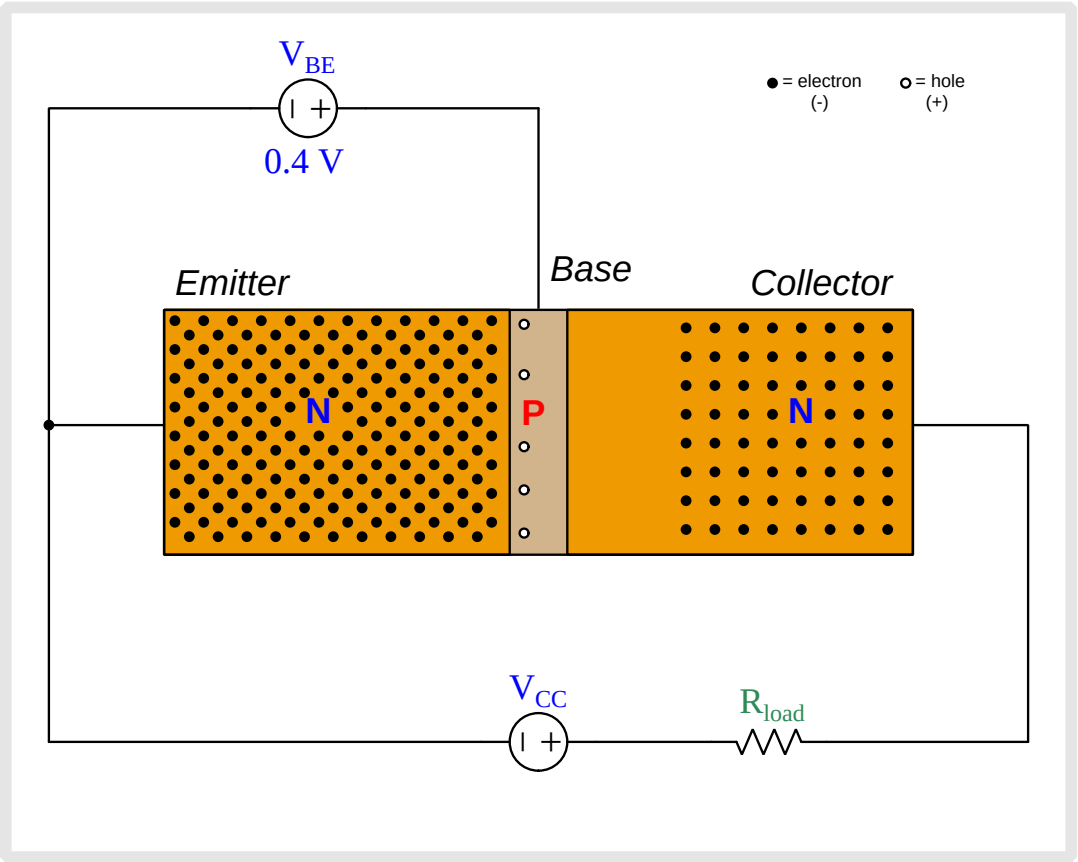

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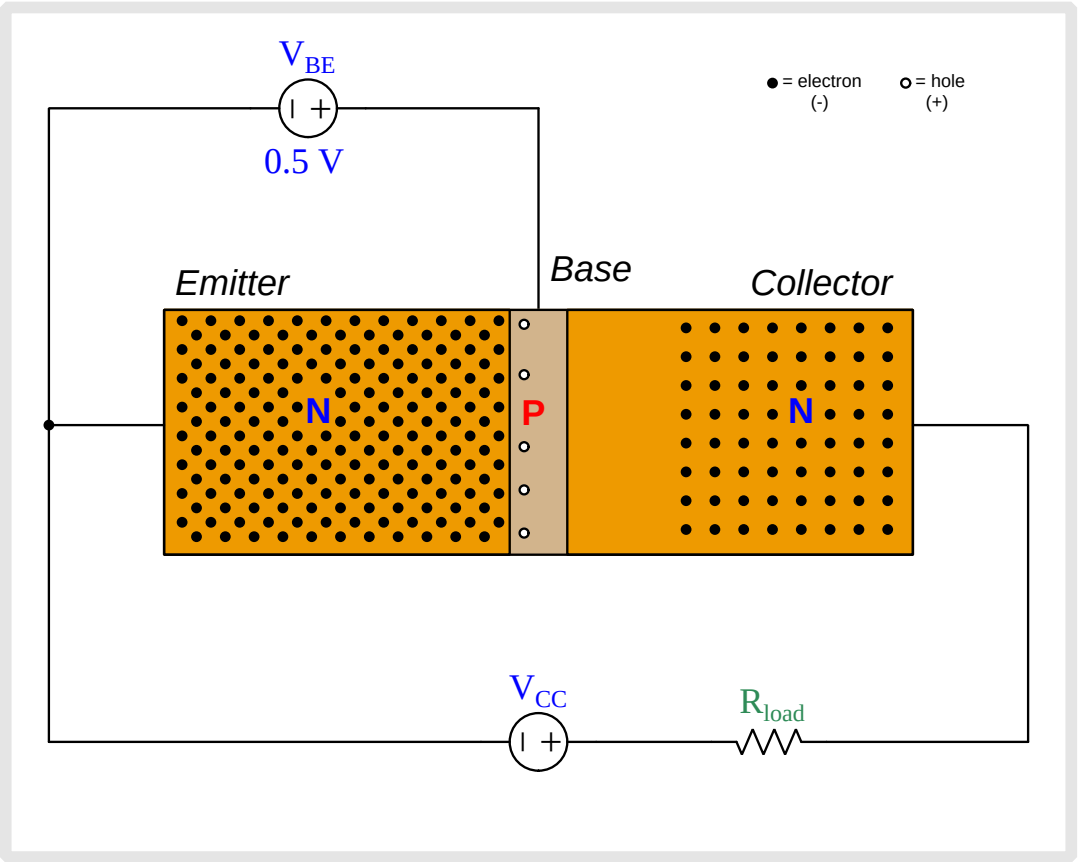

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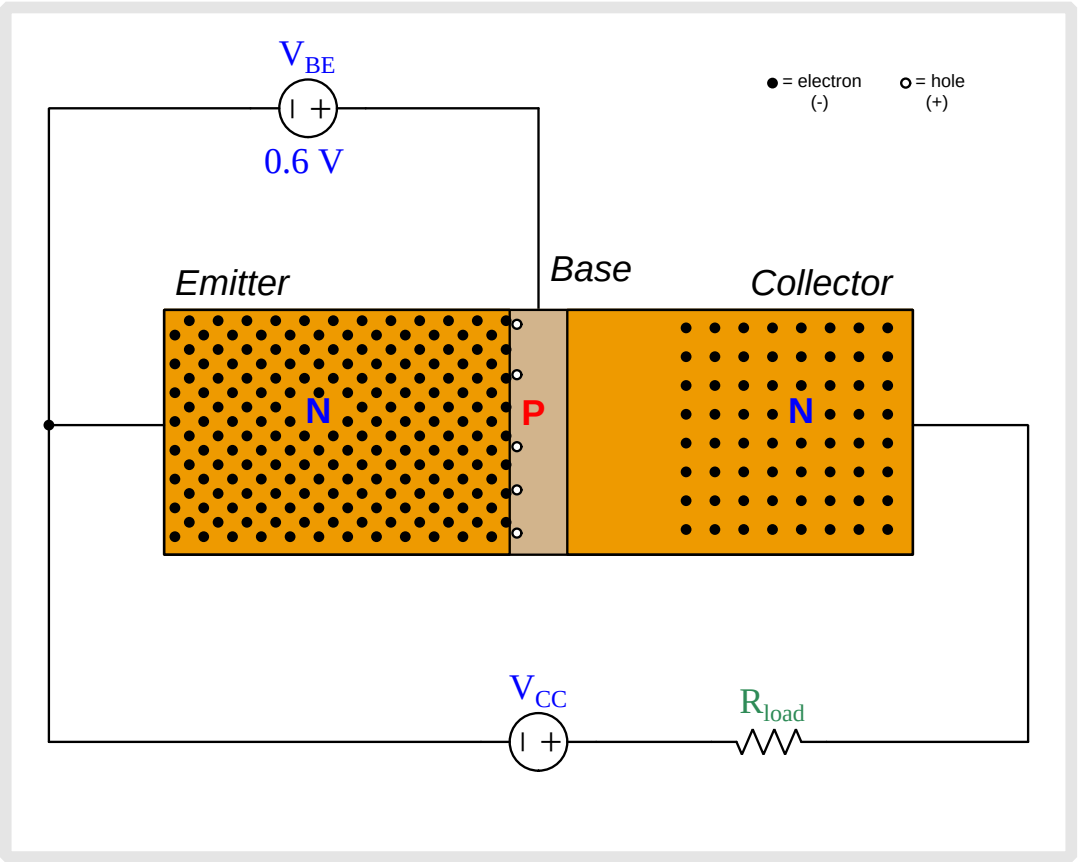

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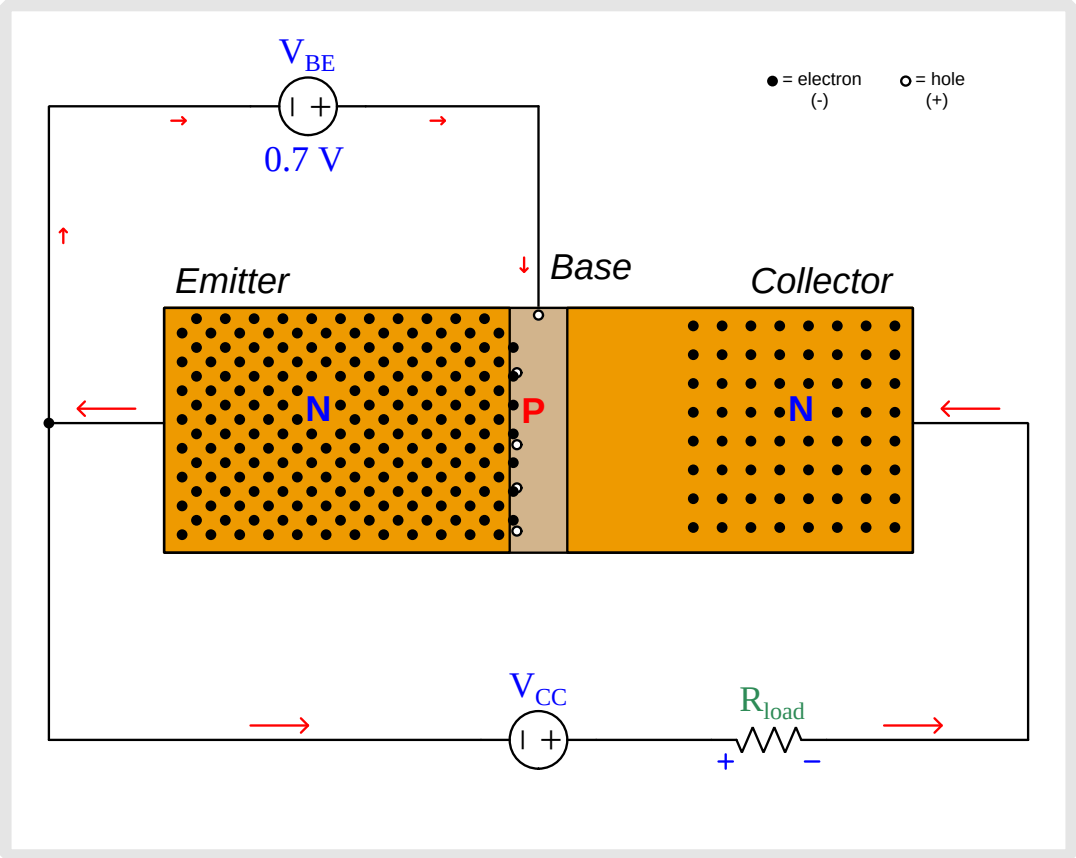
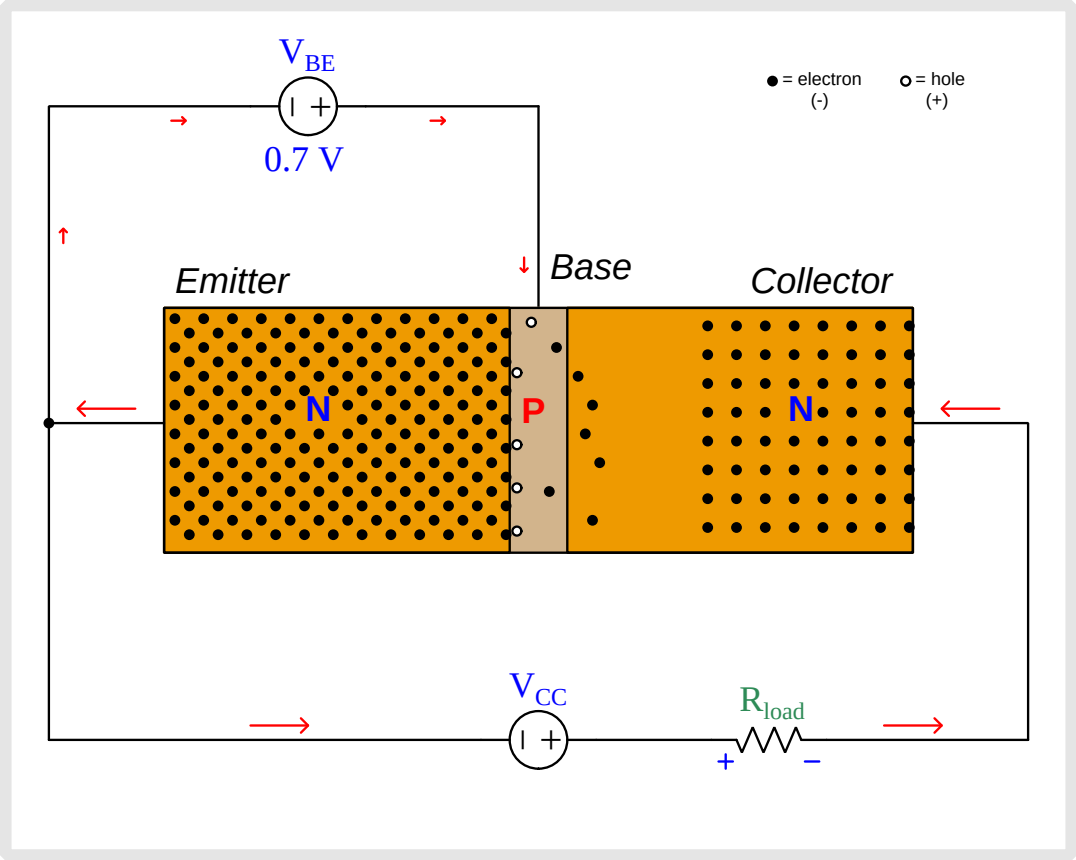
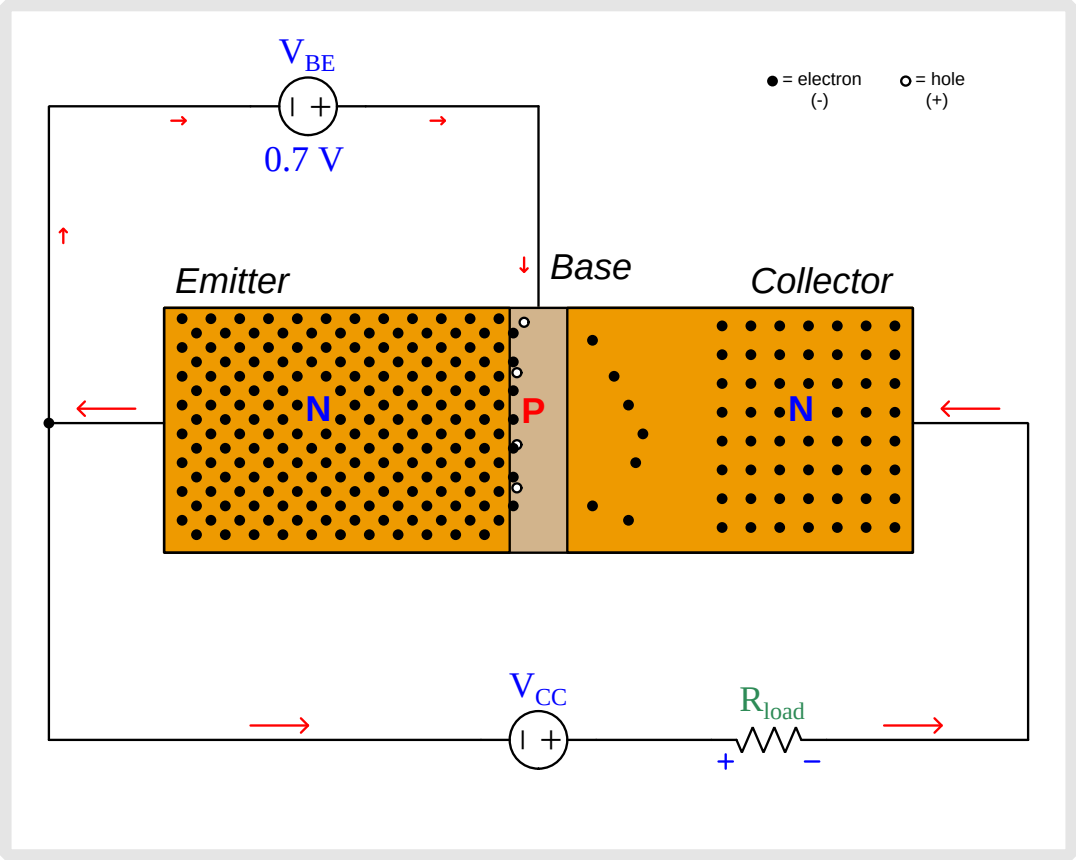


Now there is enough base-to-emitter voltage to fully collapse the base-emitter depletion region which allows base current to flow through the V_{BE} source. New holes enter into the base region from the base terminal to replenish any holes that have "re-combined" with electrons from the emitter region. Most of the emitter-injected electrons do *not* combine with holes, though, because the lightly-doped base region provides few holes to combine with. Therefore, most of the electrons injected into the base region from the emitter region begin to drift toward the collector.



The electric field imposed by V_{CC} across the base-collector PN junction quickly "sweeps" electrons toward the collector terminal, constituting current through the load resistor. A small number of electrons injected into the base "recombined" with holes there to constitute base current rather than collector current.



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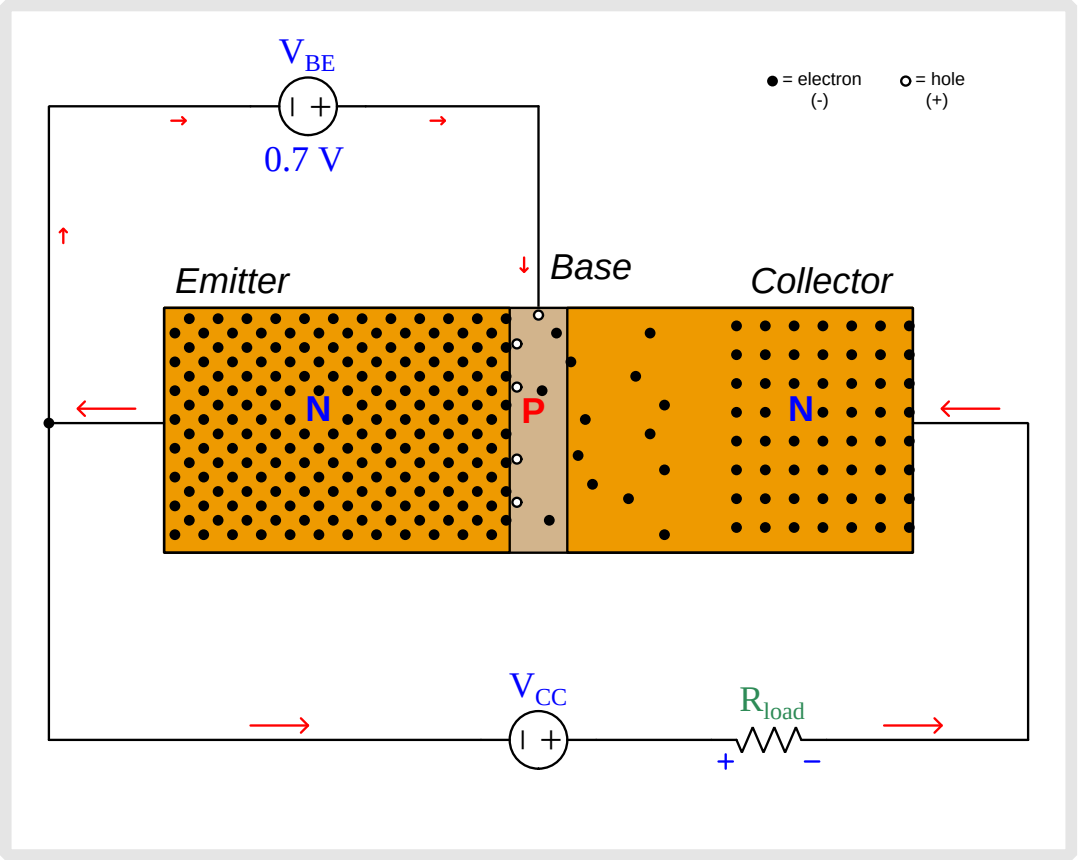

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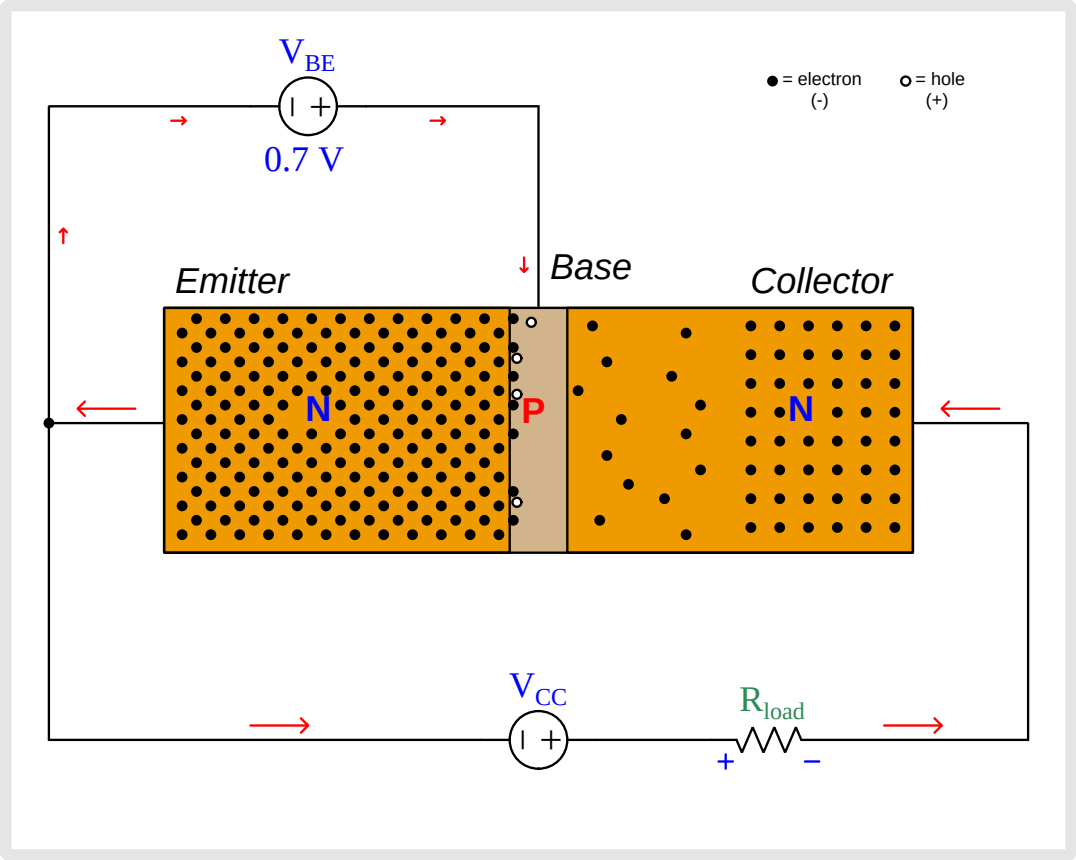

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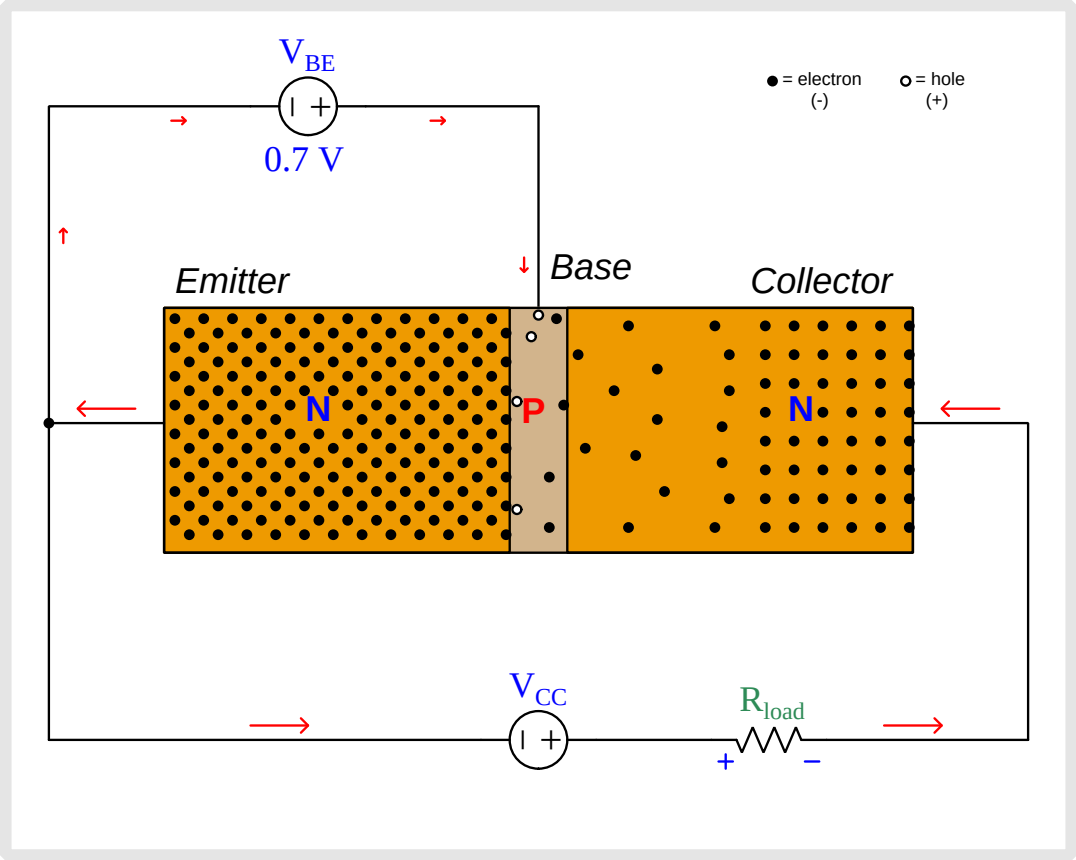
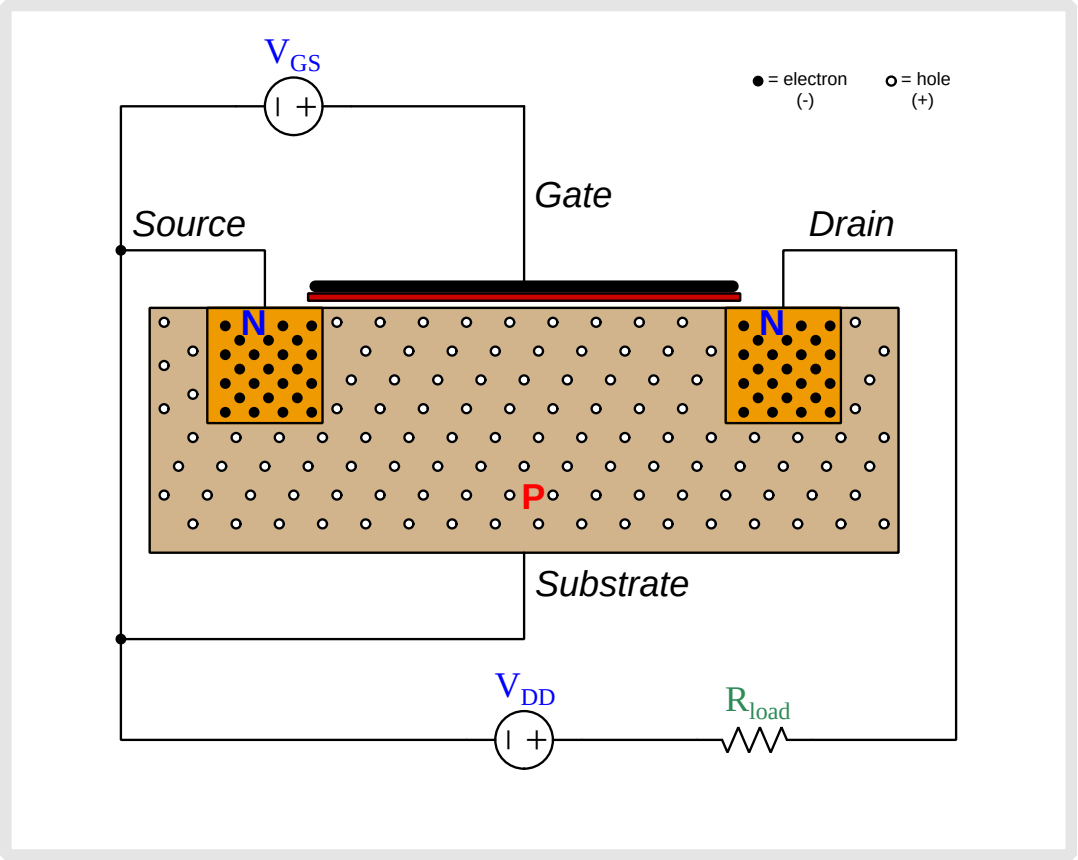


The electric field imposed by V_{CC} across the base-collector PN junction quickly "sweeps" electrons toward the collector terminal, constituting current through the load resistor. A small number of electrons injected into the base "recombined" with holes there to constitute base current rather than collector current.

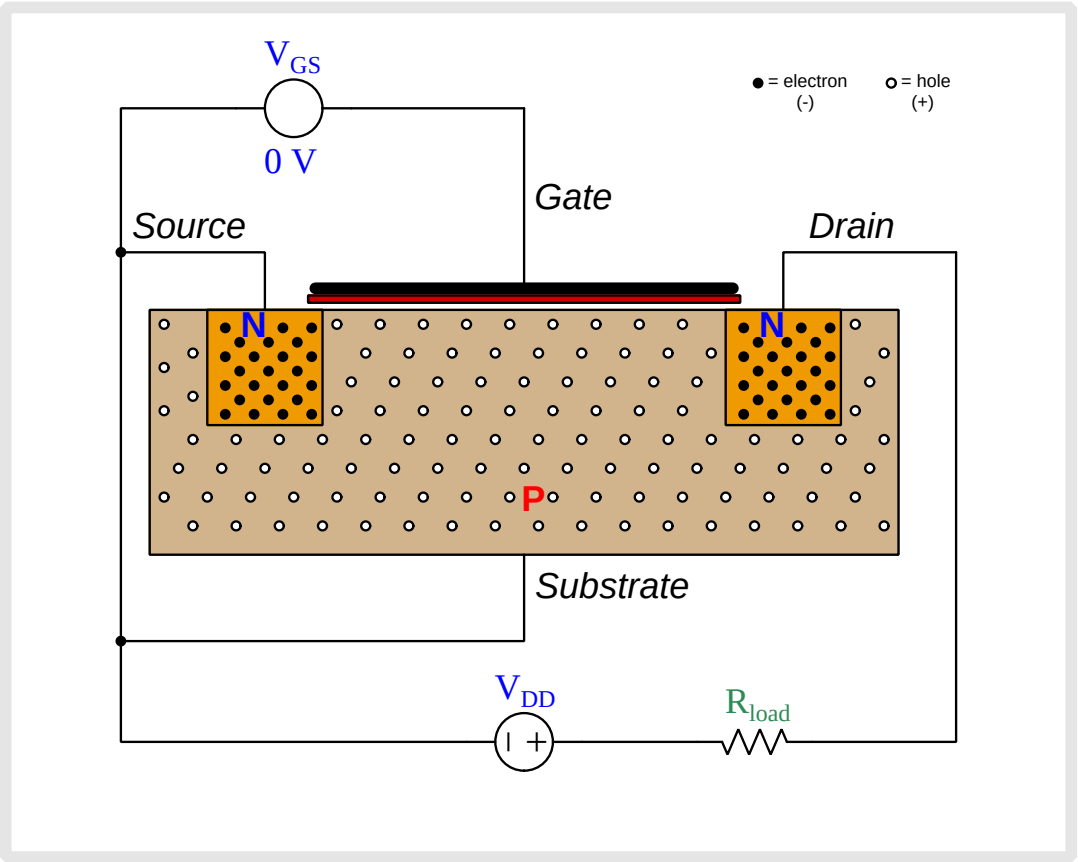
5.3 Animation of an E-type MOSFET turning on

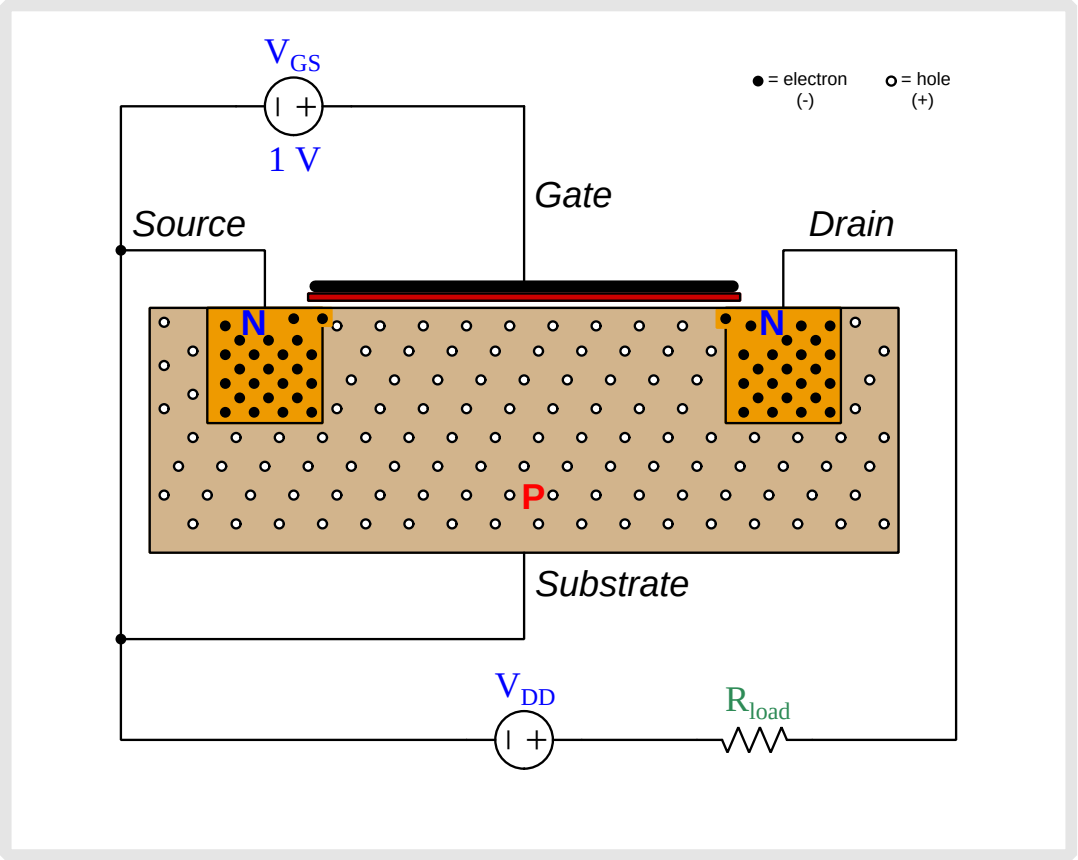
Enhancement-type (E-type) MOSFET transistors are naturally "off" devices, having no continuous channel of conductive semiconductor material joining source and drain by default the way D-type MOSFETs do. Instead the substrate semiconductor material, which is doped oppositely of the source and drain regions, interrupts that path with two series-opposed PN junctions. However, when a transverse electric field is applied between gate and substrate by an external voltage source, the surface-layer of the substrate in direct contact with the insulating metal-oxide layer converts to the opposite type of semiconductor. For an N-channel MOSFET with N-doped source and drain regions and with P-doped substrate, this means the surface of the P-doped substrate just beneath the gate effectively turns into N-type by the force of the electric field drawing free electrons from source and drain (and a few minority electrons existing within the substrate) to that surface region to form a thin film of free electrons capable of supporting source-drain conduction.



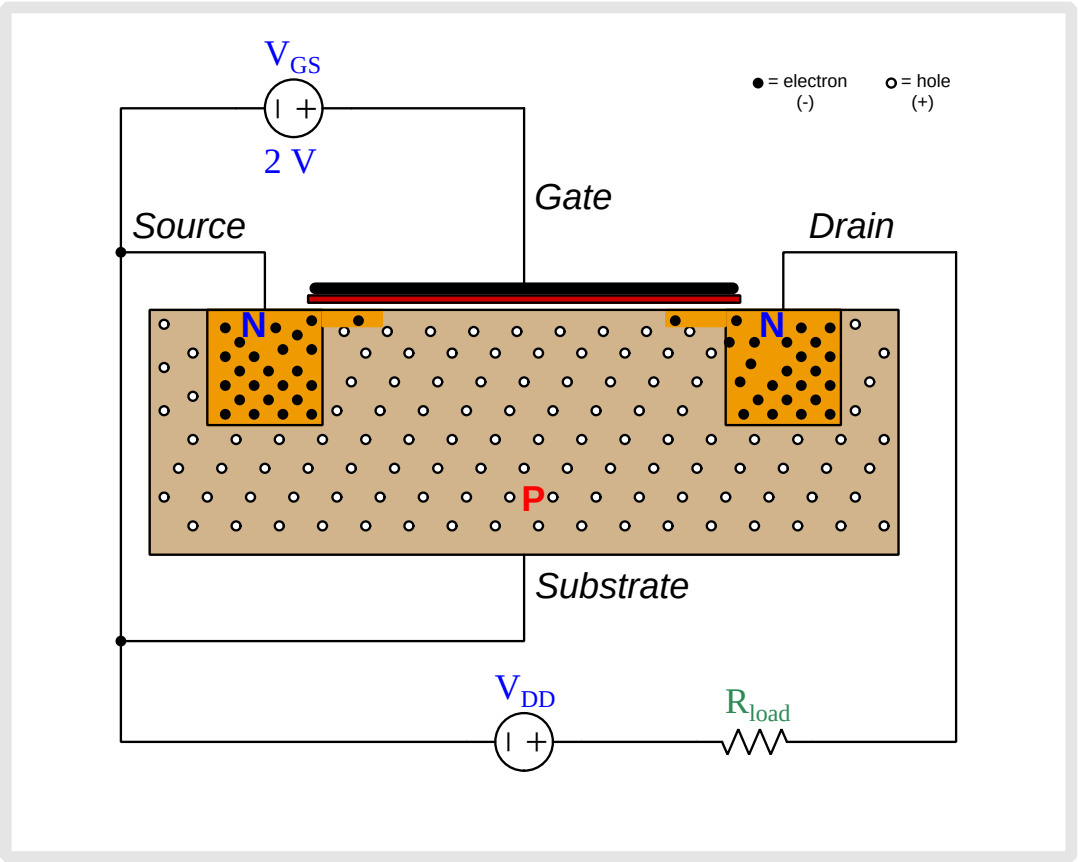
Above we see an N-channel, E-type MOSFET connected to two sources. V_{GS} applies a controlling voltage between the gate and the substrate, with the substrate connected to the source terminal to be one and the same. V_{DD} is the voltage source which will drive current through the load resistor once the transistor begins to conduct.

The N-doped source and drain regions have numerous free electrons (negatively-charged) as mobile charge carriers, while the P-doped substrate has holes (positively-charged). Note that when load current begins to flow, its direction will be shown in *conventional flow notation* which is the same direction in which holes move but is opposite to the direction free electrons move.

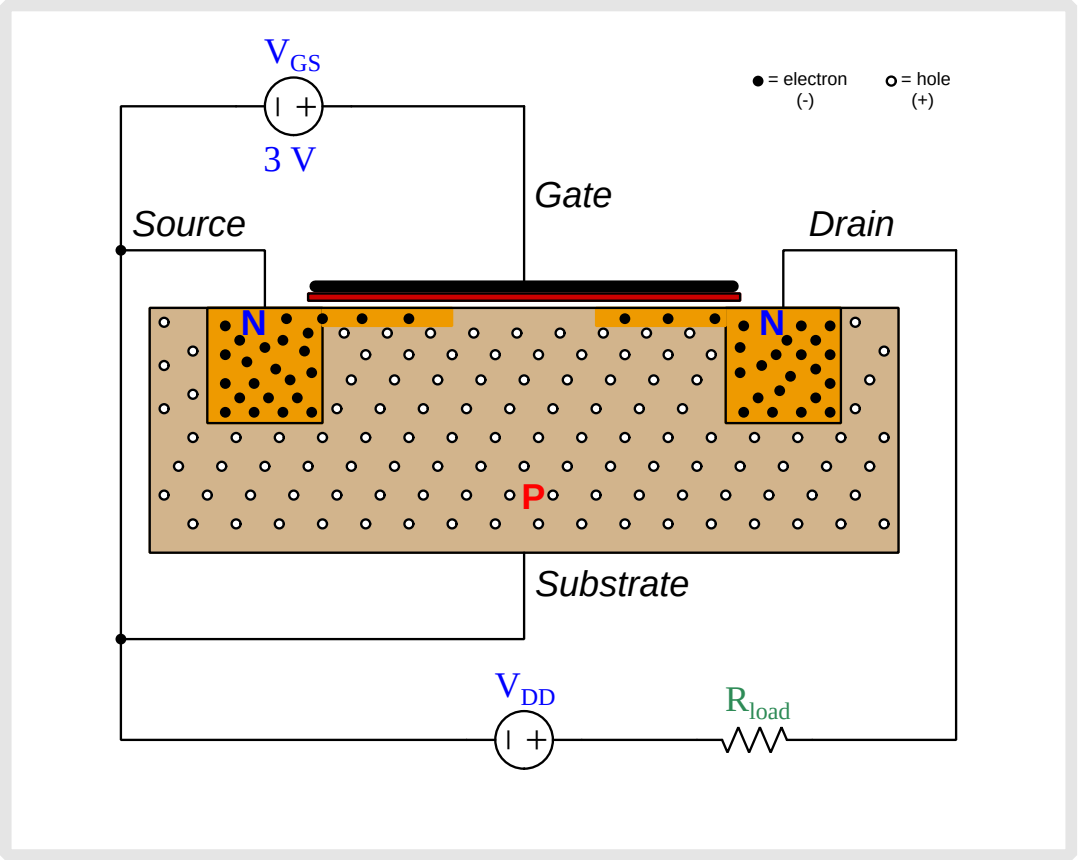

V_GS
0 V
● = electron (-)
○ = hole (+)
Gate
Source
Drain
N
N
P
Substrate
V_DD
R_load



As we begin to apply a gate-to-substrate voltage with the gate positive and substrate negative, negatively-charged free electrons from the source and drain regions are attracted toward the metal gate while positively-charged holes in the substrate are repelled from the gate and driven downward.



As this V_{GS} voltage increases, a thin film of free electrons begins to form beneath the gate, effectively turning what used to be P-type semiconductor material into N-type. This is called an *inversion layer*.



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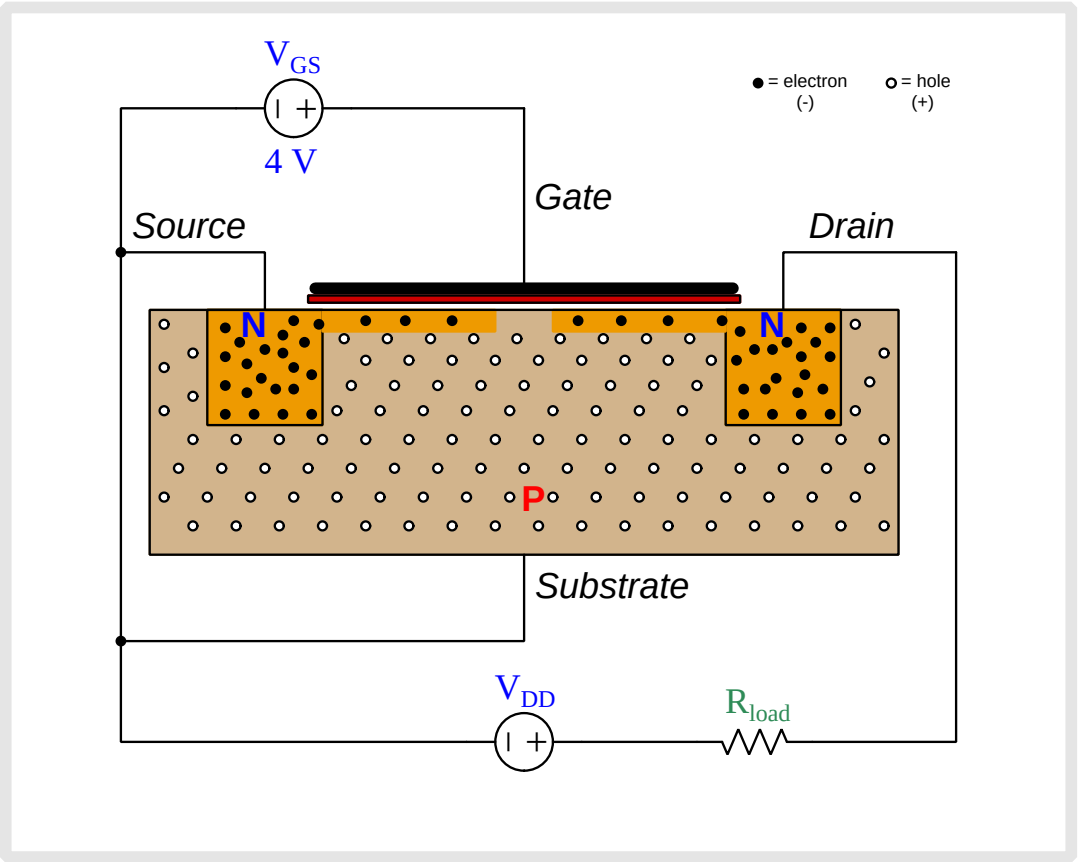

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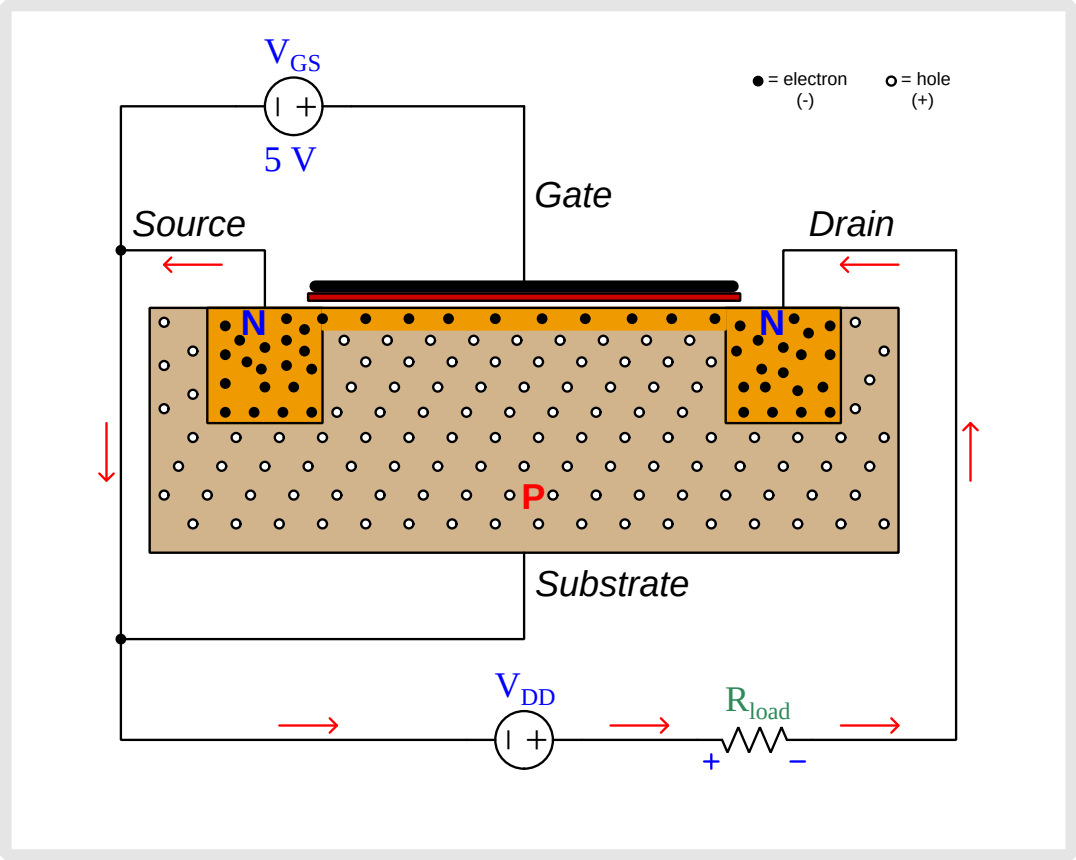
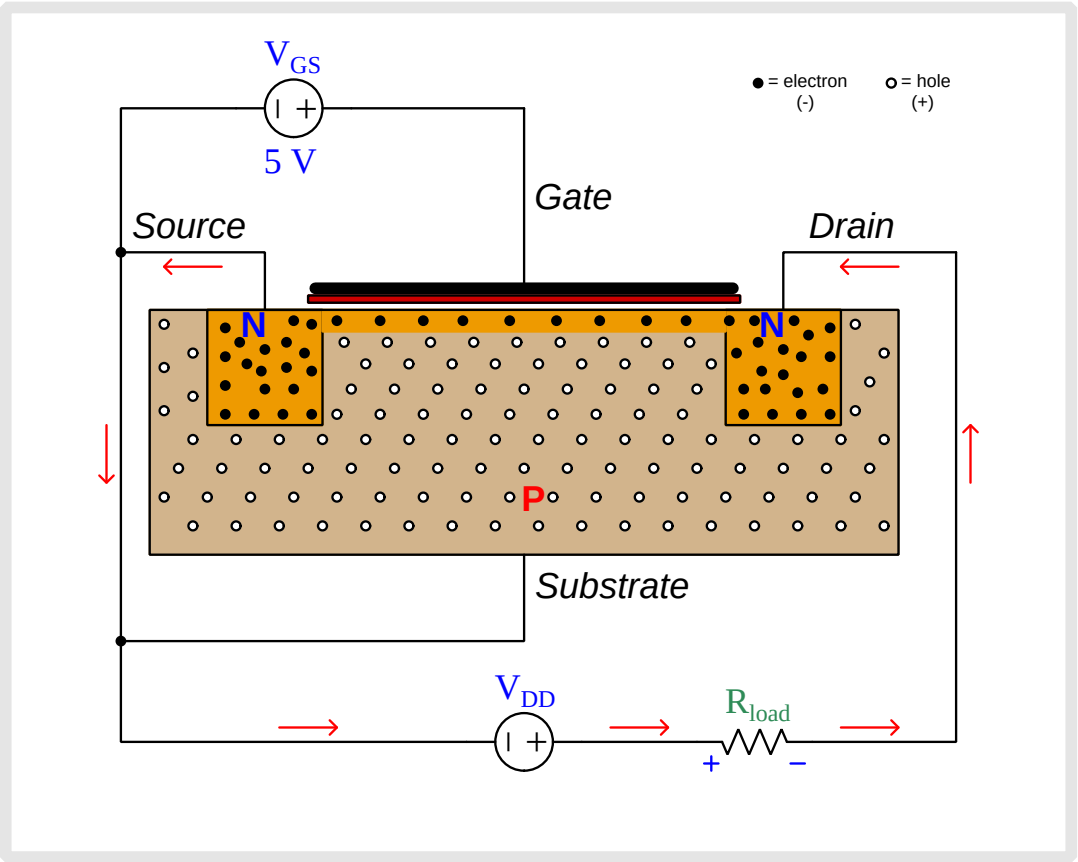
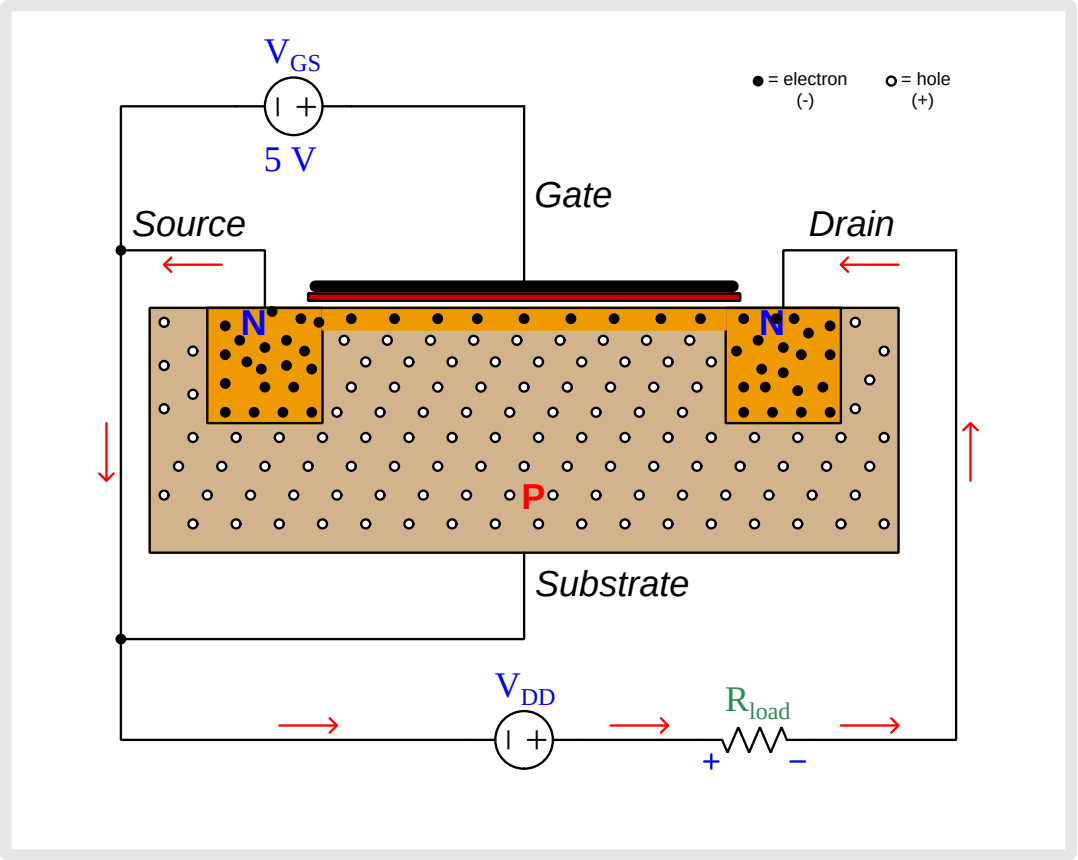


Once V_{GS} reaches the threshold or "turn-on" level, this inversion layer completely connects drain and source to form a new N-type channel permitting conduction between source and drain. The V_{DD} source is now able to promote a current through the MOSFET.



Note how the mobile charge carriers within the inversion layer are electrons, which flow opposite the direction of "conventional flow" as notated by the red arrows. Notice also how new electrons enter the inversion layer from the source region of the MOSFET, which is why that region is so-named (because that is the "source" of fresh charge carriers entering the inversion layer).



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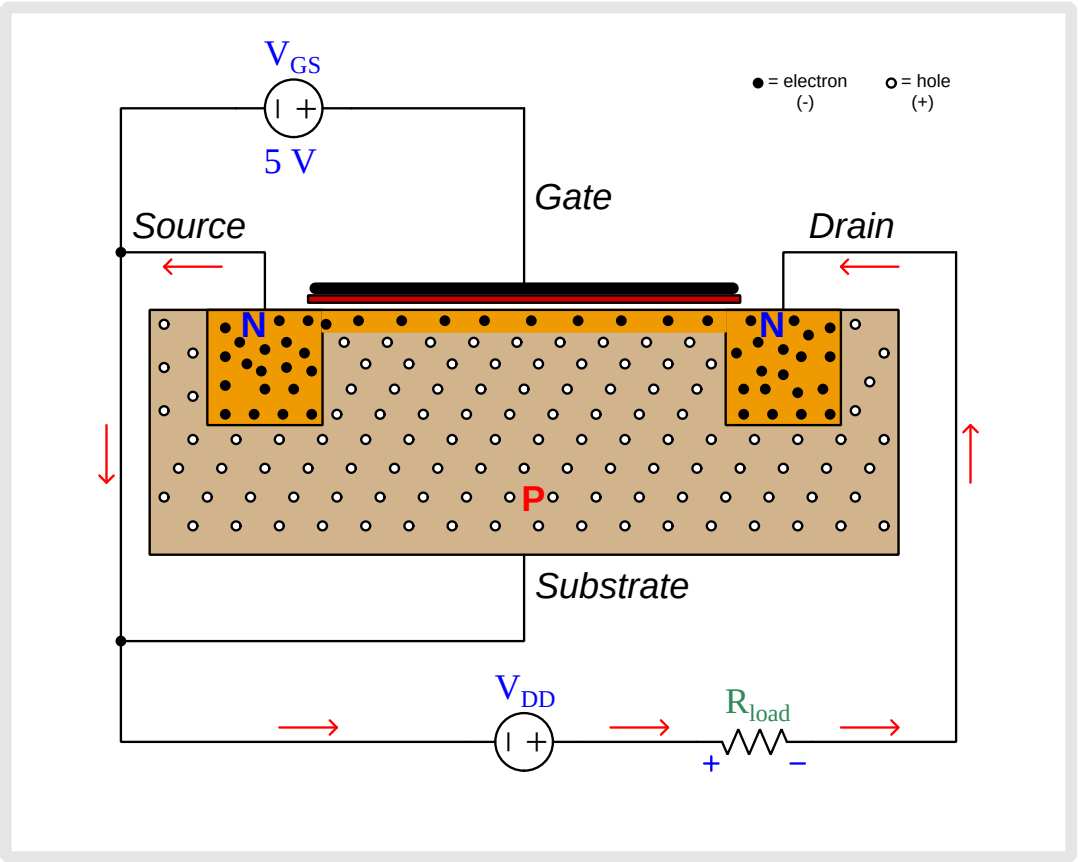

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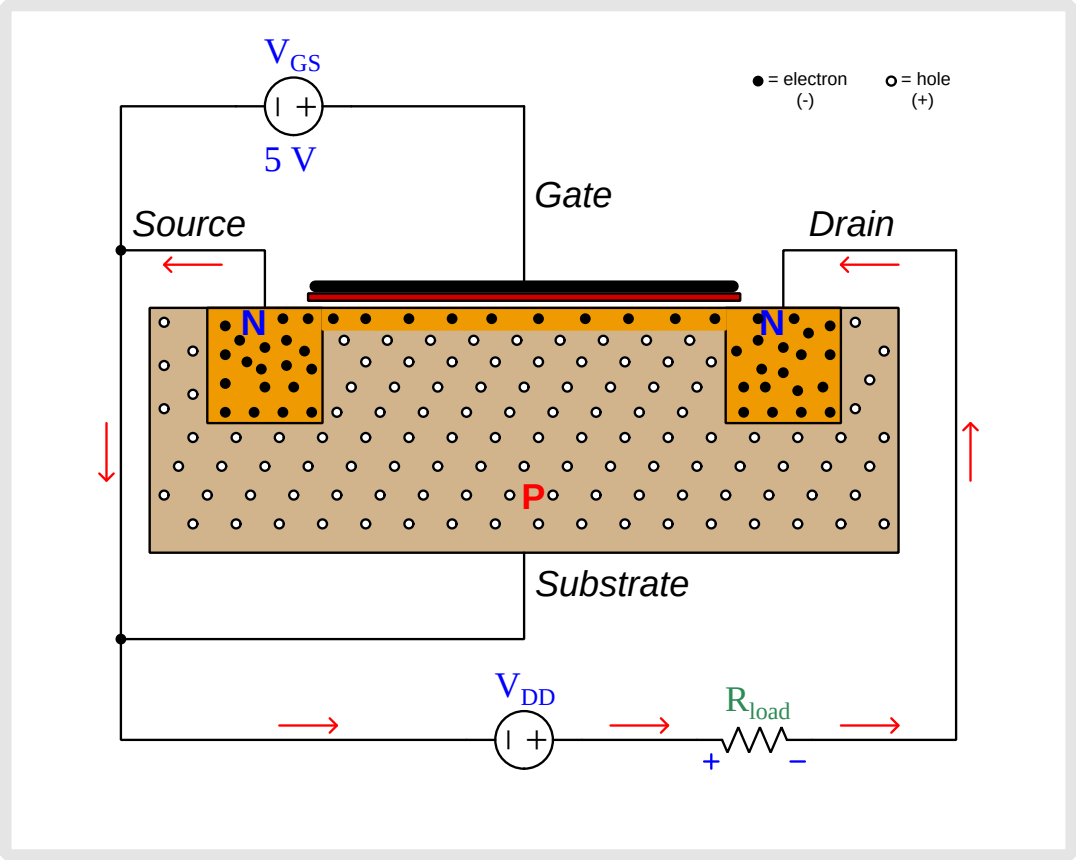

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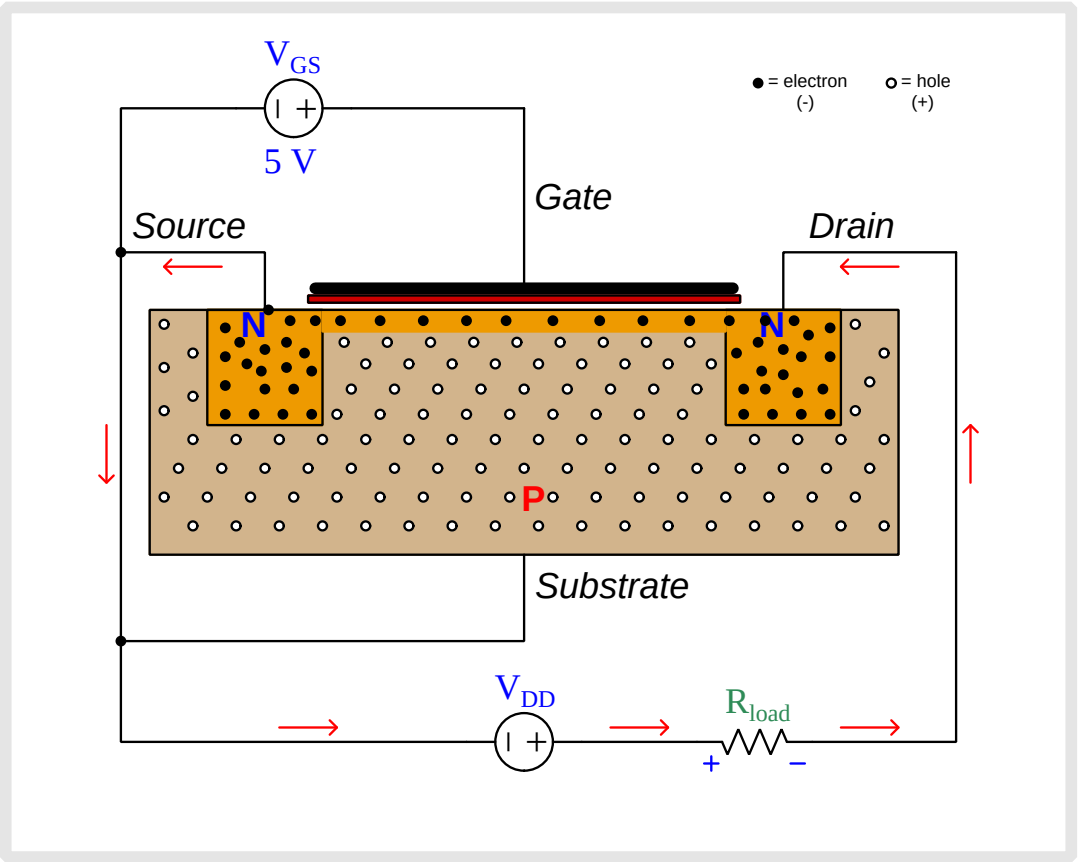

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Chapter 6

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

6.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

6.1.1 Reading outline and reflections

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

6.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Energy

Thought experiments as a problem-solving strategy

Direct Current (DC)

Alternating Current (AC)

Frequency

Electrical source

Electrical load

Energy conversion

Rectification

Diode

Amplification

Multivibrator

BJT principles

FET principles

Bridge network

Logic state

NOT function

Transformer

Hysteresis

Positive feedback

Capacitance

Inductance

Commutation

Thyristor

Comparator

Periodic

Fundamental frequency

Harmonic frequency

Sinusoidal decomposition (i.e. Fourier's Theorem)

Inverter

Pulse-Width Modulation (PWM)

Duty cycle

V/F ratio

Noise

Capacitive coupling

Inductive coupling

6.1.3 Bright/Royer self-excited inverter circuits

Examine the schematic diagrams of Figures 1, 4, and 5 in the "Example: inverter circuits from the Bright/Royer 1957 patent" section of the *Case Tutorial* chapter of this module and answer the following questions:

- Identify the DC power source(s)
- Identify any DC bias source(s), if any
- Identify how the circuit begins to oscillate
- Trace all circuit currents when the upper transistor is conducting
- Trace all circuit currents when the lower transistor is conducting

Challenges

- Identify transformer "dot" polarity mark placement to make the upper AC output terminal positive and the lower AC output terminal negative when the upper transistor is conducting.
- Identify what would have to be altered to make each of these circuits function properly using the opposite type of bipolar junction transistor.
- Are these circuits wired to give the transistors positive feedback, or negative feedback?

6.1.4 Bright/Royer externally-excited inverter circuits

Examine the schematic diagrams of Figures 6, 7, and 8 in the "Example: inverter circuits from the Bright/Royer 1957 patent" section of the *Case Tutorial* chapter of this module and answer the following questions:

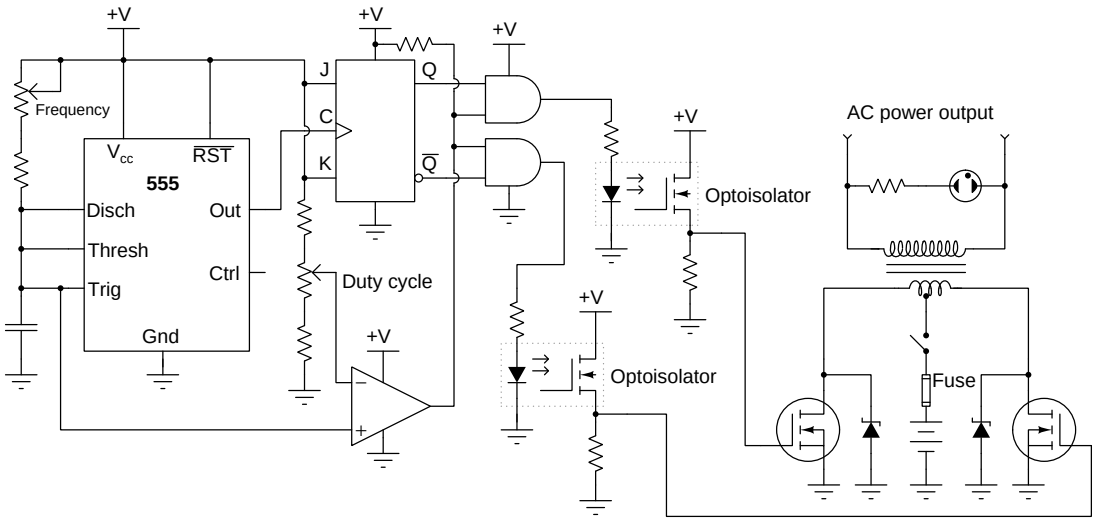
- Identify the DC power source(s)
- Identify the AC output transformer
- Annotate the diagram to show where the AC load would connect to this circuit
- Identify the excitation input transformer
- Annotate the diagram to show where the AC signal (excitation) source would connect to this circuit
- Trace all circuit currents when the upper transistor is conducting
- Trace all circuit currents when the lower transistor is conducting

Challenges

- Identify what would have to be altered to make each of these circuits function properly using the opposite type of bipolar junction transistor.
- Explain why no feedback is necessary for the power transistors in any of these circuits.

6.1.5 555-based inverter circuit

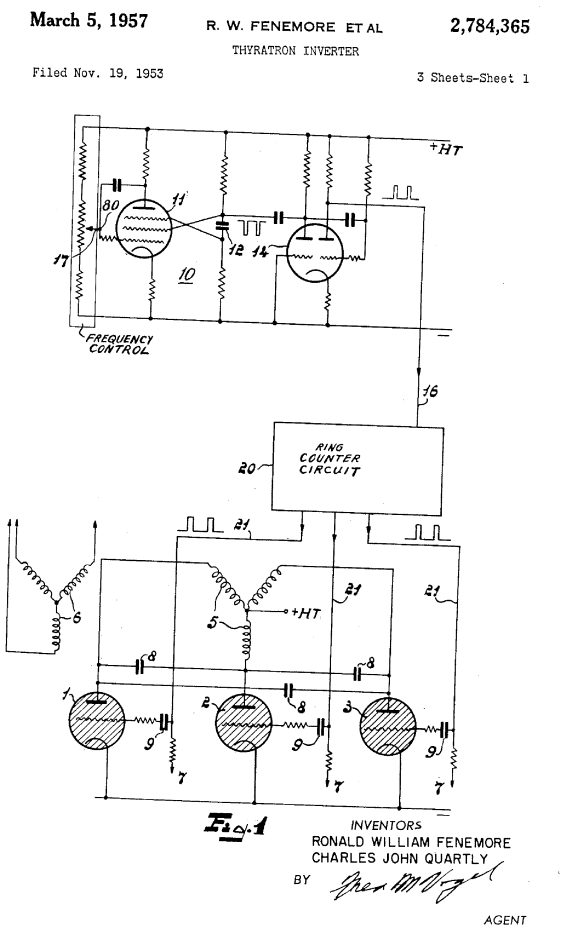
Examine the schematic diagram for the following DC-AC inverter circuit and explain how it functions:



- Identify the effect on the AC output voltage if the duty cycle wiper moves up.

6.1.6 Early three-phase inverter design

The following diagram comes from a United States patent (number 2,784,365 granted 5 March 1957) submitted by inventors Ronald William Fenemore and Charles John Quartly of England, illustrating a circuit designed in invert DC into three-phase AC. This design uses *thyratron* gas tubes (components 1, 2, and 3 in the schematic) which function similar to SCRs:



Study this diagram, then answer the following questions:

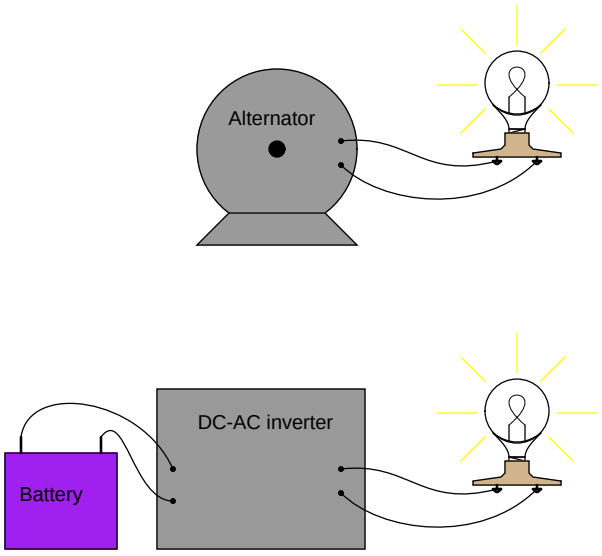
- Where should the three-phase load connect to this inverter circuit?
- How is proper three-phase sequencing ensured, so that there is a definite phase rotation in the power delivered to the load?
- Explain how you would design/build a "Ring Counter Circuit" for an inverter circuit such as this.

Challenges

- What is the purpose of the three capacitors labeled (8) in this circuit?

6.1.7 Voltmeter discrepancy

An electromechanical alternator (AC generator) and a DC-AC inverter both output the same RMS voltage, and deliver the same amount of electrical power to two identical loads:



When the AC load voltage is measured in these two circuits using a True-RMS digital multimeter, they read as equal amounts of voltage. However, when measured by an analog voltmeter the inverter's output voltage is slightly greater than the alternator's output voltage. Explain this discrepancy in measurements.

Can you think of any test we might perform on these two circuits that would shed more light on this problem?

Challenges

- Explain what *crest factor* means for an AC waveform.
- Explain what *form factor* means for an AC waveform.

6.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

6.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

6.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[7] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

[10] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

6.2.3 Converter efficiency

Suppose a DC-AC inverter has a conversion efficiency of 85%. Calculate the input (DC) power to this inverter as well as its thermal power dissipation, as it continuously delivers 1200 Watts to a load.

Also, sketch a simple block diagram showing all the power inputs and outputs (shown as arrows) for the converter circuit.

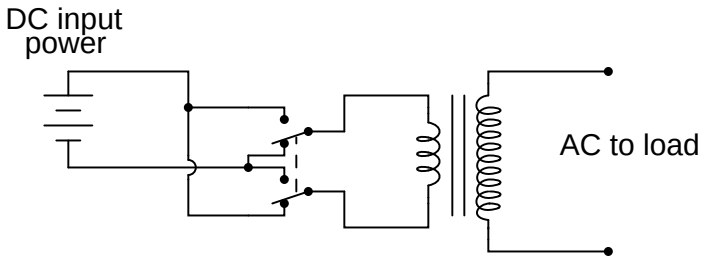
If this same DC-AC converter happens to draw 850 Watts from a source while operating at 82% efficiency, how much power will it be delivering to a load, and how much power will it dissipate in the form of heat?

Challenges

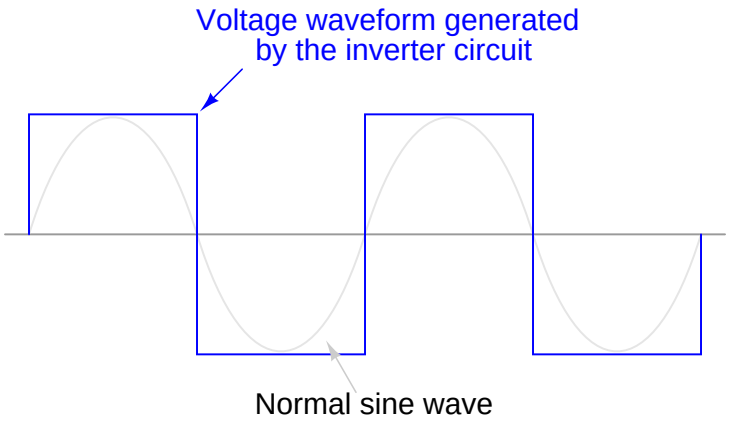
- Explain how the *Conservation of Energy* relates to this problem.
- Identify practical ways to maximize the efficiency of any solid-state power converter circuit.

6.2.4 Modified duty cycle

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:

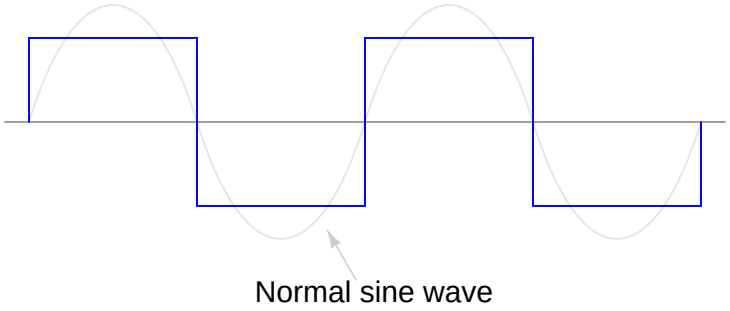


The first commercially available inverters produced simple square-wave output:

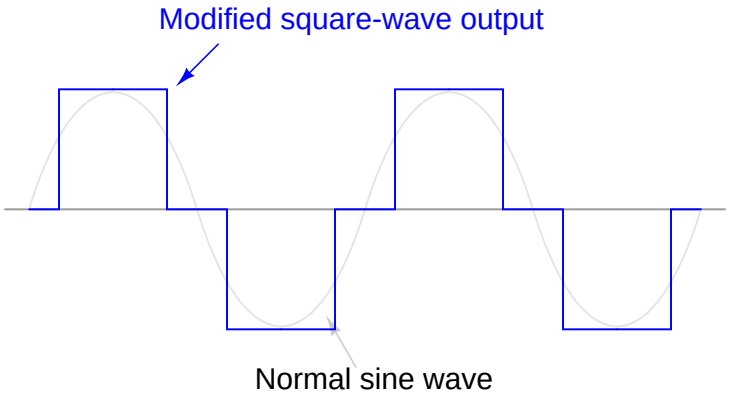


However, this caused problems for most power transformers designed to operate on sine-wave AC power. When powered by the square-wave output of such an inverter, most transformers would *saturate* due to excessive magnetic flux accumulating in the core at certain points of the waveform's cycle. To describe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

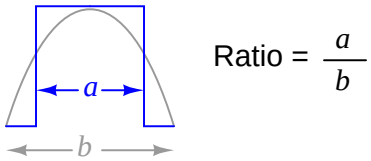
This problem could be avoided by decreasing the peak voltage of the square wave, but then some types of powered equipment would experience difficulty due to insufficient (maximum) voltage:



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 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.

Challenges

- Design a circuit that would produce this waveform.

6.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

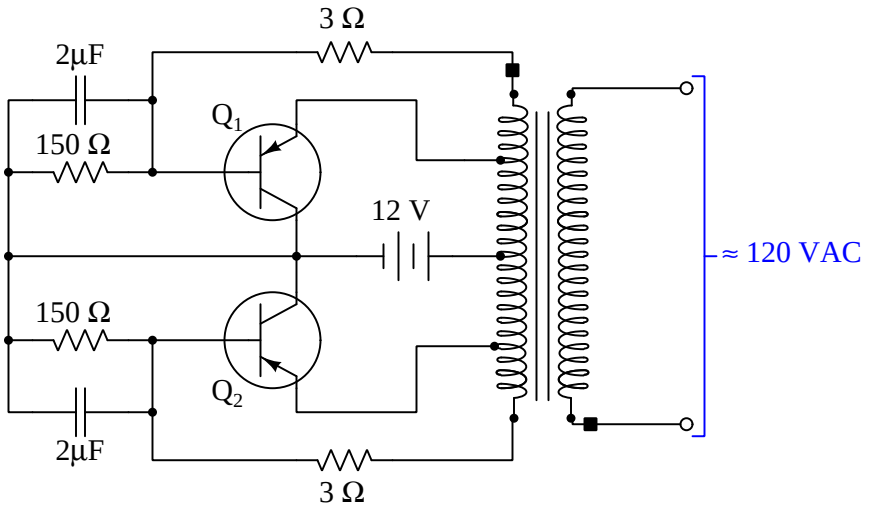
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

6.3.1 Tracing fault current

Suppose transistor Q_1 has failed shorted between its collector and emitter terminals in this DC-AC inverter circuit. Trace the direction of the fault current when the DC power is first applied, and also determine the polarity of the output voltage during that initial power-up period:

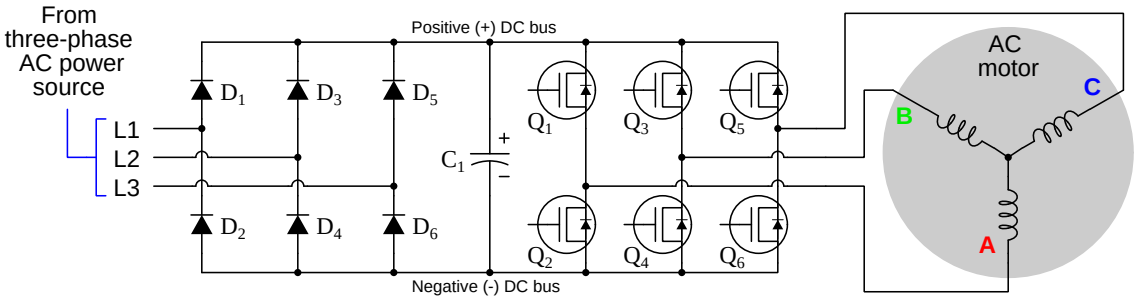


Challenges

- What do the solid-colored square symbols represent by each of the transformer windings?
- Re-design this circuit to include some overcurrent protection against faults such as this.

6.3.2 Faults in a VFD circuit

The following schematic diagram shows the power components for a *VFD*, a special-purpose converter circuit designed to take AC power at a fixed frequency and fixed voltage and convert it into AC power at variable frequency and variable voltage. All control circuitry (e.g. the circuits generating the pulse signals to send to the transistor gates) has been omitted for simplicity:



- Identify the effect(s) of diode D_3 failing open
- Identify the effect(s) of diode D_4 failing shorted
- How many diodes could fail open and still allow the motor to run at all?
- Identify the effect(s) of transistor Q_5 failing open
- Identify the effect(s) of transistor Q_1 failing shorted

Challenges

- Explain the operating principle of a VFD: what must be done to alter the rotational speed of a three-phase AC induction motor?
- What type of transistor would you recommend for this application, and why?

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

References

Bright, Richard L. and Royer, George H. *US Patent 2,783,384*, "Electrical Inverter Circuits", application 6 April 1954, patent granted 26 February 1957.

Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

8 April 2026 – typographical error correction courtesy of Caleb Wing.

18 November 2025 – added a new Tutorial section on three-phase inverter circuits, corrected a mis-spelling, and capitalized the word "Zener" in one instance.

3 November 2025 – corrected a typographical error (used the word "in" rather than "to"), courtesy of Elijah Ross.

4 November 2024 – added two new animations to the module: one showing a BJT turning on and the other showing an E-type MOSFET turning on.

25 October 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors.

4 April 2024 – minor grammatical correction to the Tutorial chapter regarding thyristor forced commutation.

6 November 2023 – clarified which Case Tutorial section to reference in the "Bright/Royer externally-excited inverter circuits" Conceptual Reasoning question.

24 April 2023 – added a new Case Tutorial section showing a proof-of-concept DC-AC inverter circuit using Schmitt-trigger NOT gates.

10 April 2023 – corrected minor typo in "Voltmeter discrepancy" Conceptual Reasoning question.

28 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

8 November 2021 – fixed an error in the "Tracing fault current" Diagnostic Reasoning question, a mismatch between the fault scenario proposed to the student in the question and the answer shown to the instructor. It was easier to change the question than to change the answer, so now it asks what happens if Q_1 fails shorted (instead of Q_2).

13 May 2021 – divided the Tutorial into sections. Also added review_10.latex to the Tutorial to give students a refresher on transistor operation.

9 May 2021 – commented out or deleted empty chapters.

18 April 2021 – changed all lower-case Greek letter "phi" symbols (ϕ) to upper-case (Φ).

6 April 2021 – added a Case Tutorial section showing a sine-wave inverter based on the Texas Instruments MSP430 microcontroller.

5 April 2021 – minor edits to the "Bright/Royer externally-excited inverter circuits" Conceptual Reasoning question.

1 April 2021 – minor edits to the Tutorial regarding "soft" magnetic materials, and also to some of the questions.

27 March 2021 – minor edits to the Tutorial regarding optical isolation, to eliminate any implication that this hardware technique might be limited to PWM applications.

11 November 2020 – added instructor notes to the "Example: inverter circuits from the Bright/Royer 1957 patent" Case Tutorial section describing in detail how the self-oscillating circuits work.

9 November 2020 – clarified the "Bright/Royer self-excited inverter circuits" Conceptual question, where it was assumed there was only one section in the Case Tutorial chapter. Also, added some instructor comments to that Case Tutorial section, and a Challenge question to the "Early three-phase inverter design" Conceptual question.

7-8 November 2020 – added labels to several components in several schematic diagrams that were unlabeled. Also added resistors to image_4611.eps that serve to limit base current through the power transistors.

5 November 2020 – minor edits to the Tutorial and to the Introduction, and some Challenge questions added. Also fixed typographical error identified by Ty Weich. Lastly, corrected a major error in the MOSFET H-bridge circuit diagram where I had the wrong transistor channel-types on the high and low sides of the H-bridge.

2 November 2020 – added mention of optoisolators to Tutorial. Also, added a Case Tutorial section showing the 555-based inverter circuit I designed in 2006.

13 October 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

8-9 July 2020 – added content to Tutorial.

7 July 2020 – document first created.

Index

AC, 17
Adding quantities to a qualitative problem, 120
Alternating current, 17
Amplification, 19
Annotating diagrams, 119

B-H curve, 18
Base, 20
Bipolar, 20
Bipolar junction transistor, 19
BJT, 19

Capacitive coupling, 29
Cassier's Magazine, 18
Charge carrier injection, BJT, 20
Checking for exceptions, 120
Checking your work, 120
Clock pulse, 24
Code, computer, 129
Collector, 20
Commutation, SCR, 27
Coupling, 29

DC, 17
Dimensional analysis, 119
Diode, 18
Direct current, 17
Drain, 21
Drive, variable frequency, 28

Edwards, Tim, 130
Emitter, 20

FET, 19
Field-effect transistor, 19
Forced commutation, 27
Fundamental, 29

Gate, 21
Graph values to solve a problem, 120
Greenleaf, Cynthia, 93

H-bridge circuit, 25
Harmonic, 29
How to teach with these modules, 127
Hwang, Andrew D., 131
Hysteresis, magnetic, 18

Identify given data, 119
Identify relevant principles, 119
Induction motor, 28
Inductive coupling, 29
Injection, charge carriers in BJT, 20
Insulated-gate field effect transistor, 21
Integrated circuit, 31
Intermediate results, 119
Inversion layer, 84
Inverted instruction, 127
Inverter, 3

JFET, 21
Junction field-effect transistor, 21

Knuth, Donald, 130

Lamport, Leslie, 130
LASCR, 31
LED, 31
Light-activated thyristor, 31
Limiting cases, 120

Magnetic hysteresis, 18
Maxwell, James Clerk, 33
Metacognition, 98
Metal-oxide-semiconductor field-effect transistor, 21

Moolenaar, Bram, 129
MOSFET, 21
Motor, induction, 28
Multivibrator, 24
Murphy, Lynn, 93

Noise, 29

Open-source, 129
Optocoupler, 31
Oscillator, 24

Phototransistor, 31
Photovoltaic panel, 17
Pinch-off voltage, 19
Problem-solving: annotate diagrams, 119
Problem-solving: check for exceptions, 120
Problem-solving: checking work, 120
Problem-solving: dimensional analysis, 119
Problem-solving: graph values, 120
Problem-solving: identify given data, 119
Problem-solving: identify relevant principles, 119
Problem-solving: interpret intermediate results, 119
Problem-solving: limiting cases, 120
Problem-solving: qualitative to quantitative, 120
Problem-solving: quantitative to qualitative, 120
Problem-solving: reductio ad absurdum, 120
Problem-solving: simplify the system, 119
Problem-solving: thought experiment, 28, 119
Problem-solving: track units of measurement, 119
Problem-solving: visually represent the system, 119
Problem-solving: work in reverse, 120

Qualitatively approaching a quantitative problem, 120

Reading Apprenticeship, 93
Rectifier, 18
Reductio ad absurdum, 120, 126, 127
Rotary converter, 18

Schoenbach, Ruth, 93
Scientific method, 98
Simplifying a system, 119
Socrates, 126
Socratic dialogue, 127
Soft magnetic material, 18
Solar panel, 17
Source, 21
SPICE, 93
Stage, 26
Stallman, Richard, 129

Thought experiment, 28, 119
Torvalds, Linus, 129
Transistor, 18
Turn-on voltage, 19

Units of measurement, 119

Variable frequency motor drive, 28
Variable-frequency AC motor drive, 31
VFD, 28, 31
Visualizing a system, 119
Voltage, pinch-off, 19
Voltage, turn-on, 19
Volts-per-Hertz ratio, 31

Work in reverse to solve a problem, 120
WYSIWYG, 129, 130