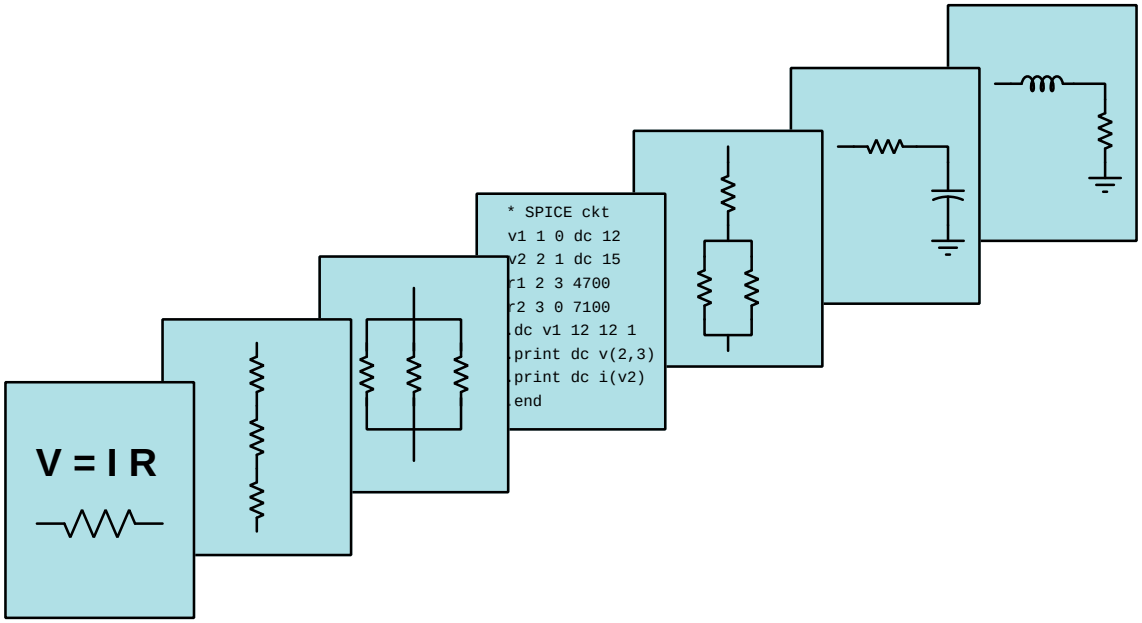
Modular Electronics Learning (ModEL) project



Efficiency and Power Factor

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Chapter 1

Introduction

1.1 Recommendations for students

The way in which energy is exchanged between components in an electric power system, especially alternating current (AC) electric power circuits, can be quite confusing. Two related but distinct topics – *efficiency* and *power factor* – are treated together in this module. Although these two concepts are quite distinct from each other, they are often incorrectly conflated, sometimes even treated as one and the same. By exploring these two concepts in the same module, and by demonstrating that they represent two entirely different concepts regarding energy exchange in AC circuits, the hope is that this confusion may averted.

Important concepts related to efficiency and power factor include the **Conservation of Energy**, the **First and Second Laws of Thermodynamics**, **resistance**, **reactance**, **impedance**, **capacitance**, **inductance**, **right-triangle** trigonometry, **phase shift**, **apparent power**, **true power**, **reactive power**, **sine** and **cosine** functions, and **phasor diagrams**.

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

- How might an experiment be designed and conducted to explore the concept of power factor in an AC circuit? 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 explore the concept of power factor correction in an AC circuit? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What does it mean to say that energy is *conserved*?
- What does it mean when we say that a component *dissipates* energy?
- How does reactance differ from resistance?
- How does impedance relate to resistance and reactance?
- Of what consequence is reactive power in an AC power system?

- Where does the "wasted" energy go in a system that is less than perfectly efficient?
- What is detrimental about an AC circuit with a low efficiency?
- What is detrimental about an AC circuit with a low power factor?
- What differentiates power factor from efficiency?
- Which type of power (reactive, true, or apparent) may be calculated as the simple product of voltage and current?
- What does it mean to say that an AC circuit has a "leading" or a "lagging" power factor?
- What role does an oscilloscope play in the empirical determination of a circuit's power factor?
- If power factor could somehow be made exactly 100% (1), would poor efficiency matter?
- If efficiency could somehow be made exactly 100% (1), would poor power factor matter?
- How may we redesign a circuit to improve its power factor?
- How may we redesign a circuit to improve its efficiency?

1.2 Challenging concepts related to power factor and efficiency

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

- **Resistance versus Reactance versus Impedance** – these three terms represent different forms of opposition to electric current. Despite the fact that they are measured in the same unit (ohms: Ω), they are not the same concept. Resistance is best thought of as electrical *friction*, whereas reactance is best thought of as electrical *inertia*. Whereas resistance creates a voltage drop by dissipating energy, reactance creates a voltage drop by *storing* and *releasing* energy. Impedance is a term encompassing both resistance and reactance, usually a combination of both. Resistance, reactance, and impedance relate to power in the forms of true power (P), reactive power (Q), and apparent power (S).

- **Confusing power factor and efficiency** – these two concepts are definitely related, but not synonymous. Efficiency is a ratio of energy directed out of a system toward useful work versus total energy put in to that system. Power factor, on the other hand, is a ratio of real power (P) to apparent power (S) in an AC circuit.

- **Prime movers** – for any electromechanical generator, the "prime mover" is the mechanical energy source spinning the shaft. Some students mistakenly think the "prime mover" is something *electrical* when it is not. For example, the prime mover for a generator at a hydroelectric power plant is the turbine which is spun by the kinetic energy of falling water.

- **Interpreting oscillograph phase shift** – phase shift is typically expressed in degrees, calculated from the shift between two waves' similar peaks as well as their period. Phase shift may be computed from a time-domain oscillograph, as well as from a Lissajous figure.

The *Case Tutorial* chapter contains examples showing various calculations related to efficiency and to power factor.

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 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 power factor to realistic circuits

  Assessment – Calculate the various powers (P, Q, S) and/or power factor for an AC circuit given component values; e.g. pose problems in the form of the "Three AC loads" and "AC generator horsepower" and "Power factor for a capacitive circuit" Quantitative Reasoning questions.

  Assessment – Calculate the various powers (P, Q, S) and/or power factor for an AC circuit given empirical measurements; e.g. pose problems in the form of the "Power factor from wattmeter" and "Power factor from Lissajous figure" and "Power factor measurement using instrument transformers" Quantitative Reasoning questions.

- **Outcome** – Apply the concept of power factor correction to realistic circuits

  Assessment – Calculate the effect(s) of connecting correction capacitors to a predominantly inductive AC circuit; e.g. pose problems in the form of the "L versus LC circuit powers" Quantitative Reasoning question.

  Assessment – Determine the amount of capacitance necessary to connect to a predominantly inductive AC circuit to correct its power factor to unity; e.g. pose problems in the form of the "Correcting an arbitrary load's power factor" and "Correcting a lagging power factor" and "Correcting a motor's power factor" Quantitative Reasoning questions.

- **Outcome** – Independent research

  Assessment – Locate electrical generator datasheets and properly interpret some of the information contained in those documents including rated output power, efficiency, and ideal power factor range.

Chapter 2

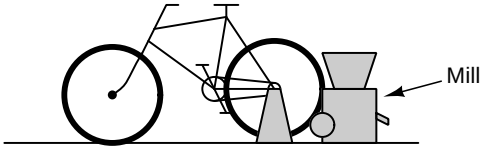
Case Tutorial

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.

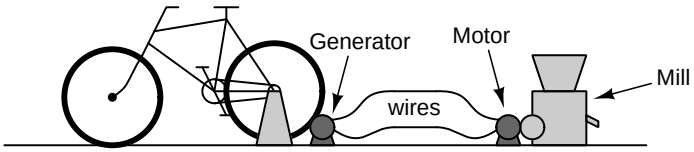
These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: bicycle-driven grain mill

An engineer wants to build a machine useful to people living in rural areas of the world with no electricity service, to be able to grind their own grain using human muscle power. The invention is a bicycle-driven grain mill, where the rear wheel of the bicycle contacts a wheel on the grain mill which turns the grinding stone to convert grain into flour:



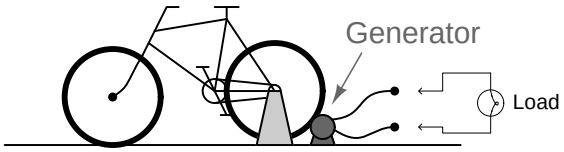
This machine works well, but then the engineer has another idea. Why not couple the bicycle to an electrical generator, then send that energy to a motor which can drive the mill at some remote location? This way the mill could be located within a food-preparation area and not have to be in the same place as the bicycle.



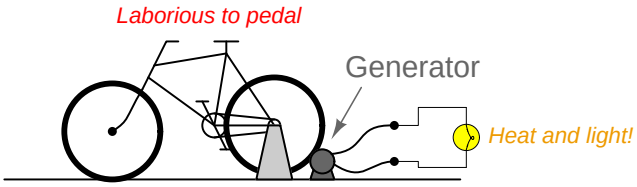
When tested, it is found that this system does not work as well as the first. The same effort expended on the bicycle now is only able to grind about 75% of the grain as the previous (simpler) system. The only advantage of the electric system is that the people baking bread have found they can use the heat dissipated by the electric motor and the heat dissipated by the generator to help make the dough rise in cool-weather conditions (i.e. by placing the rising dough on the housing of each electrical machine).

2.2 Example: bicycle-driven loads

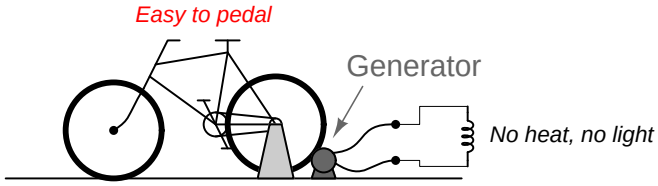
An AC generator is coupled to the rear wheel of a bicycle to allow a person to spin it using the power of their legs. The experiment will be to test the function of this generator powering different loads:



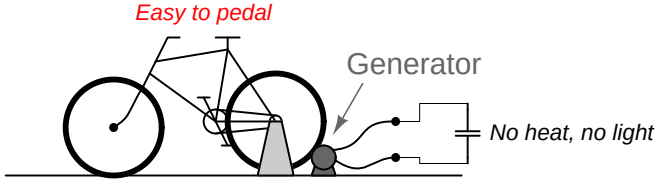
When cranked at a moderate speed, the generator outputs 120 VAC at 60 Hz. Connected to a 60 Watt incandescent lamp, an ammeter registers 0.5 Amperes of current and the lamp glows brightly, growing warm as it does. The bicyclist also notes that substantial effort is required to maintain this moderate pace.



Next, a 637 milli-Henry inductor is exchanged for the incandescent lamp and the experiment re-run. Once again, the ammeter registers 0.5 Amperes of current at 120 Volts (60 Hz). However, two noteworthy details are evident: the bicycle is *much* easier to pedal at the same moderate speed, and the inductor does not become warm like the lamp did.



Next, an 11.05 μF capacitor is exchanged for the inductor and the experiment re-run. The ammeter once again registers 0.5 Amperes at 120 Volts (60 Hz), and once again it is noted that the bicycle is very easy to pedal and there is no sensible heat dissipated at the load.



2.3 Example: electric versus gasoline car efficiency

The following examples compare energy conversion efficiencies from raw fuel to kinetic energy of a moving vehicle:

Typical gasoline-engine automobile:

Energy conversion	Efficiency
Crude oil refined into gasoline	86.5%
Typical gasoline engine	20%
Total efficiency	**17.3%**

Typical diesel-engine automobile:

Energy conversion	Efficiency
Crude oil refined into diesel	89.9%
Typical diesel engine	30%
Total efficiency	**26.97%**

Battery-electric automobile powered entirely by coal:

Energy conversion	Efficiency
Average US coal-fired power plant	37.4%
Electrical transmission/distribution grid	94.8%
Lithium-ion batteries	99%
Electric motor and drive electronics	81.2%
Total efficiency	**28.5%**

Battery-electric automobile powered entirely by natural gas:

Energy conversion	Efficiency
Average combined-cycle turbine power plant	57%
Electrical transmission/distribution grid	94.8%
Lithium-ion batteries	99%
Electric motor and drive electronics	81.2%
Total efficiency	**43.4%**

Reasons why power plant conversion efficiencies exceed typical internal-combustion engine efficiencies include the following:

- Connected to a nation-wide power grid allows power plants to operate closer to a true steady-state condition than an automobile engine which often must contend with rapidly-varying load conditions.
- Power plant boilers and turbines operate at higher temperatures than most internal-combustion engines, increasing the Carnot efficiency limit. Supercritical boilers are an example of a thermal power-plant technology operating at exceptionally high temperatures.
- Some power plants incorporate *combined-cycle* technology (using two different types of heat engine to convert thermal energy into mechanical energy) which is only practical for large, stationary applications.

One major factor ignored in these calculations is the ability of battery-electric vehicles to *recover braking energy*. This means when an electric vehicle decelerates, its motor (normally a load) behaves as a generator (now a source), converting the vehicle's kinetic energy back into electrical energy and then into chemical energy in the battery. Thus, "braking" an electric vehicle does not waste energy in the same way that "braking" an engine-powered vehicle does (where nearly 100% of the kinetic energy becomes dissipated as heat in the brake mechanism). In stop-and-go driving applications typical of urban commutes this advantage is enormous, and is why hybrid-electric cars obtain superior fuel mileage in city driving than on highways! All the conversion efficiencies presented in the previous tables assume braking energy is completely wasted, which is not the case in battery-electric vehicles. Thus, the effective energy efficiencies of electric vehicles are even higher than what is shown – just how *much* greater depends on how the vehicle is to be driven.

Some of the sources referenced for this comparison include the following:

`https://processbarron.com/u-s-coal-power-plant-efficiency-stack/`, updated 2 March 2017.

This web page cites conversion efficiencies for various coal-fueled power plants in the United States.

Proctor, Darrell, "Another World Record for Combined Cycle Efficiency", Power Magazine, 30 September 2018.

This article chronicles the success of a combined-cycle natural gas turbine power plant setting a then-record conversion efficiency of 63.08%.

US Energy Information Administration (EIA) State Electricity Profiles database, `https://eia.gov/electricity/state`, accessed 7 April 2020.

This web page hosts spreadsheet documents with annual data for electric power energy values in all 50 states of the United States. Conversion efficiency was calculated by subtracting "direct-use" energy (i.e. not requiring transmission or distribution) from "total supply" to arrive at grid-transmitted energy. Estimated losses were subtracted from this figure, and that difference divided by the amount of grid-transmitted energy. These efficiency figures were averaged for every year from 1996 to 2018, for six states (California, Florida, Idaho, North Carolina, Washington, and Wyoming). Interestingly, the first four of these states were within a several hundreths of a percent of each other (median = 93.97%), with Washington being about a percent higher (94.86%), and Wyoming being a few percent higher than that (97.89%).

`https://batteryuniversity.com/learn/article/comparing_the_battery_with_other_power_sources/`, updated 28 March 2019.

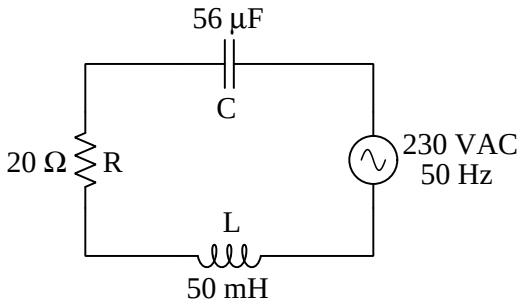
This web page lists lithium-ion batteries as having a 99% charge efficiency.

Williamson, Sheldon; Emadi, Ali; Rajashekara, Kaushik; "Comprehensive Efficiency Modeling of Electric Traction Motor Drives for Hybrid Electric Vehicle Propulsion Applications", IEEE Transactions on Vehicular Technology, Volume 56, Number 4, July 2007.

This research paper lists conversion efficiencies for components within a typical electric-drive automobile, assuming the use of a 45 kW induction motor.

Wikipedia served as the source for some of the other conversion efficiencies including gasoline engines, diesel engines, and combined-cycle natural gas turbines.

2.4 Example: RLC circuit power factor



$X_L = 2\pi(50)(50 \times 10^{-3}) = 15.7080\,\Omega$
$Z_L = 15.7080\,\Omega\angle 90^o$

$X_C = \frac{1}{2\pi(50)(56\times 10^{-6})} = 56.8411\,\Omega$
$Z_C = 56.8411\,\Omega\angle -90^o$

$Z_T = Z_R + Z_L + Z_C$
$Z_T = (20\,\Omega 0^o) + (15.7080\,\Omega\angle 90^o) + (56.8411\,\Omega\angle -90^o) = 45.7376\,\Omega\angle -64.07^o$

$I = \frac{V_{source}}{Z_T} = \frac{230\text{ V}\angle 0^o}{45.7376\,\Omega\angle -64.07^o} = 5.02868\text{ A}\angle 64.07^o$

$V_R = IZ_R = (5.02868\text{ A}\angle 64.07^o)(20\,\Omega\angle 0^o) = 100.574\text{ V}\angle 64.07^o$
$V_L = IZ_L = (5.02868\text{ A}\angle 64.07^o)(15.7080\,\Omega\angle 90^o) = 78.9904\text{ V}\angle 154.07^o$
$V_C = IZ_C = (5.02868\text{ A}\angle 64.07^o)(56.8411\,\Omega\angle -90^o) = 285.836\text{ V}\angle -25.93^o$

Note: all power calculations use scalar values (i.e. current and impedance values taken from polar-form magnitudes only).

Resistor powers:
$P_R = I^2R = (5.02868\text{ A})^2(20\,\Omega) = 505.753\text{ W}$
$Q_R = I^2X_R = (5.02868\text{ A})^2(0\,\Omega) = 0\text{ VAR}$
$S_R = I^2Z_R = (5.02868\text{ A})^2(20\,\Omega) = 505.753\text{ VA}$

Inductor powers:
$P_L = I^2R_L = (5.02868\text{ A})^2(0\,\Omega) = 0\text{ W}$
$Q_L = I^2X_L = (5.02868\text{ A})^2(15.7080\,\Omega) = 397.217\text{ VAR (lagging)}$
$S_L = I^2Z_L = (5.02868\text{ A})^2(15.7080\,\Omega) = 397.217\text{ VA}$

Capacitor powers:
$P_C = I^2R_C = (5.02868\text{ A})^2(0\,\Omega) = 0\text{ W}$
$Q_C = I^2X_C = (5.02868\text{ A})^2(56.8411\,\Omega) = 1437.38\text{ VAR (leading)}$
$S_C = I^2Z_C = (5.02868\text{ A})^2(56.8411\,\Omega) = 1437.38\text{ VA}$

Total powers:

$P_T = P_R = 505.753$ W

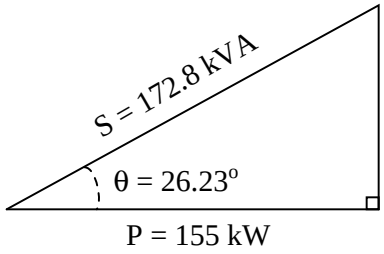
$Q_T = Q_C - Q_L = 1437.38$ VAR (leading) $- 397.217$ VAR (lagging) $= 1040.16$ VAR (leading)

$S_T = \sqrt{P_T^2 + Q_T^2} = 1156.60$ VA

2.5 Example: power factor from V,I,P measurements

A large electrical load is outfitted with a wattmeter to measure its true power. Load voltage is 7.2 kV and load current is 24 A (both RMS), while the wattmeter measures 155 kW:

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



2.6 Examples: power factor correction

2.6.1 Given PF, V, I, f

An AC load exhibits a lagging power factor of 0.73 at 230 Volts and 315 Amperes, both RMS quantities. At a frequency of 60 Hz:

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

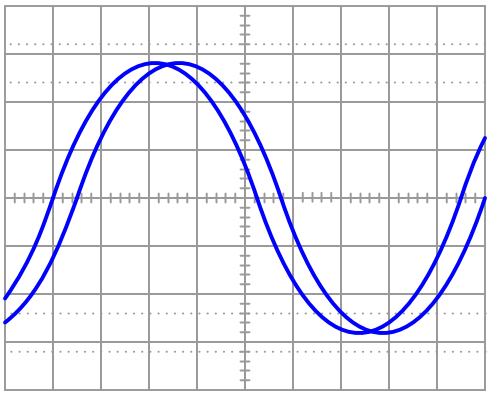
2.6.2 Given P, V, I, f

Another AC load (containing some inductance) consumes 15.2 MW of true power at a voltage of 115 kV and 149.8 A, both RMS quantities. At a frequency of 50 Hz:

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

2.6.3 Given oscillograph, V, I, f

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



Load voltage of 110 V and load current is 3.2 A (both RMS), at a frequency of 60 Hz.

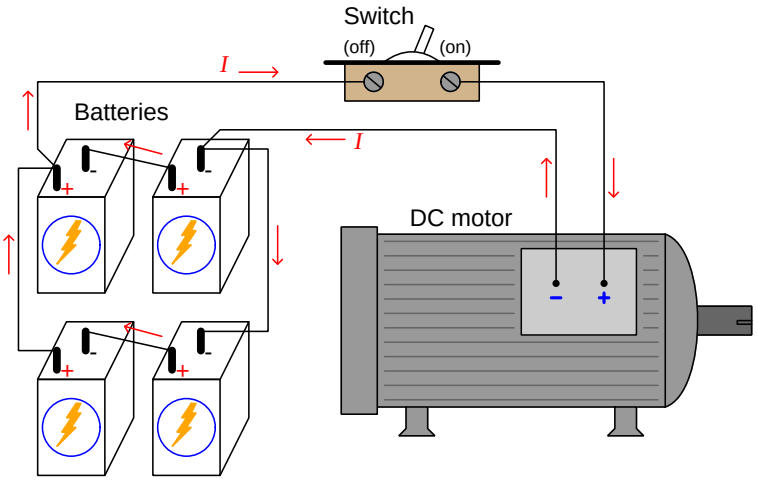
- Apparent power (S) = 352 VA
- True power (P) = 328.2 W
- Reactive power (Q) = 127.2 VAR
- $\Theta = 21.2^o$
- Power factor = 0.932 (lagging)
- Necessary parallel C size to correct power factor to unity = 27.9 μF

Chapter 3

Simplified Tutorial

The study of electricity and of electric circuits is fundamentally an application of the more general concept of *energy transfer*. Energy may be simply defined as that which has the ability to set matter into motion, and it takes many forms. Regardless of which forms we happen to find energy in, the sum total of all energy in the universe is constant, which means energy is never created from nothing nor does it ever vanish. This foundational principle is known as the *Law of Energy Conservation*, and it has proven true at all scales from the interaction of subatomic particles to the motions of planets and stars.

To begin, let us consider a very simple circuit consisting of several electrochemical batteries powering a DC (direct current) electric motor:

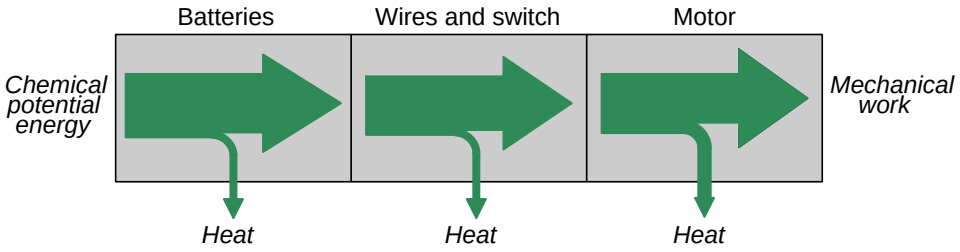


As usual, "conventional-flow" current direction notation and +/− voltage polarity notation helps us understand the transfer of energy in this system. We see charge carriers (electric current) entering into the − terminals of the batteries and exiting from the + terminals of the batteries, indicating those charge carriers enter at a low energy state and exit at a high energy state, picking up energy

from the chemicals within the batteries. We also see current entering the electric motor at its + terminal and exiting from its − terminal, indicating those charge carriers enter at high energy and exit at low energy as they deliver their energy to the motor's shaft to do mechanical work. Electric charge carriers therefore serve as a medium for energy transfer, ultimately moving the stored energy of the batteries' chemicals to the motor's shaft. When the batteries are finally exhausted, current will cease and the motor's shaft will stop turning: all the energy that used to be stored up in the batteries has now been released through the motor.

The Law of Energy Conservation is also known as the *First Law of Thermodynamics*, especially when applied to thermal systems. Another universal law of energy, just as well-founded as the Law of Energy Conservation, is the *Second Law of Thermodynamics* which simply states that energy *diffuses* (i.e. spreads out) over time. Put in other words, the Second Law declares the impossibility of transferring energy from a source to only one destination – some of that energy inevitably finds its way to other destinations too. If you imagine energy transfer being analogous to transporting water in a bucket, the First Law of Thermodynamics tells us you can never get more water out of a bucket than what you put into it, while the Second Law of Thermodynamics tells us *the bucket always leaks*.

Referring back to our electric motor circuit, we can see the Second Law in action by noting that the motor becomes hot with use. Instead of 100% of the electrical charge carriers' energy being delivered to the motor shaft, a small portion of that energy manifests[1] as heat where it does no useful work at all. In fact, energy doesn't just diffuse at the motor – some of it converts to heat in every part of the system! We may show this in another type of diagram, using arrows of different size to represent energy flow from one component to the other:



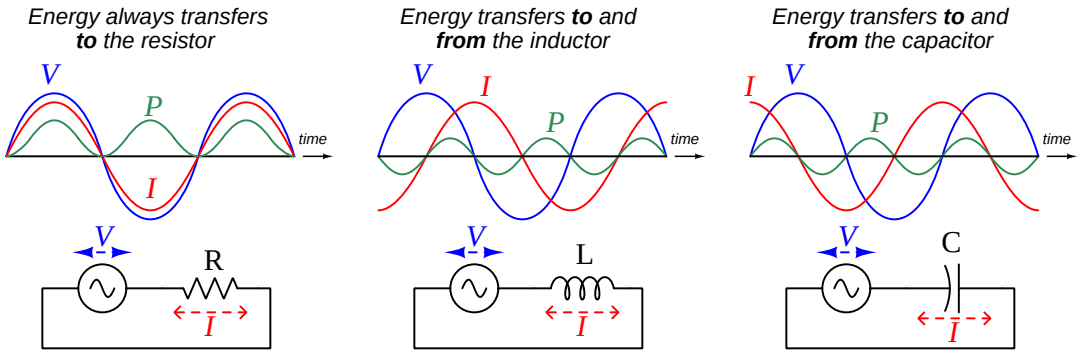
At each step in the energy transfer process, we see a small portion of the energy diverted into heat rather than to its intended purpose at the motor shaft such that the total amount of mechanical work done is guaranteed to be somewhat less than the total amount of chemical energy depleted within the batteries.

This unintentional diversion of energy into heat is called *inefficiency* or *waste*. Mathematically stated, the *efficiency* of any system is the ratio between the amount of energy converted by that system into the intended form versus the amount of energy delivered to that system:

$$\text{Efficiency} = \frac{\text{Energy converted to intended form}}{\text{Energy input to system}}$$

[1] The dominant mechanism for this heat is I^2R losses in the electrical conductors: Joules Law of energy conversion from electrical to thermal as a result of electric charge carriers randomly colliding as they pass through imperfect conductors.

The Second Law of Thermodynamics applies to all physical systems and therefore over all types of electrical circuits, direct current (DC) and alternating current (AC) alike. However, AC circuits face an additional energy-conversion challenge known as *reactance*. Devices such as electric motors which convert electrical energy into useful work may be electrically modeled as resistors, in that they function as *loads* to extract energy from passing charge carriers in order to perform that work. As with any load, the energy extracted from passing charge carriers never returns to the circuit but instead is *dissipated* away from the circuit. Capacitance and inductance within AC circuits function alternately as loads and sources, periodically extracting energy from charge carriers and then infusing that energy back into charge carriers. Simply put, resistance "spends" energy while reactance "borrows" and "returns" energy:



Reactance of any form in an AC circuit, be it capacitive or inductive, has the effect of making the system less effective at delivering energy because only some of it ends up being converted into useful work at the end. If the reactance happens to overshadow resistance in an AC circuit, *most* of the energy carried by charge carriers will simply alternate back and forth through the wires rather than leave the circuit to do useful work. This can be a significant problem in AC electric power systems because imperfect conductors (having some resistance) must shuttle all that energy, losing some of it as it travels in both directions (to and from the reactance).

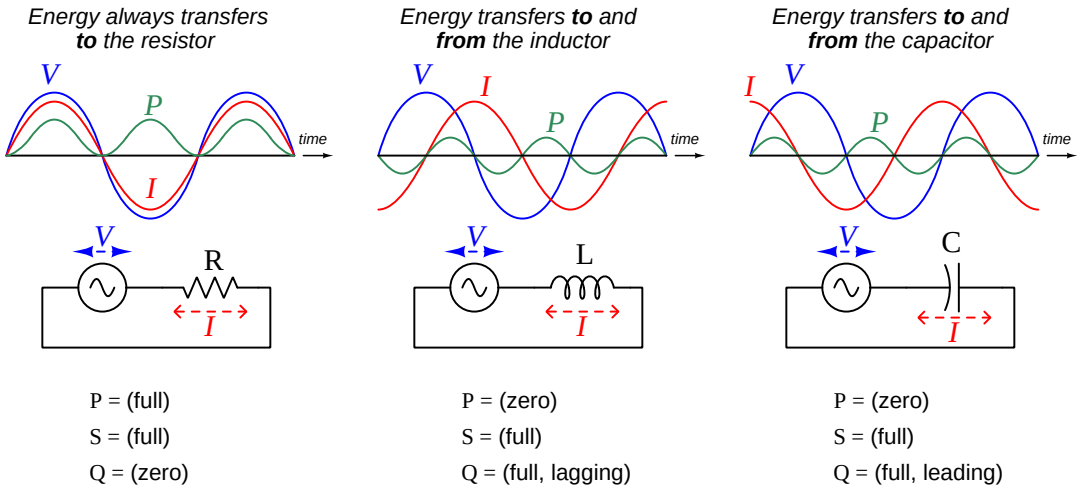
Electric motors and other energy-conversion devices typically exhibit some amount of reactance (usually inductive), which means they do not process all the energy given but return some of it back to the circuit. In order to make sense of all this energy transfer when we calculate and measure electric power[2], we refer to power that is dissipated by the device as *true power* (P measured in Watts), power that is alternately stored and released as *reactive power* (Q measured in Volt-Amperes Reactive), and the combined total of true and reactive power as *apparent power* (S measured in Volt-Amperes). The mathematical ratio of true power to apparent power is called *power factor*:

$$\text{Power factor} = \frac{\text{True power}}{\text{Apparent power}} = \frac{P}{S}$$

True power, Apparent power, Reactive power, and Power Factor are all real (i.e. scalar) quantities rather than complex numbers, and are generally calculated from the same.

[2]Recall that power is simply energy per unit time. The unit of the Watt, for example, is defined as a Joule of energy transferred during every second of time.

Returning to our example circuits with an ideal resistor, ideal inductor, or ideal capacitor connected to an AC source, we may compare the different types of AC power represented within each:



P = (full)
S = (full)
Q = (zero)

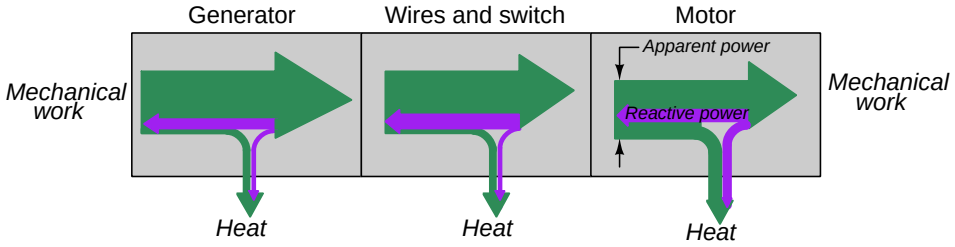
P = (zero)
S = (full)
Q = (full, lagging)

P = (zero)
S = (full)
Q = (full, leading)

Only in the resistor circuit does energy leave the circuit (in the form of heat) never to return, and so we have true power (P) but no reactive power (Q). In the inductive and capacitive circuits, however, none of the energy ever leaves the circuit because it just gets sent back and forth between the reactive component and the AC source, each of those alternately acting as source and load. Therefore, with the L or C what we have is zero true power (P) but full reactive power (Q). In every case we have apparent power (S), which is the calculated value based on meter measurements of voltage and current.

When reactive power is such that the current waveform lags behind the voltage waveform, we say that the reactive power is *lagging*. Likewise for net-capacitive circuits where current leads voltage: we say that the reactive power is *leading*. Without these qualifying labels, there is no way to tell from a numerical Q value nor from a power factor ratio whether the less-than-perfect power factor results from too much inductance or from too much capacitance.

Replacing batteries with an electromechanical (AC) generator and the DC motor with an AC motor, we may re-draw our energy diagram to show the relationship between true power, reactive power, apparent power, and waste in a realistic AC electric circuit:



Reactive power is not "waste" in the sense of energy leaving the system as heat, yet it is not being utilized to do the intended work. Some of that reactive power, just like some of the true (useful) power, does get converted into heat through the various inefficiencies along the way, which means more reactive power *indirectly leads to* more waste. In a large-scale electric power system this waste results in additional heating of line conductors and additional heating of generator windings.

The bucket of water analogy proves useful here: imagine someone transporting water from one reservoir to another using a bucket, dipping the bucket into one reservoir to fill it, walking over to the other reservoir with the bucket, and then emptying the bucket's contents into that other reservoir. The bucket leaks, and this is inefficiency: water falling on the ground where we cannot use it. A poor power factor, by contrast, is the equivalent of *partially* rather than *fully* emptying the bucket at the destination reservoir, returning back to the source reservoir carrying some of the original water. The un-emptied bucket does not represent waste in the same way that water falling on the ground is wasted, but the fact that the bucket still contains water on the return trip means the bucket's leak has more opportunity to waste water.

A perfect power factor is where no reactive power exists in the AC circuit at all, making true power equal to apparent power (i.e. power factor ratio = 1). In this scenario the AC generator and power conductors conduct only as much energy as what is truly needed at the point of use, which in turn makes the entire system more efficient. In the bucket analogy, this is when the bucket is entirely emptied at the destination and returned to the first reservoir dry: it may leak some water on the way to the destination, but at least it doesn't also leak water on the way back.

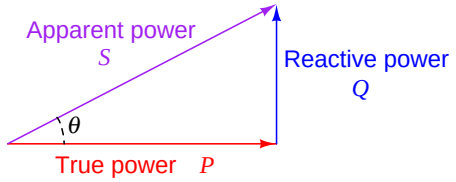
As we see here, power factor and efficiency are *related* but not *synonymous*. To further illustrate this distinction, consider the scenario of a tree limb accidently bridging between two power line conductors: the tree limb represents an almost perfectly resistive load with a power factor of unity (1), yet it is 0% efficient because none of the energy dissipated in the tree limb does any useful work. In the bucket analogy this is equivalent to accidently spilling all of the bucket's contents on the ground – there is no "reactive" water here (i.e. water carried back to the first reservoir) and therefore the power factor is at a perfect value of unity (1), but the *efficiency* is still zero. This singular example is sufficient to prove[3] that power factor and efficiency cannot be the same concept.

[3] This is a logical technique known as *reductio ad absurdum*, where a counter-example renders an assertion absurd.

The degree to which power leaves an electric circuit (P) versus shuttles back and forth between components of that circuit (Q) depends on the phase angle separating voltage from current. When voltage and current are in-phase, as is the case with a purely resistive load, all the energy delivered by charge carriers to the resistive load becomes converted to a form where it leaves the circuit never to return. We would say such a circuit has a perfect power factor, equal to 1. Purely reactive circuits exhibit either a $+90$ or a -90 degree phase shift between voltage and current, which accounts for power alternately flowing into and away from components rather than dissipating from the circuit. We would say that a perfectly reactive circuit has a power factor of zero because none of the energy exchanged actually ever leaves the circuit. Mathematically, power factor is equal to the cosine of the angle between voltage and current waveforms, that phase angle being identical to the impedance's angle since Z is defined as the ratio of voltage to current, and polar-form complex number angles subtract when the complex numbers are divided:

$$(\text{PF}) = \cos\theta$$

We may represent power factor graphically in the form of a *phasor diagram*, where the phase shift between voltage and current in an AC circuit is represented as the angle of the vector, and the magnitude (length) of the vector represents the circuit's apparent power (S):



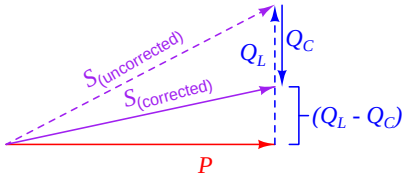
If we happen to know a single circuit component to be purely dissipative (e.g. a resistor), then we may conclude its power to be entirely true and non-reactive, and furthermore we may calculate that true power based on the component's resistance: $P = I^2R$ and $P = \frac{V^2}{R}$. If we happen to know a single component to be purely reactive (e.g. a pure inductance or capacitance), then we may conclude its power to be purely reactive, and furthermore we may calculate that reactive power based on the component's reactance: $Q = I^2X$ and $Q = \frac{V^2}{X}$. Again, these quantities are all real numbers, not complex numbers. When calculating any of these from complex voltage and current quantities, you will use the polar magnitude – otherwise known as the *absolute value* of the complex number – for V or I.

To review, apparent power (S) is the gross[4] product of voltage and current as measured by a voltmeter and an ammeter, respectively, and is expressed in the very appropriate unit of *Volt-Amperes* (VA). True power (P) is power that actually leaves the circuit never to return, whether this is doing useful work or is merely waste, and is always expressed in *Watts* (W). Efficiency is the ratio of energy doing useful work by a system versus total energy input to that system. Reactive power (Q) is power that cycles back and forth between circuit components, never leaving the circuit, and is always expressed in *Volt-Amperes-Reactive* (VAR). Power factor is a unitless ratio of true

[4] All we mean by "gross" is that we are taking the polar magnitudes, or absolute values, of the voltage and current phasors as would be indicated by metering instruments.

power (P) to apparent power (S), and is equal to the cosine of the phase angle separating voltage and current waveforms.

Interestingly, poor power factor may be corrected by adding the complementary form of reactance to an AC circuit, preferably as close to the offending reactance as possible so that none of the power conductors need be burdened with carrying reactive power. Since most low-power-factor machines tend to be inductive (e.g. electric motors), this means added capacitance may be used to improve power factor.



Terms commonly used to distinguish inductive Q from capacitive Q are *lagging* and *leading*, respectively, so named because of the phase relationship between current and voltage for each component type. In a typical power system where loads are connected in parallel with one or more sources and therefore all share the same voltage, it is current that distinguishes one load from another, and since current lags behind voltage for inductance we say that inductive loads have a *lagging* power factor. Capacitive loads exhibit current waveforms leading ahead of voltage, and so we say theirs is a *leading* power factor.

If inductive and capacitive reactive power are equal to each other in an AC circuit (i.e. $Q_L = Q_C$) their reactive effects will completely cancel and the power factor will be perfect, with true power equal to apparent power ($P = S$) and reactive power being zero ($Q = 0$). In an AC circuit with perfect power factor, there will be no phase shift between total voltage and total current because any amount of lagging power is perfectly canceled by an equal amount of leading power.

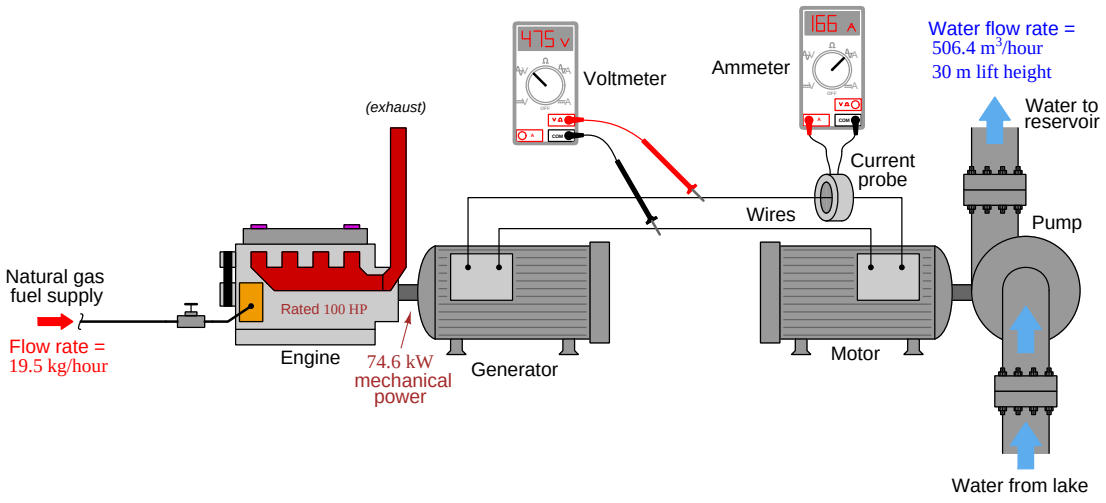
Determining the proper amount of capacitance to add to an inductive circuit to correct that circuit's power factor is relatively simple. First, we need to calculate the amount of reactive power exhibited by the inductance in that circuit (Q_L). If component values are known, we may do this by $Q_L = I^2 X_L$ or $Q_L = \frac{V^2}{X_L}$, using current or voltage values as indicated by meters placed in the circuit. If component values are not known, we may measure apparent power (S) and phase shift between source voltage and source current (θ), then calculate reactive power using $Q_L = S \sin \theta$. Either way, once we know the inductance's reactive power, all we need to do is add enough capacitance to the circuit so that the capacitance will have its own reactive power equal to and opposite in phase from the inductance's reactive power ($Q_C = I^2 X_C$ or $Q_C = \frac{V^2}{X_C}$).

Chapter 4

Full Tutorial

4.1 Energy efficiency

Let's begin our exploration of efficiency and power factor by examining a simple AC electrical system consisting of an engine-driven AC generator, wires, and an AC electric motor connected to a water pump. The engine uses natural gas as fuel, and the pump lifts water from a lake to a reservoir atop a nearby hill.



Energy transforms from one form to another at several places in this system. At the engine the natural gas fuel is burned with air to liberate heat, representing a transformation from chemical energy to thermal energy. This heat causes air to expand, driving pistons inside the engine to produce mechanical energy at the output shaft. This mechanical energy spins the generator, which in turn translates that energy into electrical form by boosting the electrical potential of charge carriers passing through the generator's terminals. That electrical energy is delivered to the motor

where it converts again into mechanical energy to spin the pump's shaft. There, the spinning pump moves water molecules to transport them from the lake up to the water reservoir 30 meters uphill, causing the water to gain potential energy as they lift to a higher altitude.

In an ideal system all the chemical energy delivered to the engine in the form of uncombusted natural gas becomes perfectly converted into potential energy of water in the elevated reservoir. This perfect conversion of fuel energy into useful work never happens in reality, though. Although energy is conserved (i.e. none of the chemical energy in the fuel *disappears* without a trace), much of the original energy "spreads" into less-useful forms along the way. The ultimate accounting, or conservation, of energy is called the *First Law of Thermodynamics*, while the inevitable "spreading" of energy into less-useful forms is called the *Second Law of Thermodynamics*. We typically refer to the mis-directed energy as *waste*, and the forms it takes include heating of the surrounding environment, vibration, and noise.

The Second Law of Thermodynamics applies to all instances of energy conversion, and one way to gauge its action is to calculate the ratio of useful energy out versus raw energy in, that ratio being known as *efficiency*:

$$\text{Efficiency} = \frac{\text{Energy output by system in its intended form}}{\text{Energy input to system}}$$

Whatever difference exists between these two energy quantities is the energy *wasted*.

We may calculate the over-all efficiency of our water-pumping system by calculating the ratio of the water's potential energy increase as it gets pumped to the elevated reservoir to the natural gas fuel's chemical energy as it feeds the engine. A close inspection of the figures in the illustration reveal a reference to *time*, the natural gas fuel expressed as a flow rate *per hour* and the water pumping also expressed as a flow rate *per hour*. Energy per unit time is technically known as *power*, and so long as the system operates in a steady-state condition we may regard efficiency as the ratio of output power to input power:

$$\text{Efficiency} = \frac{\text{Steady-state power out}}{\text{Steady-state power in}}$$

Output power for this system may be calculated in terms of the water's weight lifted 30 meters vertically from the lake to the reservoir. Gravitational potential energy is equal to weight times height ($E_p = Wh$), and with each cubic meter of water weighing 9800 Newtons and being lifted 30 meters from lake to reservoir, each cubic meter pumped requires 294,000 Newton-meters, or 294,000 Joules of potential energy. Pumping 506.4 cubic meters of water per hour represents a water-lifting power value of 148.88 million Joules per hour, or 41.356 kiloJoules per second. Since one Joule of work done in one second's time is equivalent to a Watt of power, this is 41.356 kiloWatts of power.

Already we can see a discrepancy in the figures, as the 100 "horsepower" engine outputs a substantially larger figure of 74.6 kiloWatts mechanical power to the generator. The difference between the engine's output power of 74.6 kW and the water's pumped power of 41.356 kW is 33.244 kW of energy wasted mostly in the form of heat (e.g. heating inside the generator, heating of water traveling through the pump). Calculating efficiency from the engine's output shaft to the water, we have:

$$\text{Efficiency} = \frac{\text{Steady-state power into useful work}}{\text{Steady-state power in}} = \frac{41.356 \text{ kW}}{74.6 \text{ kW}} = 55.44\%$$

However, the system's over-all efficiency is even worse that this when we factor in the engine's conversion of chemical energy into mechanical energy. Heat engines are notoriously inefficient, and this example is no exception. To calculate this efficiency we must mathematically convert the natural gas flow rate into an *energy rate*. Fortunately, this is easy to do if we know the *heat of combustion* for the specified fuel. Natural gas is mostly comprised of methane, and methane's heat of combustion is 55.67 megaJoules per kilogram. The illustration shows the natural gas flow rate into the engine as 19.5 kilograms per hour, and so we may calculate the chemical energy rate by simple multiplication: 55.67 MJ/kg $\times$ 19.5 kg/hour = 1.0856×10^9 Joules per hour, which is 301.55 kiloJoules per second, or 301.55 kiloWatts. The energy efficiency of the engine is now simple to calculate:

$$\text{Efficiency} = \frac{\text{Steady-state power out}}{\text{Steady-state power in}} = \frac{74.6 \text{ kW}}{301.55 \text{ kW}} = 24.74\%$$

Bear in mind that this 24.74% efficiency figure is strictly for the *engine alone*, not the entire water-pumping system. This figure is rather typical for an internal combustion engine of this size, the vast majority of the fuel's heat escaping the engine in the form of hot exhaust gases and hot air from the radiator. The over-all efficiency of our water-pumping *system* is, of course, even worse than the engine's 24.74%:

$$\text{Efficiency} = \frac{\text{Steady-state water-pumping power out}}{\text{Steady-state fuel power in}} = \frac{41.356 \text{ kW}}{301.55 \text{ kW}} = 13.71\%$$

This low efficiency figure means only 13.71% of the natural gas fuel's chemical energy actually gets translated into lifting water. The rest of that energy is wasted along the way at each energy-conversion step within the system. As you can see, the single most wasteful step in the system is the engine, and so this is where the greatest potential exists for improving the system's over-all energy efficiency. Modern thermal power plants (e.g. coal-fired, gas-fired, oil-fired) achieve conversion efficiencies upwards of 60%[1] by operating engines at very high temperatures and using multiple stages of machinery to extract mechanical energy from the heat.

[1] At the time of this writing, a new world record was set for conversion efficiency at an electric power plant: 63.08% at the Nisha Nagoya gas-fired power plant in the Ama District of Aichi Prefecture in Japan using the General Electric model 7HA gas turbine engine in combination with boilers and steam turbines to recover waste heat from the gas turbine engine exhaust gases. This "combined cycle" (i.e. gas turbine plus steam turbine) design results in greater efficiency than any one machine alone could muster. Another possible route to improved energy utilization is to use the low-temperature waste heat rejected by the steam turbines for industrial purposes and/or space heating of local structures rather than dissipating that waste heat to the atmosphere, a strategy known in the power plant industry as *co-generation*, or *combined heat and power* (CHP).

4.2 Power factor

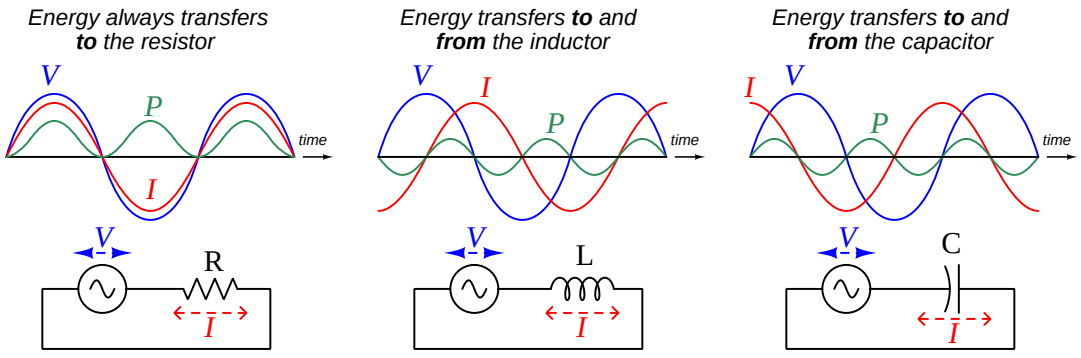
So far our analysis of this water-pumping system has excluded any electrical calculations, so let's apply what we know of voltage and current to this power problem. We know from our experiences with DC circuits that power is equal to the product of current and voltage ($P = IV$), and so we may try to calculate electrical power by multiplying the two meters' RMS readings together:

$$\text{Power} = \text{Current} \times \text{Voltage} = (166 \text{ Amperes})(475 \text{ Volts}) = 78.85 \text{ kW}$$

Something is clearly wrong here, because this power value of 78.5 kW exceeds the mechanical power input to the generator's shaft (74.6 kW). The Law of Energy Conservation tells us it should be impossible to get more energy out of a component than what we put in, and this means steady-state power out must always be less than steady-state power in.

Indeed there is an error in our calculation, but it is far from obvious. The error is assuming that power in an AC circuit is just like power in a DC circuit, when in fact it is not. Power is still energy transferred per unit time, and power is still the result of electric charge carriers flowing through a component (current) while losing or gaining potential energy across that component (voltage), but power in a DC circuit was simple to calculate when both of these quantities occurred simultaneously. In an AC circuit, both voltage and current *alternate*, and these cycles may or may not be in-step with one another.

Reviewing the differences between resistance, inductance, and capacitance, we will show here graphs of voltage (V), current (I), and power (P) for each type of AC component. Resistors are dissipative devices, with voltage drop proportional to current (Ohm's Law, $V = IR$) and no phase shift between voltage and current. Inductors are reactive devices, with voltage proportional to rate-of-change of current ($V = L\frac{dI}{dt}$) and voltage leading current by $+90^o$. Capacitors are also reactive devices, but with current proportional to rate-of-change of voltage ($I = C\frac{dV}{dt}$) which makes voltage lag current by -90^o. Pay close attention to the green-colored plot in each of these three graphs showing power:

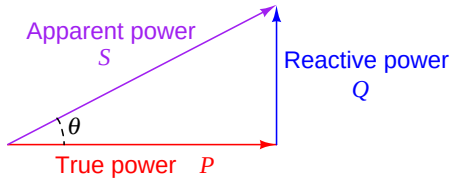


Power cycles between positive values and zero in the resistive circuit, never becoming negative. This represents pulses of energy dissipated from (i.e. leaving) the circuit. In both the inductive and capacitive circuits, however, the power waveform equally alternates between positive and negative values. This reversal of sign shows the circuit reactance alternately absorbing and returning energy

rather than dissipating energy. Note how a voltmeter and ammeter could in principle register the exact same measurements in these three circuits, but only the resistor actually transfers energy out of the circuit where it can do useful work. Therefore, calculating the product of an ammeter's and voltmeter's readings really doesn't tell us anything about how much true power that circuit passes along to a load. The product of an ammeter's and voltmeter's readings is really just an *apparent* computation of power, but not necessarily the *true* amount of power leaving the circuit.

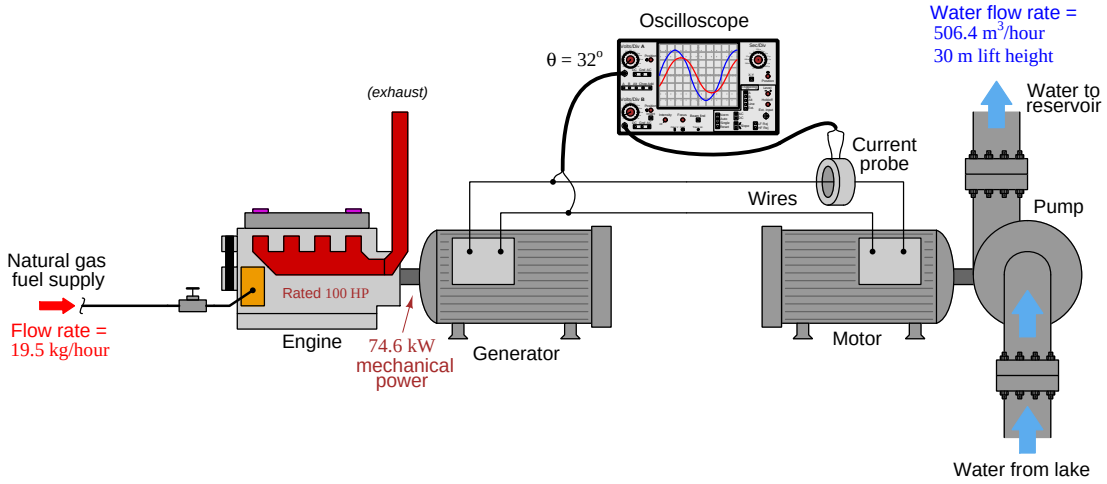
Both the generator and the electric motor in our example system contain some inductance, owing to their construction of wire coils wrapped around iron poles. Although these machines are designed for the express purpose of converting energy between mechanical and electrical forms, the presence of inductance means some of the electrical energy doesn't actually leave the machine, but instead gets reactively shuttled back and forth with the other component(s) of the circuit. This energy, which performs no pumping of water in our system, is called *reactive power*, and it accounts for the product of our ammeter and voltmeter readings being greater than expected. Please note that reactive power is *not* a form of inefficiency because that would imply energy leaving the circuit in some non-useful form such as heat. Reactive power is simply energy shuttled back and forth between AC circuit components.

The mathematical relationship between apparent power (S, expressed in *Volt-Amperes*), true power (P, expressed in *Watts*), and reactive power (Q, expressed in *Volt-Amperes Reactive*) is that of a right triangle, with angle θ representing the amount of phase shift between voltage and current:



Our previous calculation of measured current times measured voltage was actually a calculation of apparent power rather than true power, and so we should have expressed it as $S = IV = (166\text{ A})(475\text{ V}) = 78.85\text{ kVA}$. The illustration of our water-pumping system lacks enough information to compute phase shift angle, and therefore we cannot tell how much true power (P) or reactive power (Q) there might be in this AC circuit.

We could, however, connect an oscilloscope to the circuit to measure phase shift:



From the perspective of θ in the "power triangle" we see that the cosine of θ is the ratio of true power (P) to apparent power (S) and that the sine of θ is the ratio of reactive power (Q) to apparent power (S):

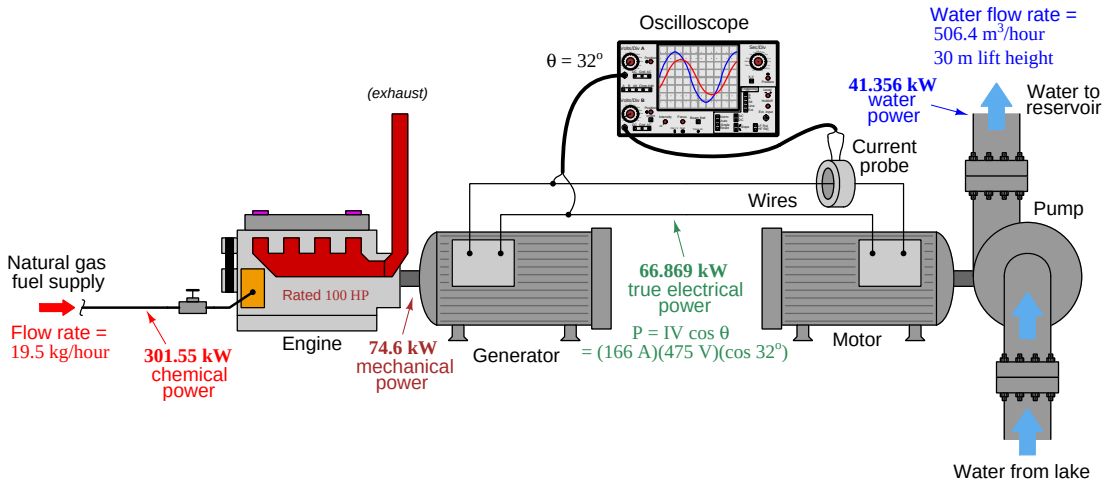
$$\cos\theta = \frac{P}{S} \qquad \sin\theta = \frac{Q}{S}$$

Solving for P and Q respectively in these formulae, we may take the measured 32^o phase shift between voltage and current in our circuit and combine that with the computed apparent power of 78.85 kVA to calculate both true power and reactive power:

$$P = S\cos\theta = (78.85\ \text{kVA})(\cos 32^o) = 66.869\ \text{kW}$$

$$Q = S\sin\theta = (78.85\ \text{kVA})(\sin 32^o) = 41.784\ \text{kVAR}$$

Annotating the illustration with the true circuit power as well as the other power values previously calculated gives us enough information to calculate the efficiency of the engine, of the generator, and of the motor and pump combined:



$$\text{Engine efficiency} = \frac{74.6\ \text{kW}}{301.55\ \text{kW}} = 24.74\%$$

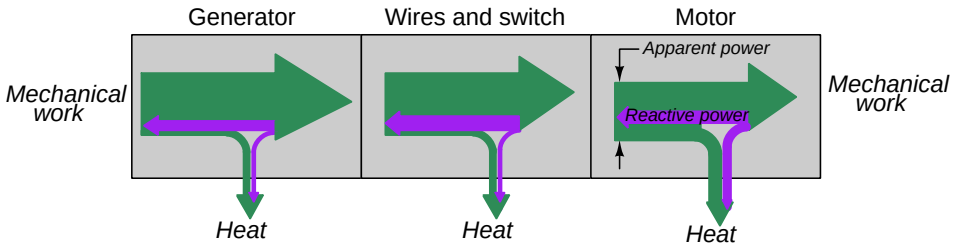
$$\text{Generator efficiency} = \frac{66.869\ \text{kW}}{74.6\ \text{kW}} = 89.63\%$$

$$\text{Motor + Pump efficiency} = \frac{41.356\ \text{kW}}{66.869\ \text{kW}} = 61.85\%$$

4.3 How power factor affects efficiency

Although power factor and efficiency are clearly not the same concept, one of them can affect the other. The poorer the power factor is in an AC circuit, the more energy is shuttled back and forth in the circuit without leaving the circuit to do useful work. For any given amount of true power, this means a greater-than-necessary amount of apparent power. For a regulated-voltage AC circuit, as most electrical power systems are, greater apparent power means greater *current*. Therefore, as power factor approaches zero, line current increases while the system struggles to perform the same amount of useful work as before. Greater line current necessitates heavier-gauge conductors, circuit breakers and other overcurrent protection devices with higher current ratings, and other costly features. Greater line current also means more energy wasted in resistive heating of conductors ($P = I^2R$), which means more of the circuit's true power gets wasted rather than does useful work at the load. So, *poor power factor has an indirect negative effect on efficiency.*

The following arrow diagram for a simple system where an electrical generator provides energy to a motor through connecting wires and switches illustrates this fact. Inductive reactance within the electric motor causes some of the received energy to return back to the generator, and along the way some of that returned energy gets "lost" in the form of heat:

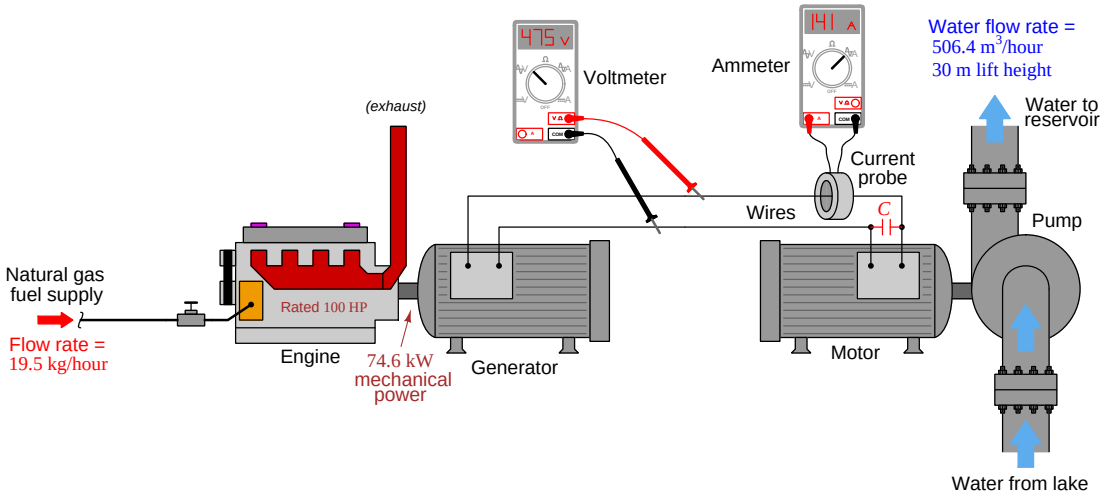


Reactive power is not "waste" in the sense of energy leaving the system as heat, yet it is not being utilized to do the intended work. Some of that reactive power, just like some of the true (useful) power, does get converted into heat through the various inefficiencies along the way, which means more reactive power *indirectly leads to* more waste. In a large-scale electric power system this waste results in additional heating of line conductors and additional heating of generator windings.

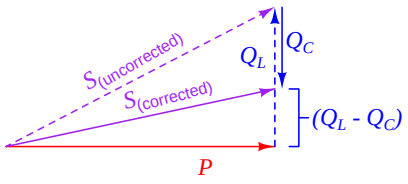
Thankfully, there are ways to mitigate poor power factor and eliminate these additional mechanisms of "wasted" energy in AC circuits. Our review of inductive versus capacitive AC circuits shows how their respective phase shifts are completely opposite: a pure inductance exhibits a current waveform that lags -90^o behind voltage, while a pure capacitance exhibits a current waveform that leads $+90^o$ ahead of voltage. This means the respective phase shifts of an inductance and a capacitance are exactly opposed to (i.e. 180^o apart from) each other. The "leading" current drawn by a capacitor is therefore able to cancel "lagging" current drawn by an inductive load, and if just the right amount of capacitance is added in parallel with an inductive load these two reactive currents can precisely cancel each other with the result being zero reactive power, and a condition where 100% of the apparent power is true power.

4.4 Power factor correction

If we add the right amount of capacitance in parallel with the motor terminals, so as to draw enough leading current to precisely cancel the motor's lagging current, the total line current will fall to a value just large enough (140.78 Amperes) to account for the 66.869 kW of true circuit power. This will reduce (but not completely eliminate) wasteful resistive heating in the lines as well as in the generator windings. The motor's windings will still experience the full 166 Amperes of current, same as before the addition of the capacitor:



The intentional addition of capacitance near an inductive load within an AC circuit is called *power factor correction*. The following phasor diagram shows the effect of adding capacitive reactance to a circuit with some inductive reactance:



In order to achieve perfect power factor correction, we must size the capacitor so that its reactive power (Q_C) is exactly equal in magnitude to the inductive load's reactive power (Q_L). Using our water-pumping system as an example, we know that the reactive power in the circuit is equal to the apparent power (S) multiplied by the sine of the 32^o voltage/current phase shift:

$$Q = S \sin \theta = (78.85 \text{ kVA})(\sin 32^o) = 41.784 \text{ kVAR}$$

Therefore, we need to calculate the correct size of capacitor to exhibit this same amount of reactive power while energized by 475 Volts AC (RMS). Reactive power is measured in Volt-Amperes

Reactive (VAR), and so if the RMS voltage is known as it is here, the amount of reactive current (in units of Amperes Reactive) may be found simply by dividing the VAR quantity by the voltage in Volts:

$$I_C = \frac{Q_C}{V} = \frac{41.784 \text{ kVAR}}{475 \text{ V}} = 87.967 \text{ AR}$$

Ohm's Law may be applied to compute the necessary impedance of this capacitor in Ohms:

$$Z_C = \frac{V}{I} = \frac{475 \text{ V}}{87.967 \text{ A}} = 5.3998 \, \Omega$$

Since capacitors are assumed to be nearly 100% pure, having very little internal resistance, we may safely assume this capacitor's reactance (X) will have the same magnitude as its impedance (Z). Assuming a 60 Hz AC frequency in this system, we may solve for capacitance in Farads:

$$X_C = \frac{1}{2\pi f C}$$

$$C = \frac{1}{2\pi f X_C}$$

$$C = \frac{1}{(2\pi)(60 \text{ Hz})(5.3998 \, \Omega)} = 491.24 \, \mu\text{F}$$

In summary:

- *Efficiency* is the ratio of usable energy out versus energy in for any system or component, and it is always less than unity (1) owing to the Second Law of Thermodynamics.
- The difference between usable energy out versus energy in for any system or component is called *waste*. The sum of usable energy plus wasted energy always equals energy input to the system or component, in accordance with the Law of Energy Conservation (also known as the First Law of Thermodynamics).
- *Apparent power* (S) is the gross product of RMS voltage and RMS current as registered by independent meters. Apparent power is expressed in the unit of the Volt-Ampere (VA) as a scalar[2] quantity.
- *True power* (P) is the amount of power actually leaving the circuit, whether as useful work or as waste. True power is expressed in the unit of the Watt (W) as a scalar quantity.
- *Reactive power* (Q) is power that is merely exchanged back and forth between reactive components in an AC circuit, without leaving the circuit. Reactive power is expressed in the unit of the Volt-Ampere Reactive (VAR) as a scalar quantity.
- *Power factor* is the ratio of true power to apparent power in an AC circuit. It is unitless, and may range between zero and unity (0 and 1) inclusive. Power factor is mathematically equal to the cosine of the phase shift between voltage and current, this shift being equal to the phase angle of the circuit's total impedance.
- Perfect efficiency is impossible to achieve in real practice, but perfect power factor is possible.
- Poor power factor exacerbates inefficiency by giving the reactive power more opportunity to go to waste through circuit resistance and other dissipative losses.
- Poor power factor may be corrected by intentionally adding the opposite form of reactance to an AC circuit.

[2] By "scalar" we mean a quantity with magnitude only and no angle. In other words, we regard these as real numbers rather than complex numbers as we ordinarily would with voltage, current, and impedance in an AC circuit.

Chapter 5

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?

5.1 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.

5.1.1 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.

5.1.2 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

Conservation of Energy

Second Law of Thermodynamics

Efficiency

Heat of combustion

Direct Current (DC)

Alternating Current (AC)

Resistance

Ohm's Law

Joule's Law

Inductance

Capacitance

True power

Reactive power

Apparent power

Reactance

Phase angle

Phasor diagram

□

□

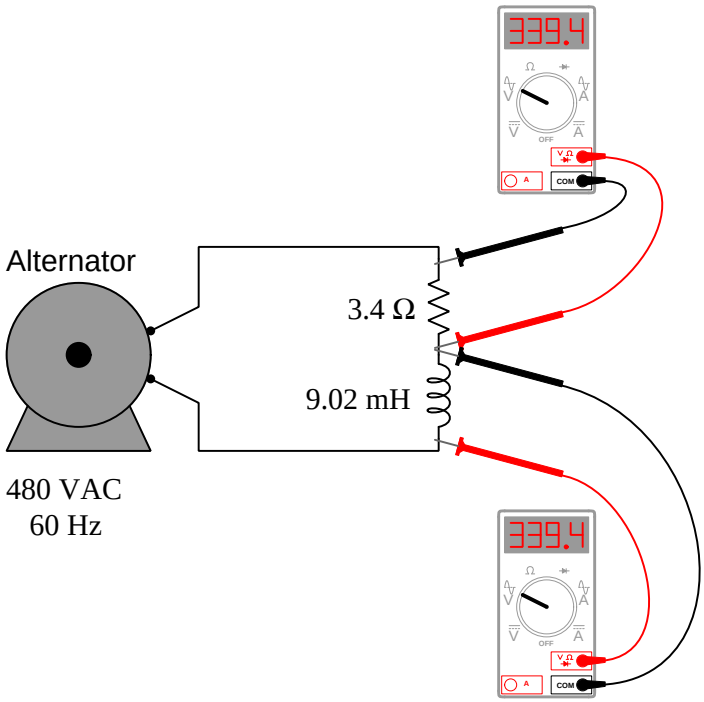
□

□

□

5.1.3 Unequal heating

As the AC generator (alternator) powers this resistor-inductor circuit, it is found that the resistor becomes much hotter than the inductor, even though both components drop the exact same amount of voltage and carry the exact same amount of current:



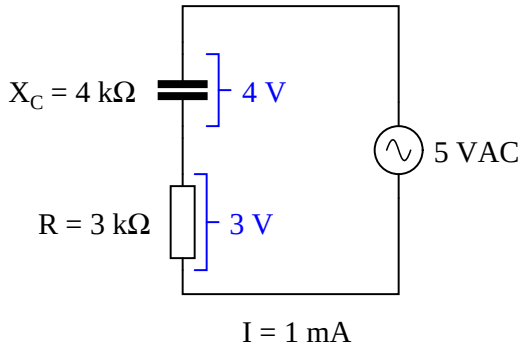
Explain why there is such a remarkable difference in heat output between these two components, given their identical voltage drops and currents.

Challenges

- Suppose we had no way to sense the temperature of these components. Is there some other way to empirically demonstrate the resistor handles energy differently than the inductor?
- What will change in this circuit if the alternator's shaft is spun faster?.

5.1.4 Misconceptions about AC power

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



It is clear by now that the 4 kΩ capacitive reactance does not directly add to the 3 kΩ resistance to make 7 kΩ total. Instead, the addition of impedances is done with complex numbers (i.e. *phasors*):

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

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

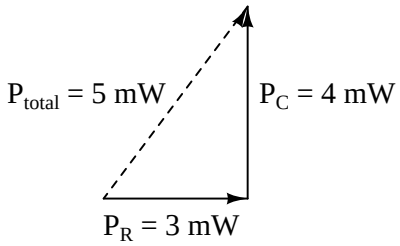
It is also clear to this student that the component voltage drops form a phasor sum as well, so that 4 Volts dropped across the capacitor in series with 3 Volts dropped across the resistor really does add up to 5 Volts total source voltage:

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

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

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

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



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

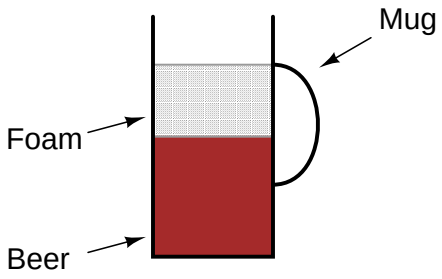
What is wrong with this student's phasor diagram? How may we make sense of the figures obtained by multiplying voltage by current for each component, and for the total circuit?

Challenges

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

5.1.5 Beer analogy for power factor

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



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

Challenges

- All analogies fail at some point. Is there a point at which the beer/foam analogy fails to properly describe the principle?

5.2 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.

5.2.1 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.

5.2.2 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	

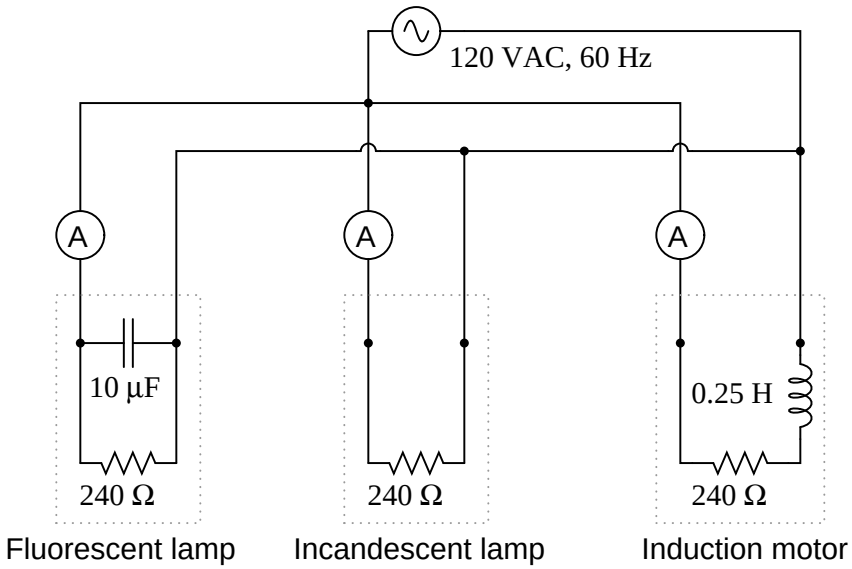
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

5.2.3 Three AC loads

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



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

Challenges

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

5.2.4 Power factor from wattmeter

A large single-phase electrical load is outfitted with a wattmeter to measure its true power. If the load voltage is 600 V and the load current is 48 Amperes (both RMS), calculate the load's apparent power (S). Calculate the power factor and also the phase angle between voltage and current in the circuit if the wattmeter registers 20 kW at those same voltage and current values.

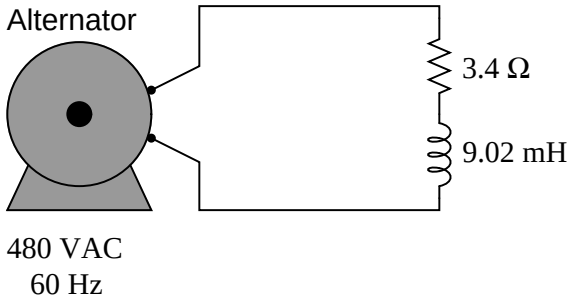
Also, sketch a "power triangle" for this circuit, graphically showing the relationships between apparent power, true power, and phase angle.

Challenges

- If power factor correction were added to this circuit, which of the measured electrical values would change as a result?
- Calculate the amount of capacitance necessary to add in parallel to this load to perfectly correct its inductive (lagging) power factor. Assume a line frequency of 60 Hz.
- Suppose this load were made to be purely reactive, but draw the same amount of current from the source. Which of the measured electrical values would change as a result of this new load?
- Is it possible to determine the *efficiency* of this load from the given measurements? Explain why or why not.

5.2.5 AC generator horsepower

Calculate the amount of current in this circuit, as well as the true, reactive, and apparent power:



$I =$

$P =$

$Q =$

$S =$

Supposing the generator is 91% efficient, calculate the amount of mechanical power necessary from the "prime mover" (e.g. engine, turbine, or other machine driving the generator) to drive it, in both Watts and Horsepower:

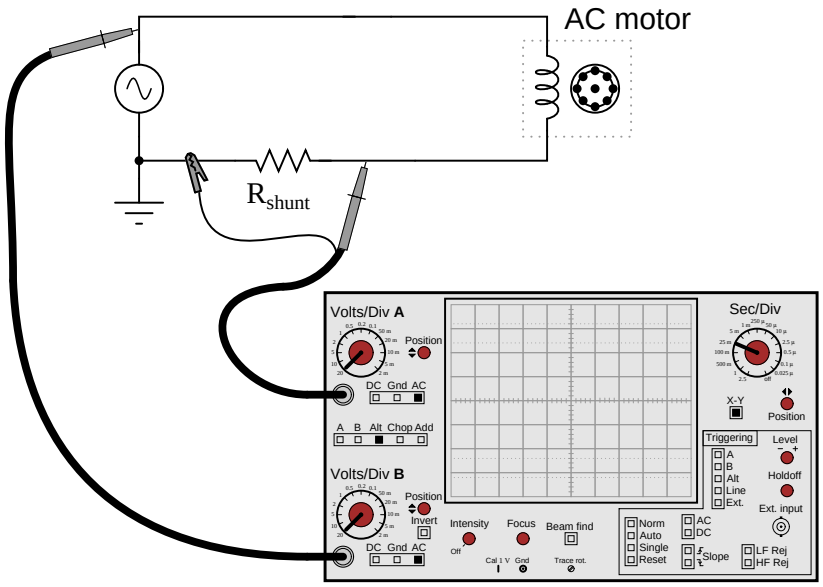
$P_{mech} =$

Challenges

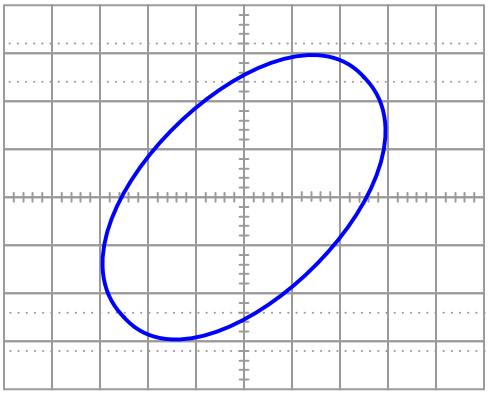
- Many students new to efficiency calculations either get stuck on problems such as this or obtain incorrect answers, not knowing how to reliably relate mechanical power to electrical power for generators and other electrical machinery. Explain how an *energy flow diagram* helps organize and contextualize these quantities.
- What happens to the energy delivered to the resistor from the generator?
- What happens to the energy delivered to the inductor from the generator?

5.2.6 Power factor from Lissajous figure

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



The following Lissajous figure is obtained from this measurement:



From this figure, calculate the phase angle between source voltage and source current (Θ) and the power factor for this motor circuit.

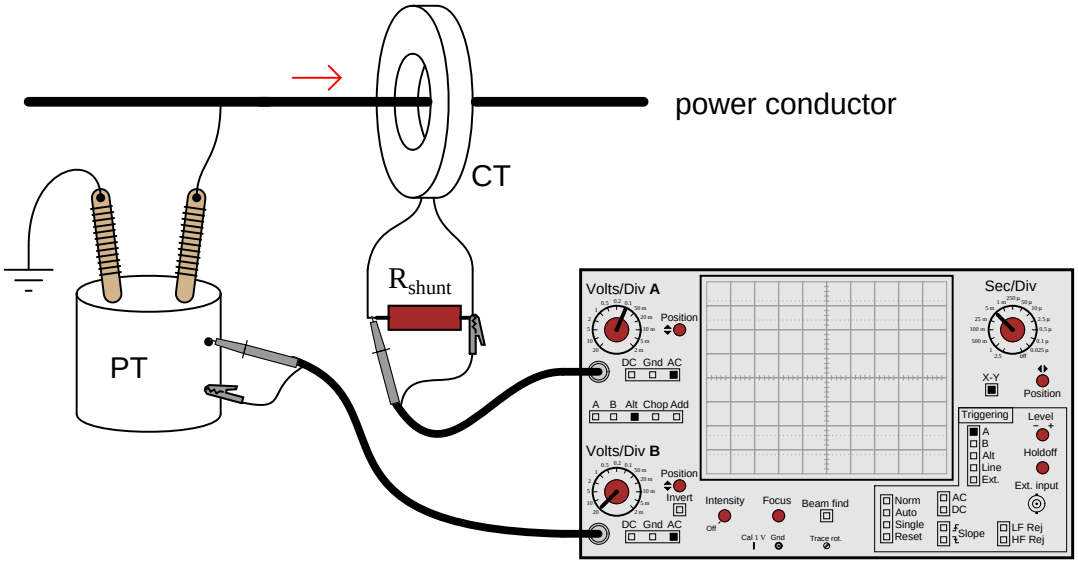
Challenges

- Devise an alternative method of measuring power factor in this circuit, other than plotting a Lissajous figure.

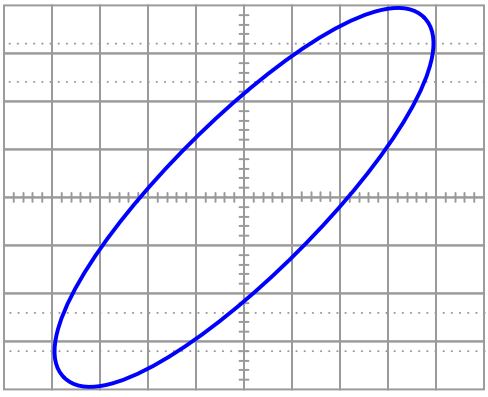
- Explain the purpose of R_{shunt} in this circuit. Are there alternatives to using a shunt resistor to obtain the necessary measurements?
- Explain why only one of the oscilloscope's measurement channels has a ground clip connected to the power circuit.
- A common mistake when connecting oscilloscope channels to a grounded circuit is to misplace the ground clip. Identify an *incorrect* placement for the ground clip, and comment on the consequences.

5.2.7 Power factor measurement using instrument transformers

Suppose you and an electrician are tasked with measuring the power factor of a high-power AC load. The electrician is familiar with using instrument transformers (PTs and CTs) to safely measure voltage and current in high-power circuits, and you understand how to interpret the oscilloscope's image to calculate power factor.



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



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

Challenges

- Can we determine whether the power factor is *leading* or *lagging* from the Lissajous figure? If so, how is this done? If not, why can we not do it?

5.2.8 Hydroelectric generator ratings

A very large 3-phase alternator located at Grand Coulee Dam in Washington state has the following continuous full-power ratings:

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

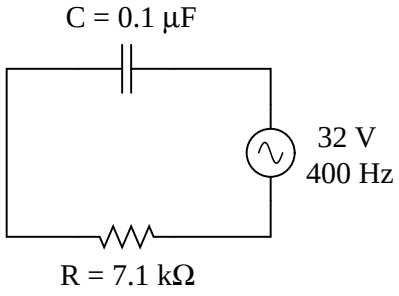
Calculate the continuous full-load apparent power for this alternator (in MVA), its continuous full-load reactive power (in MVAR), and its power factor (in percent).

Challenges

- Explain how calculations of power for three-phase systems differ from calculations of power for single-phase systems.
- The "maximum continuous overload" ratings of this same generator were 690 MW, 15 kV line voltage, and 27.239 kA line current. Does this represent the same power factor, or a different power factor?

5.2.9 Power factor for a capacitive circuit

Calculate the power factor of this circuit:



Challenges

- Will power factor improve or worsen as frequency increases?

5.2.10 Worsening power factor in a motor

Suppose a single-phase AC electric motor is performing mechanical work at a rate of 45 horsepower. Calculate the amount of line current necessary to power this motor if the line voltage is 460 Volts, assuming 100% motor efficiency and a power factor of 1.

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

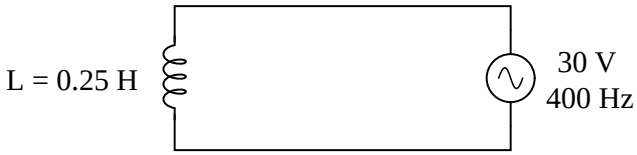
What do these calculations indicate about the importance of maintaining a high power factor value in an AC circuit?

Challenges

- What is the "extra" current in the poorer power factor scenario doing, if not contributing to the motor's mechanical power output?
- Suppose an AC motor exhibits a good (but not perfect) power factor while operating at full load. What will happen to this motor's power factor if it becomes mechanically unloaded?

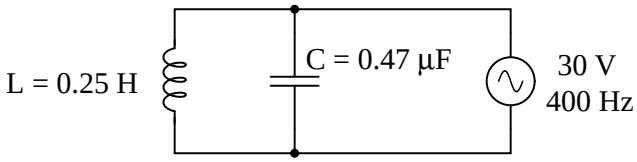
5.2.11 L versus LC circuit powers

Calculate the apparent, true, and reactive powers for the following circuit:



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

Re-calculate for this circuit following the addition of a capacitor:



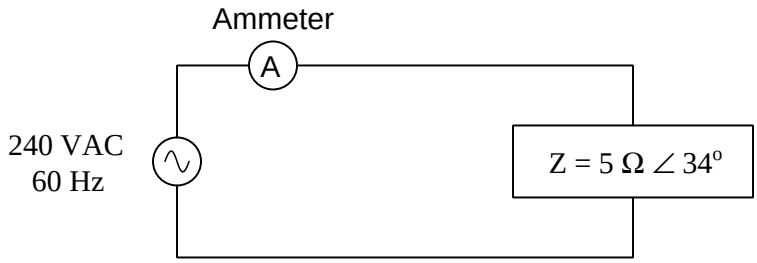
- $S =$
- $P =$
- $Q =$

Challenges

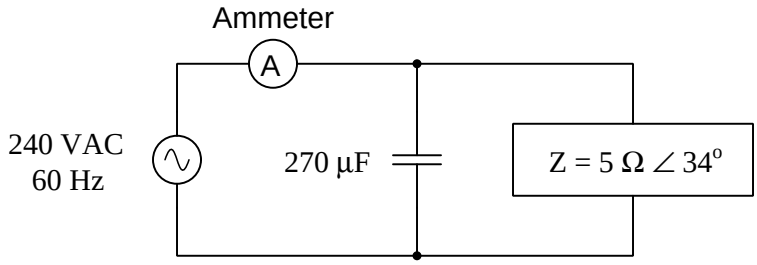
- Did the addition of the capacitor improve the circuit's power factor?

5.2.12 Correcting an arbitrary load's power factor

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



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



Challenges

- Does the addition of the capacitor affect the amount of current through the 5 Ω load? Why or why not?
- What would be the *ideal* capacitor value to perfectly correct power factor for this load?

5.2.13 Correcting a lagging power factor

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

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

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

Challenges

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

5.2.14 Correcting a motor's power factor

A 10 horsepower single-phase electric motor operating at full rated load draws 36.15 Amperes of current at a terminal voltage of 236.0 Volts AC (60 Hz). The measured phase shift between voltage and current at the motor's terminals is 18.195^o.

Calculate this motor's efficiency and its power factor.

Also, determine what you would need to add to the motor circuit to perfectly correct its power factor.

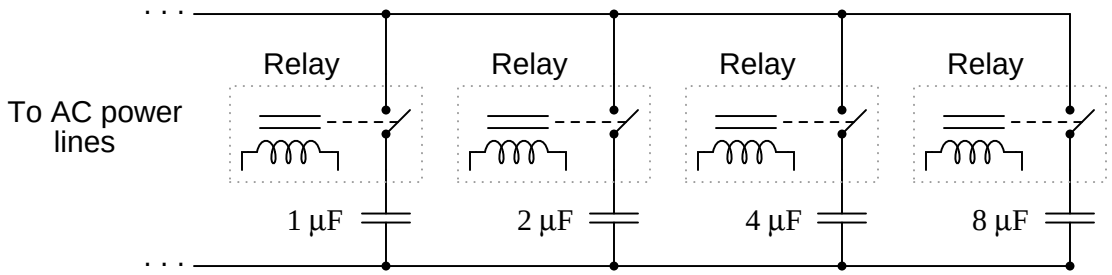
Challenges

- An all-too-common strategy employed by students when faced with problems such as this is to plug numbers into equations without regard for context and hope for the best, which never works out well. Clearly, we need a way to *organize* the information in order to make sense of what the numbers mean. Sketch a simple diagram of the motor, and annotate that diagram with the given information as well as all calculated values, to show where all the information fits.

5.2.15 Capacitor array

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

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



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

Assuming a line voltage of 13.8 kV RMS at a frequency of 60 Hz, calculate the range of reactive power this capacitor array is able to provide for corrective purposes.

Challenges

- What would be the effect of the 1 μF capacitor's relay contact failing open?
- How would a human operator at the power distribution center decide which relays to open and close?

5.3 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.

5.3.1 Misconceived power factor correction

Suppose an AC load is known to have an inductance of 0.5 Henrys, and an electrician wanting to improve the power factor of this circuit decides we need to install a 0.5 μF capacitor because *"we need to balance out the lagging with an equal amount of leading"*.

Explain what is wrong with this electrician's reasoning.

Challenges

- Articulate a procedure by which one could calculate the necessary amount of capacitance to counteract the 0.5 Henrys of inductance in this load.

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

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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.

10 February 2026 – typographical correction courtesy of Wyatt Gleason.

9-10 September 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. Also added a Challenge question to the "Correcting an arbitrary load's power factor" Quantitative Reasoning question.

3 February 2024 – added a Challenge question to the "AC generator horsepower" Quantitative Reasoning question prompting students to draw an energy diagram to help solve for prime mover horsepower.

12 September 2023 – divided the Full Tutorial chapter into sections and made minor edits to its text. Also corrected an instructor note.

6-7 February 2023 – minor edits to the Simplified Tutorial, as well as numerical changes to the "Power factor from wattmeter" Quantitative Reasoning question to make it distinct from the Case Tutorial "Example: power factor from V,I,P measurements".

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 May 2021 – commented out or deleted empty chapters.

11 February 2021 – minor additions to instructor notes, as well as a footnote and a minor text edits to the Simplified Tutorial. Also added Case Tutorial examples showing power factor calculations and correction calculations. Also changed order of some Quantitative Reasoning questions.

3 November 2020 – minor edit to image_0955, where I placed violet arrowheads to definitively show the direction of reactive energy that leaves the system as heat. Also, edited the Simplified Tutorial text to make it clearer what P, Q, and S mean in real circuits.

6 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.

17 June 2020 – added more Foundational Concepts.

7 May 2020 – minor edit to Case Tutorial section on electric car efficiencies.

7 April 2020 – fixed improper capitalization on the word "volts" in several places. Also, added Case Tutorial examples.

6 June 2019 – added comments to both the Simplified Tutorial and the Full Tutorial about how S, Q, and P calculations may be done using real (scalar) numbers and not complex.

27 May 2019 – added more content to the Simplified Tutorial, showing how to calculate true and reactive powers for individual components, and also more detail on correcting for poor inductive power factor in an AC circuit.

26 May 2019 – added questions.

11 May 2019 – deleted an unused object from one of the illustrations – a capacitor that was suspended in space, connected to nothing.

October 2018 – completed Simplified Tutorial, clarified portions of the Introduction. Wrote a Full Tutorial.

August 2018 – added content to the Introduction.

July 2018 – document first created.

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