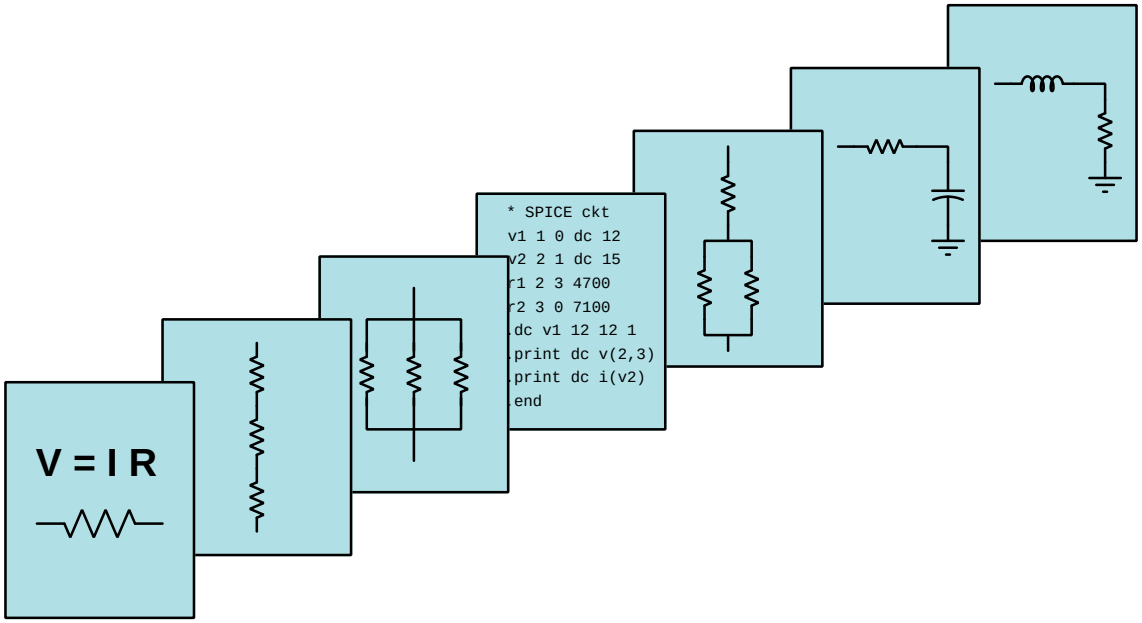
Modular Electronics Learning (ModEL) project



Instrument Transformers

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Chapter 1

Introduction

1.1 Recommendations for students

Instrument transformers are used in the electrical power industry to step down high levels of voltage and current to modest levels which may be safely measured by voltmeters, ammeters, and other electrical instruments. They are also used to provide isolation between the power conductor(s) and the meter circuit, allowing the meter circuit to operate at or near Earth ground potential while the power conductors operate at dangerously elevated potentials.

An important feature of this module is its emphasis on electrical safety, as instrument transformer circuits can be extremely dangerous if mis-wired or mishandled.

Important concepts related to instrument transformers include **electromagnetism**, **electromagnetic induction**, **Faraday's Law**, **sources** versus **loads**, **turns ratio**, **grounding**, **common-mode voltage**, **isolation**, effects of **opens** versus **shorts**, **ground loops**, **magnetic saturation**, **burden**, **apparent power**, **remanence**, **wire resistance**, **Ohm's Law**, **Kirchhoff's Voltage Law**, and **reactance**.

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

- How might an experiment be designed and conducted to demonstrate the phenomenon of mutual inductance? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to measure the turns ratio of a transformer? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to measure the polarity of a transformer? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- Why do we use instrument transformers in electrical power systems?
- What type of load should a PT always connect to, and why?

- What is the safe way to disconnect an energized PT from its load, and why?
- What type of load should a CT always connect to, and why?
- What is the safe way to disconnect an energized CT from its load, and why?
- How much voltage does a typical PT output when energized at its full rating?
- How much current does a typical CT output when energized at its full rating?
- What is the significance of a transformer's BIL rating?
- How many turns of wire are there in a typical "window" style CT?
- How do test switches ensure safe disconnection of an instrument transformer from its load?
- What might happen if we connect a load with an improper amount of burden to an instrument transformer?
- Why are CT test switches always "make-before-break"?
- What is the purpose of a multi-ratio instrument transformer?
- How do we typically specify instrument transformer accuracy ratings?
- How do CTs designed for protection purposes differ from CTs designed for metering purposes?
- What condition(s) will make a CT magnetically saturate?
- Aside from turns ratio and accuracy, what other important ratings are given to CTs?
- How may CTs be affected by transient overcurrent (i.e. fault) events?
- Why is CT circuit wire resistance an important factor in protective relay circuit design?

1.2 Challenging concepts related to instrument transformers

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

- **Voltage sources versus Current sources** – an voltage source maintains a constant output voltage regardless of current, while an ideal current source maintains a constant current regardless of voltage. Voltage sources are more common as sources of electrical power, and so they tend to be more familiar to students of electricity and electronics. However, some devices closely approach current-source behavior, and current transformers (CTs) in electrical power systems are a great example of these. As current sources, CTs are perfectly safe to short-circuit because that allows them to output current without having to do work on a load which means practically zero output voltage, but they are dangerous to open-circuit because they will output as much voltage as necessary to ignite an arc across the air gap of that open and sustain their output current!

- **Magnetic saturation** – this is a phenomenon where the ferromagnetic core material of a transformer becomes "saturated" with lines of magnetic flux, resulting in less additional magnetic flux for additional increases in winding current. Since Faraday's Law of Electromagnetic Induction shows us that voltage induced in a transformer winding is proportional to how rapidly the magnetic flux grows or decays over time ($V = N\frac{d\phi}{dt}$), a limit on magnetic flux growth means during those periods of time a transformer's ability to generate a secondary-winding voltage will be severely curtailed.

1.3 Recommendations for instructors

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

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

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

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

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

- **Outcome** – Apply foundational circuit concepts to the analysis of instrument transformer circuits

  Assessment – Calculate phasor voltages for PT and CT outputs given transformer turns ratios and three-phase line parameters; e.g. pose problems in the form of the "Transformer-isolated voltage calculations" Quantitative Reasoning question.

  Assessment – Calculate secondary voltages and currents for CT circuits given turns ratios and impedances; e.g. pose problems in the form of the "Paralleled CTs" and "Series-connected CTs" Quantitative Reasoning questions.

- **Outcome** – Properly connect instrument transformers to protective relays

  Assessment – Sketch a schematic diagram of a circuit employing one or more instrument transformers to send power system information to a protective relay; e.g. pose problems in the form of the "Multi-ratio CT wiring" Conceptual Reasoning question.

- **Outcome** – Diagnose a faulted instrument transformer circuit

  Assessment – Determine likely root-cause(s) for a given failure in a data acquisition system using instrument transformers; e.g. pose problems in the form of the "Damaged data acquisition system" Diagnostic Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate potential transformer (PT) datasheets and properly interpret some of the information contained in those documents including turns ratio, voltage ratings, burden ratings, etc.

Assessment – Locate current transformer (CT) datasheets and properly interpret some of the information contained in those documents including turns ratio, class ratings, burden ratings, etc.

Chapter 2

Tutorial

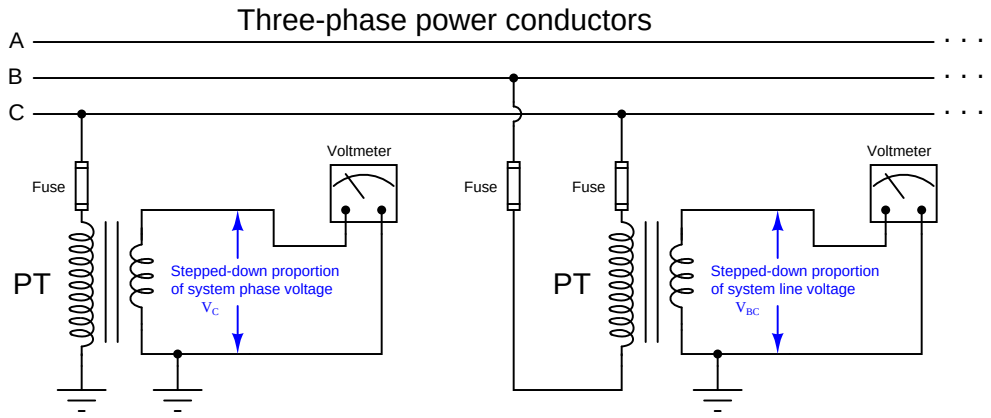
The two measured variables relied on most heavily in the field of electrical power system metering, control and protection are *voltage* and *current*. From these primary variables we may determine impedance, reactance, resistance, as well as the reciprocals of those quantities (admittance, susceptance, and conductance).

Two common types of electrical sensors used in the power industry are *potential transformers* (PTs) and *current transformers* (CTs). These are precision-ratio electromagnetic transformers used to step high voltages and high currents down to more reasonable levels for the benefit of panel-mounted instruments to receive, display, and/or process.

2.1 Potential transformers

Electrical power systems typically operate at dangerously high voltage. It would be both impractical and unsafe to connect panel-mounted instruments directly to the conductors of a power system if the voltage of that power system exceeds several hundred Volts. For this reason, we must use a special type of step-down transformer referred to as a *potential transformer* to reduce and isolate the high line voltage of a power system to levels safe for panel-mounted instruments to input.

Shown here is a simple diagram illustrating how the high phase and line voltages of a three-phase AC power system may be sensed by low-voltage voltmeters through the use of step-down potential transformers:



Potential transformers are commonly referred to as "PT" units in the electrical power industry. It should be noted that the term "voltage transformer" and its associated abbreviation VT is becoming popular as a replacement for "potential transformer" and PT.

When driving a voltmeter – which is essentially an open-circuit (very high resistance) – the PT behaves as a voltage source to the receiving instrument, sending a voltage signal to that instrument proportionately representing the power system's voltage. The grounded secondary winding of the PT ensures the high common-mode voltage of the power conductors will never manifest at the voltmeter.

It is important to draw as little power from an instrument transformer as possible in order to avoid "loading" it or "burdening" it and thereby cause its output signal to droop to some value less than a correct proportion of the measured power system quantity. For a PT this means maintaining any load above some minimum value in Ohms. Ideally a PT would drive voltage-sensing instruments having infinite input impedance, presenting no power load at all, but all real meters and protective relays demand some amount of energy from the instrument transformer. PTs will usually bear a *burden* rating stating the minimum load resistance (or alternatively, maximum load power) required to operate within a specified transformation accuracy.

The following photograph shows a potential transformer sensing the phase-to-ground voltage on a three-phase power distribution system. The normal phase voltage in this system is 7.2 kV (12.5 kV three-phase line voltage), and the PT's normal secondary voltage is 120 Volts, necessitating a ratio of 60:1 (as shown on the transformer's side):

Any voltage output by this PT will be $\frac{1}{60}$ of the actual phase voltage, allowing panel-mounted instruments to read a precisely scaled proportion of the 7.2 kV (typical) phase voltage safely and effectively. A panel-mounted voltmeter, for example, would have a scale registering 7200 Volts when its actual input terminal voltage was only 120 Volts.

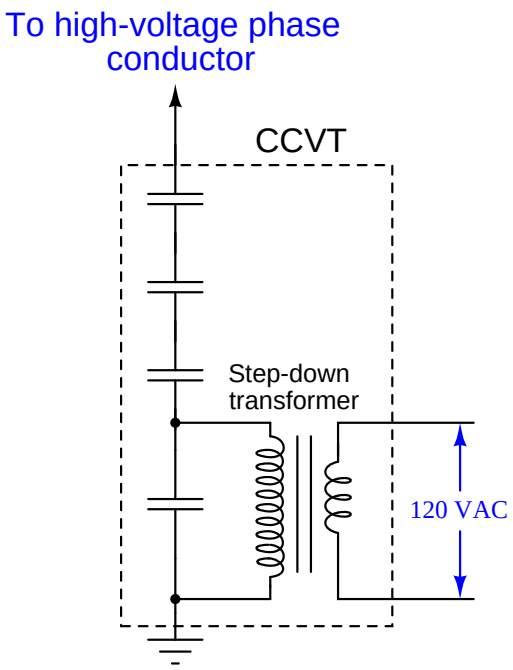
This next photograph shows a set of three PTs used to measure voltage on a 13.8 kV substation bus. Note how each of these PTs is equipped with *two* high-voltage insulated terminals to facilitate phase-to-phase (line voltage) measurements as well as phase-to-ground:

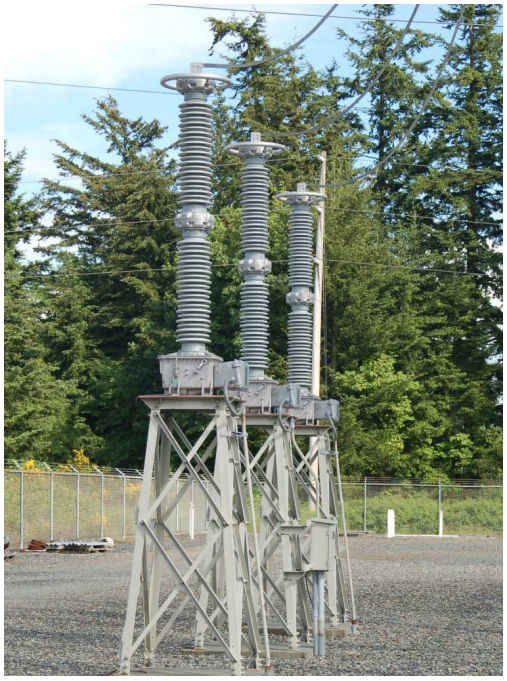
Another photograph of potential transformers appears here, showing three large PTs used to precisely step the phase-to-ground voltages for each phase of a 230 kV system (230 kV line voltage, 133 kV phase voltage) all the way down to 120 Volts for the panel-mounted instruments to monitor:

A loose-hanging wire joins one side of each PT's primary winding to the respective phase conductor of the 230 kV bus. The other terminal of each PT's primary winding connects to a common neutral point, forming a Wye-connected PT transformer array. The secondary terminals of these PTs connect to two-wire shielded cables conveying the 120 volt signals back to the control room where they terminate at various instruments. These shielded cables run through underground conduit for protection from weather.

Just as with the previous PT, the standard output voltage of these large PTs is 120 Volts, equating to a transformer turns ratio of about 1100:1. This standardized output voltage of 120 Volts allows PTs of any manufacture to be used with receiving instruments of any manufacture, just as the 4-20 mA standard for analog industrial instruments allows "interoperability" between different manufacturers' brands and models.

A special form of instrument transformer used on very high-voltage systems is the *capacitively-coupled voltage transformer*, or CCVT. These sensing devices employ a series-connected set of capacitors dividing the power line voltage down to a lesser quantity before it gets stepped down further by an electromagnetic transformer. A simplified diagram of a CCVT appears here, along with a photograph of three CCVTs located in a substation:

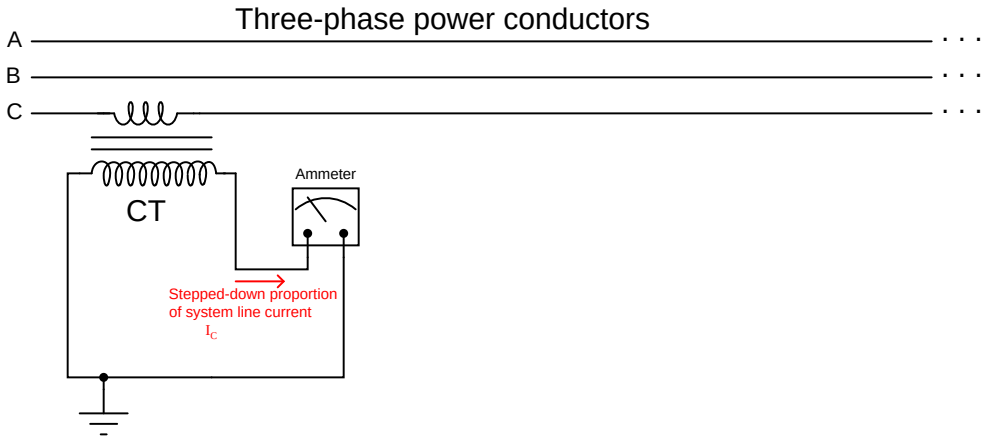




2.2 Current transformers

For the same reasons necessitating the use of potential (voltage) instrument transformers, we also see the use of *current transformers* to reduce high current values and isolate high voltage values between the electrical power system conductors and panel-mounted instruments.

Shown here is a simple diagram illustrating how the line current of a three-phase AC power system may be sensed by a low-current ammeter through the use of a current transformer:

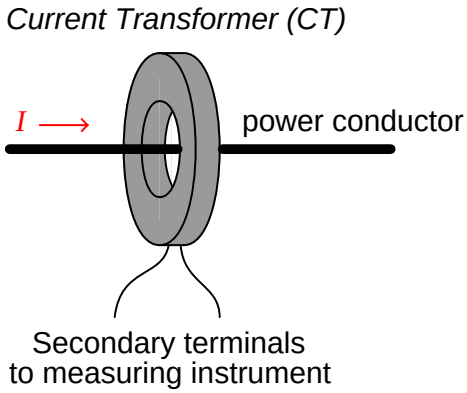


When driving an ammeter – which is essentially a short-circuit (very low resistance) – the CT behaves as a current source to the receiving instrument, sending a current signal to that instrument proportionately representing the power system's line current. The grounded secondary winding of the CT ensures the high common-mode voltage of the power conductors will never manifest at the ammeter[1].

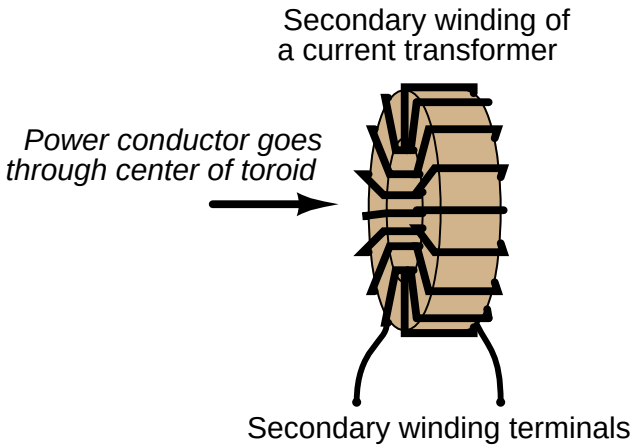
It is important to draw as little power from an instrument transformer as possible in order to avoid "loading" it or "burdening" it and thereby cause its output signal to droop to some value less than a correct proportion of the measured power system quantity. For a CT this means maintaining any load below some maximum value in Ohms. Ideally a CT would drive current-sensing instruments having zero input impedance, presenting no power load at all, but all real meters and protective relays demand some amount of energy from the instrument transformer. CTs will usually bear a *burden* rating stating the maximum load resistance (or alternatively, maximum load power) required to operate within a specified transformation accuracy.

[1] An important safety rating for current transformers is the *Basic Insulation Level*, or *BIL*. This states the dielectric strength between primary and secondary, typically expressed in kiloVolts (kV), that the CT is able to routinely withstand. If you closely examine the nameplates of CTs shown in some of the photographs contained in this tutorial, you will see voltage ratings printed on them.

In typical practice a CT consists of an iron toroid[2] functioning as the transformer core. This type of CT does not have a primary "winding" in the conventional sense of the word, but rather uses the line conductor itself as the primary winding. The line conductor passing once through the center of the toroid functions as a primary transformer winding with exactly 1 "turn". The secondary winding consists of multiple turns of wire wrapped around the toroidal magnetic core:



A view of a current transformer's construction shows the wrapping of the secondary turns around the toroidal magnetic core in such a way that the secondary conductor remains parallel to the primary (power) conductor for good magnetic coupling:



With the power conductor serving as a single-turn[3] winding, the multiple turns of secondary

[2] A "toroid" is shaped like a donut: a circular object with a hole through the center.

[3] This raises an interesting possibility: if the power conductor were to be wrapped around the toroidal core of the CT so that it passes through the center *twice* instead of *once*, the current step-down ratio will be cut in half. For example, a 100:5 CT with the power conductor wrapped around so it passes through the center twice will exhibit an actual current ratio of only 50:5. If wrapped so that it passed through the CT's center three times, the ratio would be reduced to 33.33:5. This useful "trick" may be used in applications where a lesser CT ratio cannot be found, and one must make do with whatever CT happens to be available. If you choose to do this, however, beware that the current-measuring capacity of the CT will be correspondingly reduced. Each extra turn of the power conductor

wire around the toroidal core of a CT makes it function as a step-up transformer with regard to voltage, and as a *step-down* transformer with regard to current. The turns ratio of a CT is typically specified as a ratio of full line conductor current to 5 Amperes, which is a standard output current for power CTs. Therefore, a 100:5 ratio CT consists of 20 turns of wire wrapped around the toroidal iron core (for a 20:1 turns ratio with the power conductor), and outputs 5 Amperes when the power conductor carries 100 Amperes.

The turns ratio of a current transformer suggests a danger worthy of note: if the secondary winding of an energized CT is ever open-circuited, it may develop an extremely high voltage as it attempts to force current through the air gap of that open circuit. An energized CT secondary winding acts like a current source, and like all current sources it will develop as great a potential (voltage) as it can when presented with an open circuit. Given the high voltage capability of the power system being monitored by the CT, and the CT turns ratio with more turns in the secondary than in the primary, the ability for a CT to function as a *voltage step-up* transformer poses a significant hazard.

Like any other current source, there is no harm in short-circuiting the output of a CT. Only an open circuit poses risk of damage. For this reason, CT circuits are often equipped with *shorting bars* and/or *shorting switches* to allow technicians to place a short-circuit across the CT secondary winding before disconnecting any other wires in the circuit. Later subsections will elaborate on this topic in greater detail.

adds to the magnetic flux experienced by the CT's core for any given amount of line current, making it possible to magnetically saturate the core if the line current exceeds the reduced value (e.g. 50 Amperes for the home-made 50:5 CT where the line passes twice through the center of a 100:5 CT).

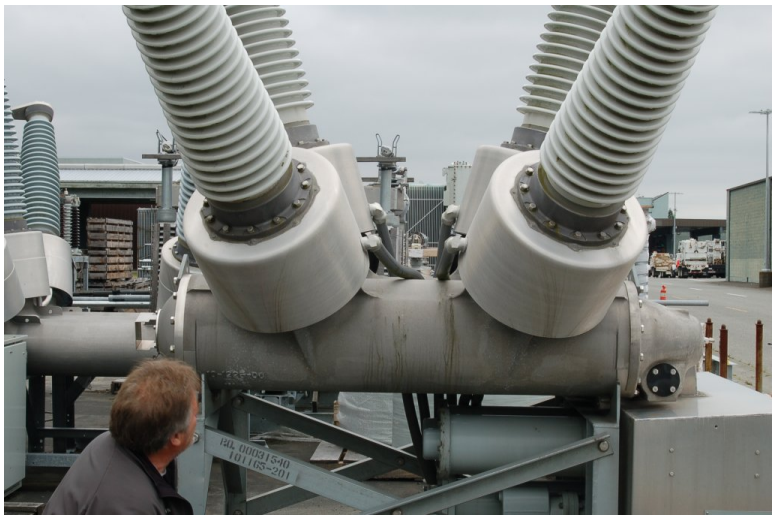
Current transformers are manufactured in a wide range of sizes, to accommodate different applications. Here is a photograph of a current transformer showing the "nameplate" label with all relevant specifications. This nameplate specifies the current ratio as "100/5" which means this CT will output 5 Amperes of current when there is 100 Amperes flowing through a power conductor passed through the center of the toroid:

The black and white wire pair exiting this CT carries the 0 to 5 Ampere AC current signal to any monitoring instrument scaled to that range. That instrument will see $\frac{1}{20}$ (i.e. $\frac{5}{100}$) of the current flowing through the power conductor.

The following photographs contrast two different styles of current transformer, one with a "window" through which any conductor may be passed, and another with a dedicated busbar fixed through the center to which conductors attach at either end.

Here is a photograph of some much larger CTs intended for installation inside the "bushings[4]" of a large circuit breaker, stored on a wooden pallet:

The installed CTs appear as cylindrical bulges at the base of each insulator on the high-voltage circuit breaker. This particular photograph shows flexible conduit running to each bushing CT, carrying the low-current CT secondary signals to a terminal strip inside a panel on the right-hand end of the breaker:

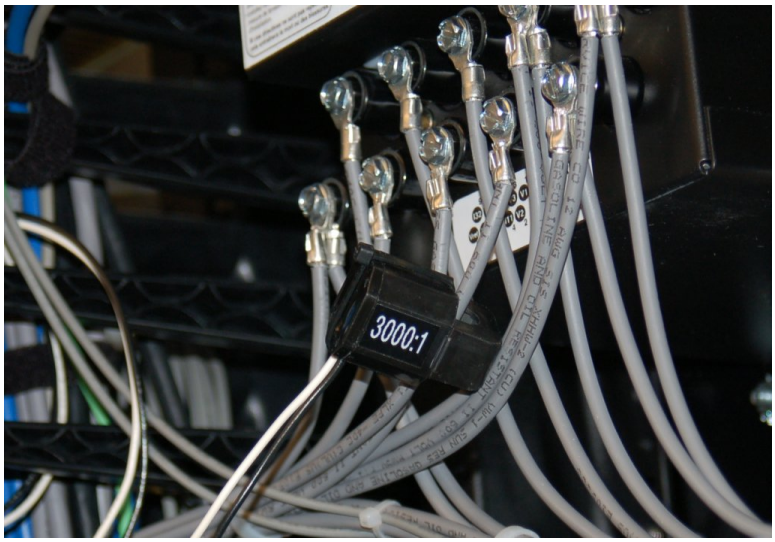


Signals from the bushing CTs on a circuit breaker may be connected to *protective relay* devices to trip the breaker in the event of any abnormal condition. If unused, a CT's secondary terminals are simply short-circuited at the panel.

[4]High-voltage devices situate their connection terminals at the ends of long insulators, to provide a large air gap between the conductors and the grounded metal chassis of the device. The point at which the long insulator (with a conductor inside of it) penetrates the housing of the device is called the *bushing*.

Shown here is a set of three very large CTs, intended for installation at the bushings of a high-voltage power transformer. Each one has a current step-down ratio of 600-to-5:

In this next photograph we see a tiny CT designed for low current measurements, clipped over a wire carrying only a few Amperes of current. This particular current transformer is constructed in such a way that it may be clipped around an existing wire for temporary test purposes, rather than being a solid toroid where the conductor must be threaded through it for a more permanent installation:

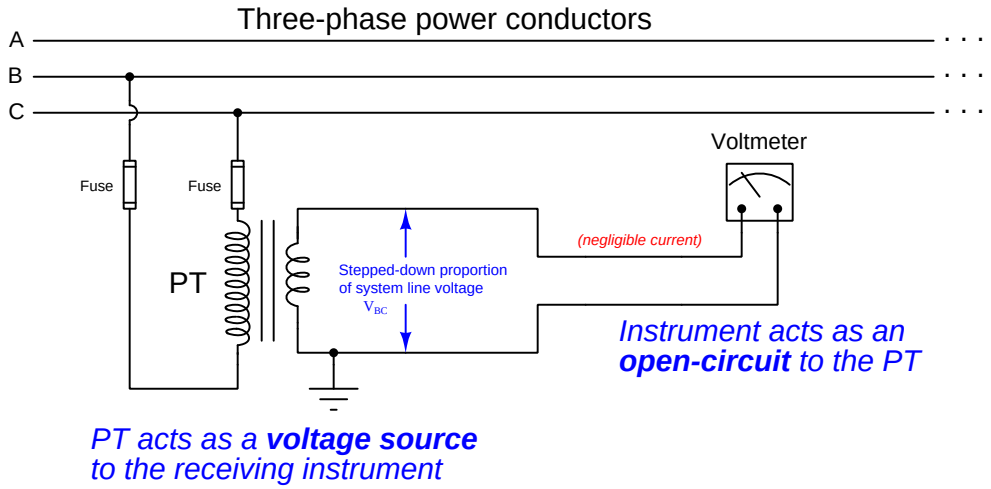


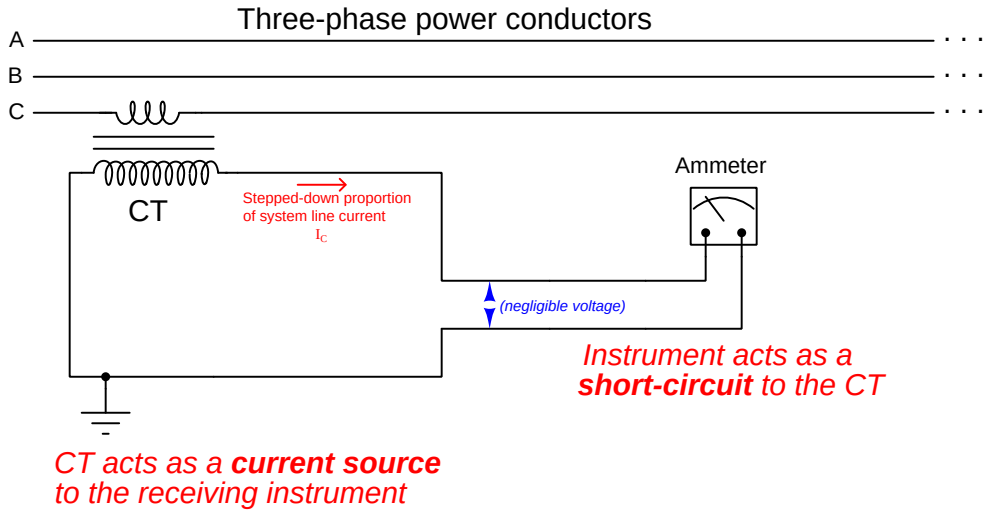
This CT's ratio of 3000:1 would step down a 5 Ampere AC signal to 1.667 milliAmperes AC.

This last photograph shows a current transformer used to measure line current in a 500 kV substation switchyard. The actual CT coil is located inside the red-colored housing at the top of the insulator, where the power conductor passes through. The tall insulator stack provides necessary separation between the conductor and the earth below to prevent high voltage from "jumping" to ground through the air:

2.3 Instrument transformer safety

Potential transformers (PTs or VTs) tend to behave as *voltage sources* to the voltage-sensing instruments they drive: the signal output by a PT is supposed to be a proportional representation of the power system's voltage. Conversely, current transformers (CTs) tend to behave as *current sources* to the current-sensing instruments they drive: the signal output by a CT is supposed to be a proportional representation of the power system's current. The following schematic diagrams show how PTs and CTs should behave when sourcing their respective instruments:





In keeping with this principle of PTs as voltage sources and CTs as current sources, *a PT's secondary winding should never be short-circuited and a CT's secondary winding should never be open-circuited!* Short-circuiting a PT's secondary winding may result in a dangerous amount of current developing in the circuit because the PT will attempt to maintain a substantial voltage across a very low resistance. Open-circuiting a CT's secondary winding may result in a dangerous amount of voltage[5] developing between the secondary terminals because the CT will attempt to drive a substantial current through a very high resistance.

This is why you will never see fuses in the secondary circuit of a current transformer. Such a fuse, when blown open, would pose a greater hazard to life and property than a closed circuit with any amount of current the CT could muster.

While the recommendation to never short-circuit the output of a PT makes perfect sense to any student of electricity or electronics who has been drilled never to short-circuit a battery or a laboratory power supply, the recommendation to never *open*-circuit a powered CT often requires some explanation. Since CTs transform current, their output current value is naturally limited to a fixed ratio of the power conductor's line current. That is to say, short-circuiting the secondary winding of a CT will *not* result in more current output by that CT than what it would output to any normal current-sensing instrument! In fact, a CT encounters minimum "burden" when powering a short-circuit because it doesn't have to output any substantial voltage to maintain that amount of secondary current. It is only when a CT is forced to output current through a substantial impedance that it must "work hard" (i.e. output more power) by generating a substantial secondary voltage along with a secondary current.

The latent danger of a CT is underscored by an examination of its primary-to-secondary turns ratio. A single conductor passed through the aperture of a current transformer acts as a winding with one turn, while the multiple turns of wire wrapped around the toroidal core of a current transformer provides the ratio necessary to step down current from the power line to the receiving instrument. However, as every student of transformers knows, while a secondary winding possessing more turns of wire than the primary *steps current down*, that same transformer conversely will *step voltage up*. This means an open-circuited CT behaves as a voltage step-up transformer. Given the fact that the power line being measured usually has a dangerously high voltage to begin with, the prospect of an instrument transformer stepping that voltage up even higher is sobering indeed. In fact, the only way to ensure a CT will not output high voltage when powered by line current is to keep its secondary winding loaded with a low impedance.

It is also imperative that all instrument transformer secondary windings be solidly *grounded* to prevent dangerously high voltages from developing at the instrument terminals via capacitive coupling with the power conductors. Grounding should be done at only one point in each instrument transformer circuit to prevent *ground loops* from forming and potentially causing measurement errors. The preferable location of this grounding is at the first point of use, i.e. the instrument or panel-mounted terminal block where the instrument transformer's secondary wires land. If any test switches exist between the instrument transformer and the receiving instrument, the ground connection must be made in such a way that opening the test switch does not leave the transformer's secondary winding floating (ungrounded).

[5] The hazards of an open-circuited CT can be spectacular. I have spoken with power electricians who have personally witnessed huge arcs develop across the opened terminals in a CT circuit! This safety tip is not one to be lightly regarded.

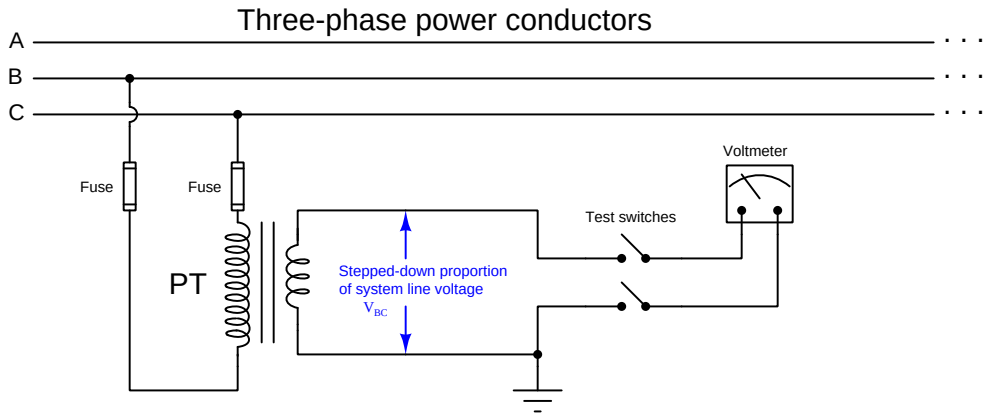
2.4 Instrument transformer test switches

Connections made between instrument transformers and receiving instruments such as panel-mounted meters and relays must be occasionally broken in order to perform tests and other maintenance functions. An accessory often seen in power instrument panels is a *test switch bank*, consisting of a series of knife switches. A photograph of a test switch bank manufactured by ABB is seen here:

Some of these knife switches serve to disconnect potential transformers (PTs) from receiving instruments mounted on this relay panel, while other knife switches in the same bank serve to disconnect current transformers (CTs) from receiving instruments mounted on the same panel.

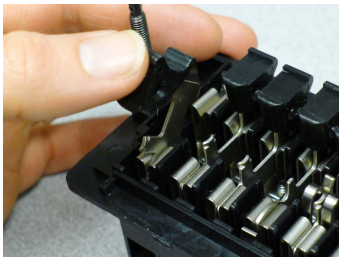
For added security, covers may be installed on the switch bank to prevent accidental operation or electrical contact. Some test switch covers are even lock-able by padlock, for an added measure of access prevention.

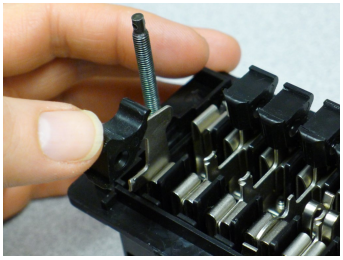
Test switches used to disconnect potential transformers (PTs) from voltage-sensing instruments are nothing more than simple single-pole, single-throw (SPST) knife switches, as shown in this diagram:



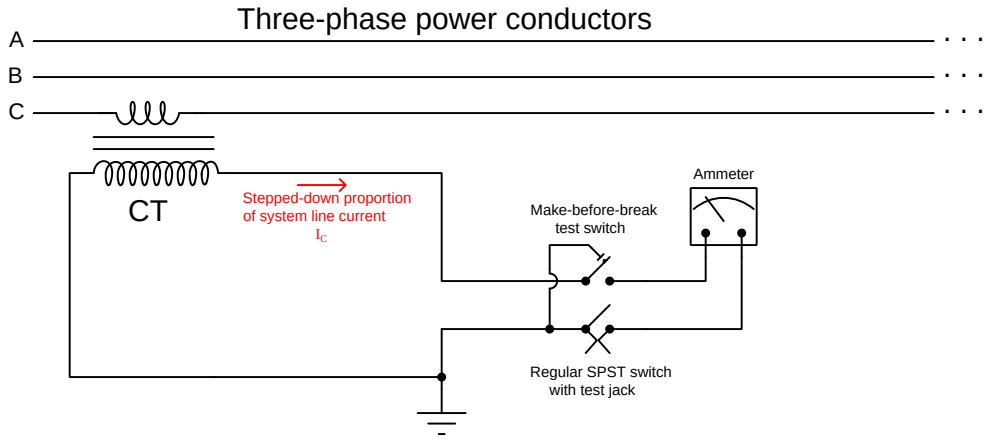
There is no danger in open-circuiting a potential transformer circuit, and so nothing special is needed to disconnect a PT from a receiving instrument.

A series of photographs showing the operation of one of these knife switches appears here, from closed (in-service) on the left to open (disconnected) on the right:

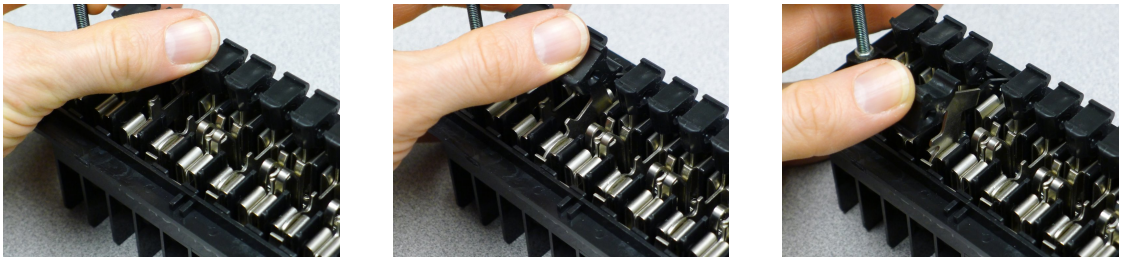




Test switches used to disconnect current transformers (CTs) from current-sensing instruments, however, must be specially designed to avoid opening the CT circuit when disconnecting, due to the high-voltage danger posed by open-circuited CT secondary windings. Thus, CT test switches are designed to place a *short-circuit* across the CT's output before opening the connection to the current-measuring device. This is done through the use of a special *make-before-break* knife switch:



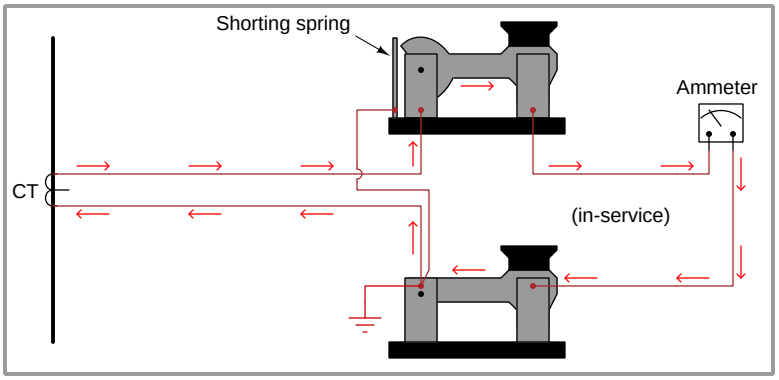
A series of photographs showing the operation of a make-before-break knife switch appears here, from closed (in-service) on the left to shorted (disconnected) on the right:



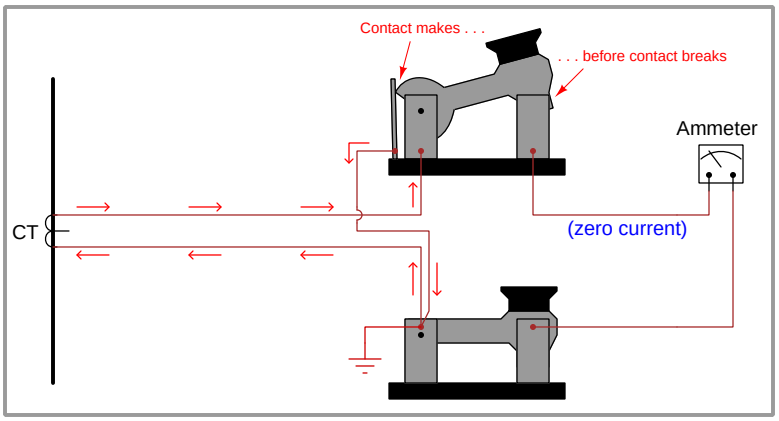
The shorting action takes place at a spring-steel leaf contacting the moving knife blade at a cam cut near the hinge. Note how the leaf is contacting the cam of the knife in the right-hand and middle photographs, but not in the left-hand photograph. This metal leaf joins with the base of the knife switch adjacent to the right (the other pole of the CT circuit), forming the short-circuit between CT terminals necessary to prevent arcing when the knife switch opens the circuit to the receiving instrument.

A step-by-step sequence of illustrations shows how this shorting spring works to prevent the CT circuit from opening when the first switch is opened:

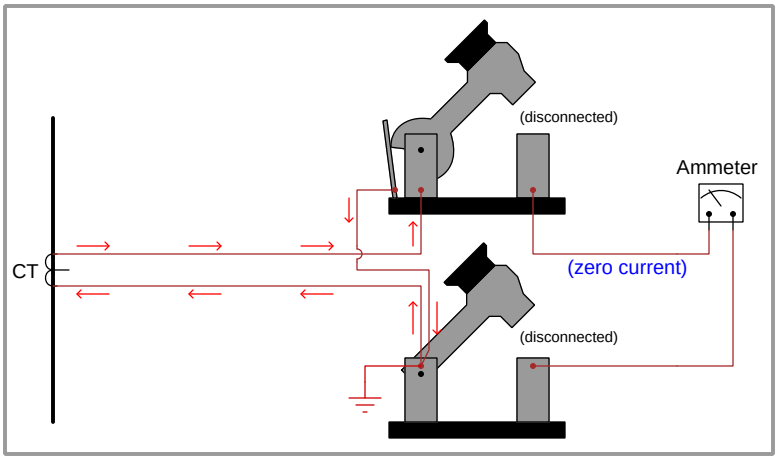
Step 1:



Step 2:



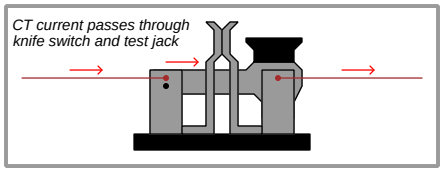
Step 3:



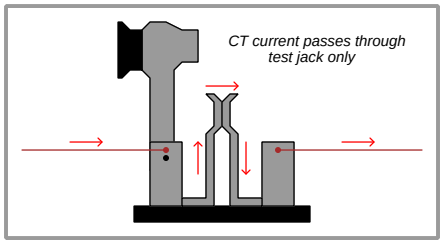
It is typical that the non-shorting switch in a CT test switch pair be equipped with a "test jack" allowing the insertion of an additional ammeter in the circuit for measurement of the CT's signal. This test jack consists of a pair of spring-steel leafs contacting each other in the middle of the knife switch's span. When that knife switch is in the open position, the metal leafs continue to provide continuity past the open knife switch. However, when a special ammeter adapter plug is forced between the leafs, spreading them apart, the circuit breaks and the current must flow through the two prongs of the test plug (and to the test ammeter connected to that plug).

A step-by-step sequence of illustrations shows how a test jack maintains continuity across an opened knife switch, and then allows the insertion of a test probe and ammeter, without ever breaking the CT circuit:

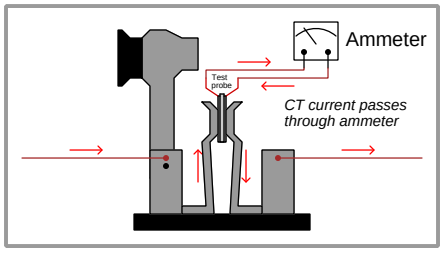
Step 1:



Step 2:

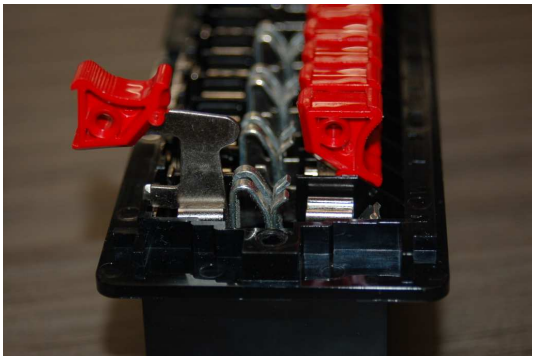


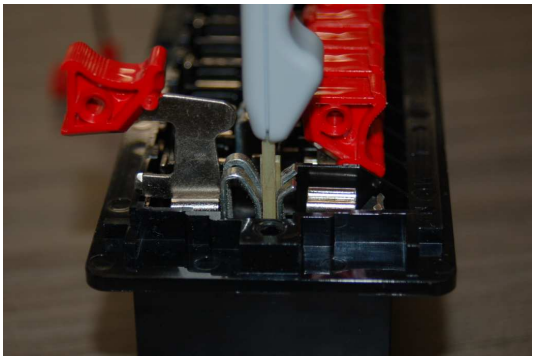
Step 3:



When using a CT test probe like this, one must be sure to thoroughly test the electrical continuity of the ammeter and test leads before inserting the probe into the test jacks. If there happens to be an "open" fault anywhere in the ammeter/lead circuit, a dangerous arc will develop at the point of that "open" the moment the test probe forces the metal leafs of the test jack apart! Always remember that a live CT is dangerous when open-circuited, and so your personal safety depends on always maintaining electrical continuity in the CT circuit.

The following close-up photographs show a closed CT test switch equipped with a test jack (left), and a test plug inserted into this jack (right). Note how the jack's spring leafs are visible in the middle of the switch in full contact with each other (left) and then forced apart by the test probe (right). The metallized faces of the test probe make contact with the left and right halves of the test jack to ensure continuity through the test probe (and by extension, through the ammeter connected to the test probe):

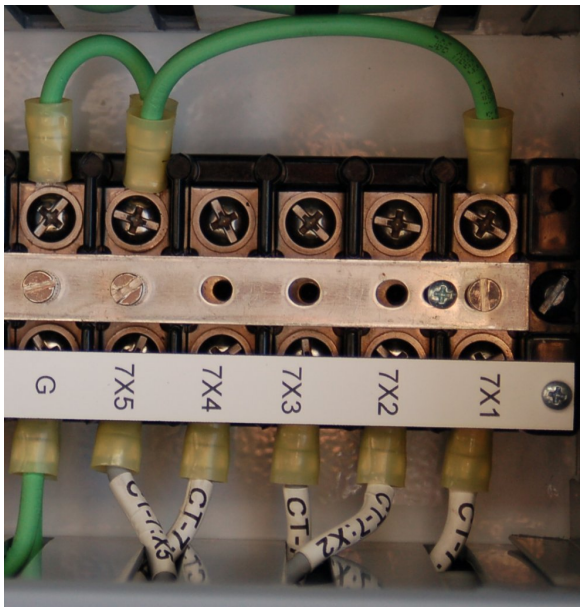




As previously mentioned, it is imperative that the ammeter and test probe as a whole assembly be electrically continuous, because inserting the probe into the jack on a live CT circuit will otherwise break that circuit and create a dangerous (high-voltage) condition. For this reason, protective relay technicians are known to replace the overcurrent protection fuse in their multimeters with a brass slug or other uninterruptible current element so that there is no chance of an open-circuit condition happening except perhaps for an open fault occurring within the ammeter itself.

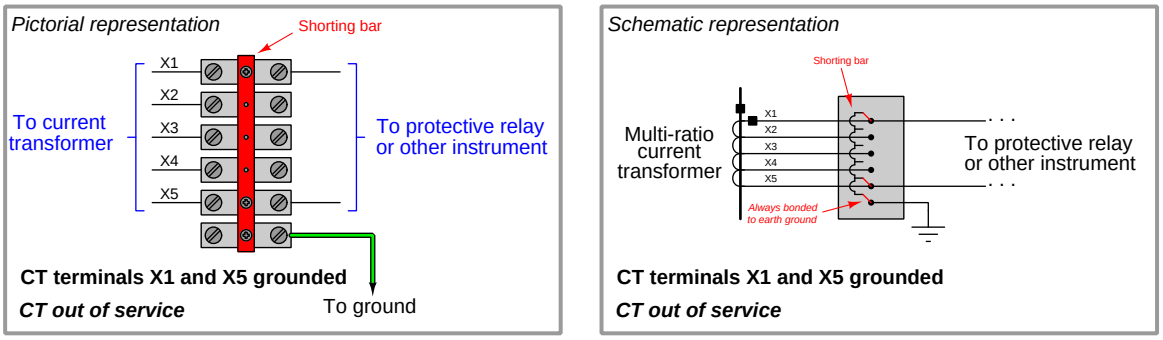
2.5 Instrument transformer terminal blocks

In addition to (or sometimes in lieu of) test switches, current transformer secondary wiring often passes through special "shorting" terminal blocks. These special terminal blocks have a metal "shorting bar" running down their center, through which screws may be inserted to engage with wired terminals below. Any terminals made common to this metal bar will necessarily be equipotential to each other. One screw is always inserted into the bar tapping into the earth ground terminal on the terminal block, thus making the entire bar grounded. Additional screws inserted into this bar force CT secondary wires to ground potential. A photo of such a shorting terminal block is shown here, with five conductors from a multi-ratio (multi-tap) current transformer labeled *7X1* through *7X5* connecting to the terminal block from below:

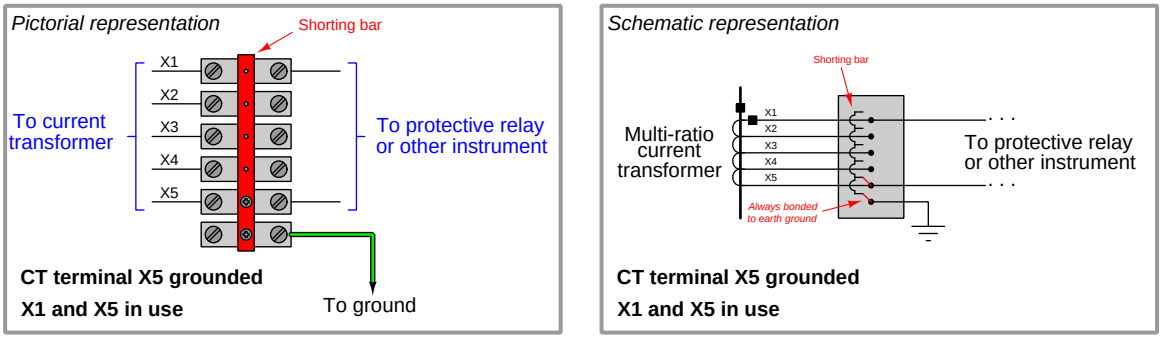


This shorting terminal block has three screws inserted into the shorting bar: one bonding the bar to the ground ("G") terminal on the far-left side, another one connecting to the "7X5" CT wire, and the last one connecting to the "7X1" CT wire. While the first screw establishes earth ground potential along the shorting bar, the next two screws form a short circuit between the outer two conductors of the multi-ratio current transformer. Note the green "jumper" wires attached to the top side of this terminal block shorting 7X1 to 7X5 to ground, as an additional measure of safety for this particular CT which is currently unused and not connected to any measuring instrument.

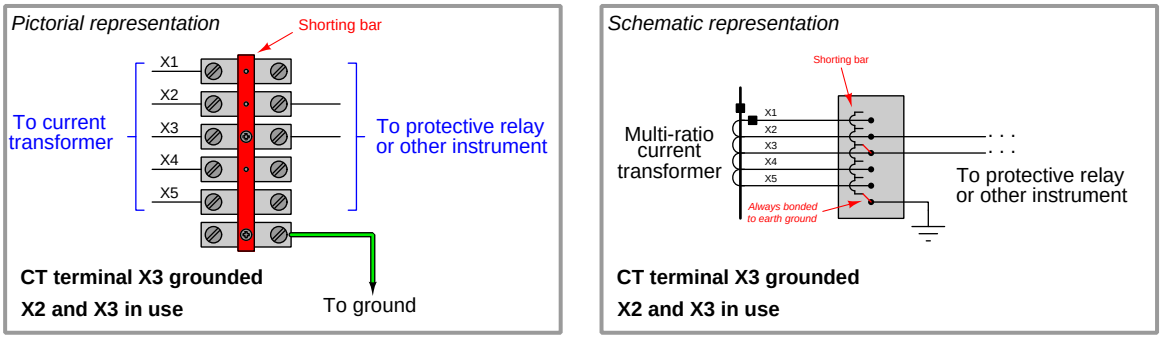
The following illustrations show combinations of screw terminal positions used to selectively ground different conductors on a multi-ratio current transformer. The first of these illustrations show the condition represented in the previous photograph, with the entire CT shorted and grounded:



This next illustration shows how the CT would be used in its full capacity, with X1 and X5 connecting to the panel instrument and (only) X5 grounded for safety:



This final illustration shows how the CT would be used in reduced capacity, with X2 and X3 connecting to the panel instrument and (only) X3 grounded for safety:



2.6 Instrument transformer burden and accuracy

In order for an instrument transformer to function as an accurate sensing device, it must not be unduly tasked with delivering power to a load. In order to minimize the power demand placed on instrument transformers, an ideal voltage-measuring instrument should draw zero current from its PT, while an ideal current-measuring instrument should drop zero voltage across its CT.

The goal of delivering zero power to any instrument is difficult to achieve in practice. Every voltmeter does indeed draw some current, however slight. Every ammeter does drop some voltage, however slight. The amount of apparent power drawn from any instrument transformer is appropriately called *burden*, and like all expressions of apparent power is measured in units of Volt-Amperes. The greater this burden, the more the instrument transformer's signal will "sag" (decrease from loading). Therefore, minimizing burden is a matter of maximizing accuracy for power system measurement.

The burden value for any instrument transformer is a function of apparent power, impedance, and either voltage or current according to the familiar apparent power formulae $S = \frac{V^2}{Z}$ and $S = I^2 Z$:

$$\text{PT burden} = \frac{V_{signal}^2}{Z_{instrument}}$$

$$\text{CT burden} = (I_{signal}^2)(Z_{instrument})$$

Burden for any device or circuit connected to an instrument transformer may be expressed as an impedance value (Z) in Ohms, or as an apparent power value (S) in Volt-Amperes. Similarly, instrument transformers themselves are usually rated for the amount of burden they may source and still perform within a certain accuracy tolerance (e.g. ± 1% at a burden of 2 VA).

2.6.1 Potential transformer burden and accuracy ratings

Potential transformers have maximum burden values specified in terms of apparent power (S,measured in Volt-Amperes), standard burden values being classified by letter code:

Letter code	**Maximum allowable burden at stated accuracy**
W	12.5 Volt-Amperes
X	25 Volt-Amperes
M	35 Volt-Amperes
Y	75 Volt-Amperes
Z	200 Volt-Amperes
ZZ	400 Volt-Amperes

Standard accuracy classes for potential transformers include 0.3, 0.6, and 1.2, corresponding to uncertainties of ± 0.3%, ± 0.6%, and ± 1.2% of the rated turns ratio, respectively. These accuracy class and burden ratings are typically combined into one label. A potential transformer rated "0.6M" therefore has an accuracy of ± 0.6% (this percentage being understood as its *turns ratio* accuracy) while powering a burden of 35 Volt-Amperes at its nominal (e.g. 120 Volts) output.

2.6.2 Current transformer burden and accuracy ratings

Current transformer accuracies and burdens are more complicated than potential transformer ratings. The principal reason for this is the wider range of CT application. If a current transformer is to be used for *metering* purposes (i.e. driving wattmeters, ammeters, and other instruments used for regulatory control and/or revenue billing where high accuracy is required), it is assumed the transformer will operate within its standard rated current values. For example, a 600:5 ratio current transformer used for metering should rarely if ever see a primary current value exceeding 600 Amperes, or a secondary current exceeding 5 Amperes. If current values through the CT ever do exceed these maximum standard values, the effect on regulation or billing will be negligible because these should be transient events. However, protective relays are designed to interpret and act upon transient events in power systems. If a current transformer is to be used for *relaying* rather than metering, it must reliably perform under overload conditions typically created by power system faults. In other words, relay applications of CTs demand a much larger dynamic range of measurement than meter applications. Absolute accuracy is not as important for relays, but we must ensure the CT will give a reasonably accurate representation of line current during fault conditions in order for the protective relay(s) to function properly. PTs, even those used for protective relaying purposes, never see voltage transients as wide-ranging as the current transients seen by CTs.

Meter class CT ratings typically take the form of a percentage value followed by the letter "B" followed by the maximum burden expressed in Ohms of impedance. Therefore, a CT with a metering classification of 0.3B1.8 exhibits an accuracy of ± 0.3% of turns ratio when powering a 1.8 Ohm meter impedance at 100% output current (typically 5 Amperes).

Relay class CT ratings typically take the form of a maximum *voltage* value dropped across the burden at 20 times rated current (i.e. 100 Amperes secondary current for a CT with a 5 Ampere nominal output rating) while maintaining an accuracy within ±10% of the rated turns ratio. Not coincidentally, this is how CT ratios are usually selected for power system protection: such that the maximum expected symmetrical fault current through the power conductor does not exceed 20 times the primary current rating of the CT[6]. Therefore, a CT with a relay classification of C200 is able to output up to 200 Volts while powering its maximum burden at 20× rated current. Assuming a rated output current of 5 Amperes, 20 times this value would be 100 Amperes delivered to the relay. If the relay's voltage drop at this current is allowed to be as high as 200 Volts, it means the CT secondary circuit may have an impedance value of up to 2 Ohms (200 V ÷ 100 A = 2 Ω). Therefore, a relaying CT rating of C200 is just another way of saying it can power as much as 2 Ohms of burden.

The letter "C" in the "C200" rating example stands for *calculated*, which means the rating is based on theory. Some current transformers use the letter "T" instead, which stands for *tested*. These CTs have been actually tested at the specified voltage and current values to ensure their performance under real-world conditions.

[6] For example, in an application where the maximum fault current is expected to be 40,000 Amperes, we would choose a CT with a ratio of at least 2000:5 to drive the protective relay, because 40,000 Amperes is twenty times this CT's primary current rating of 2000 Amperes. We could also select a CT with a larger ratio such as 3000:5. The point is to have the CT be able to faithfully transform any reasonable fault current into a proportionately lower value for the protective relay(s) to sense.

2.6.3 Current transformer saturation

It is worthwhile to explore the concept of maximum CT burden in some detail. In an ideal world, a CT acts as a current source to the meter or relay it is powering, and as such it is quite content to drive current into a short circuit (0 Ohms impedance). Problems arise if we demand the CT to supply more power than it is designed to, which means forcing the CT to drive current through an excessive amount of impedance. In the days of electromechanical meters and protective relays where the devices were entirely powered by instrument transformer signals, the amount of burden imposed by certain meters and relays could be quite substantial[7]. Modern electronic meters and relays pose much less burden to instrument transformers, approaching the ideal conditions of zero impedance for current-sensing inputs.

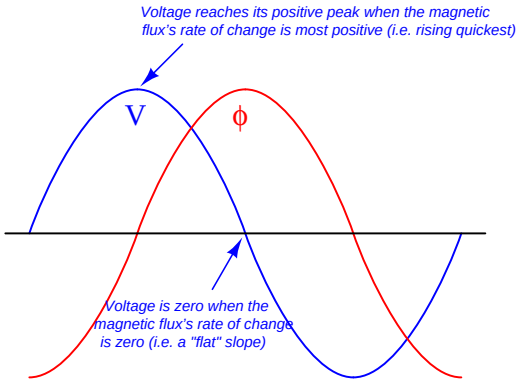
The voltage developed by any inductance, including transformer windings, is described by Faraday's Law of Electromagnetic Induction:

$$V = N\frac{d\Phi}{dt}$$

Where,

V = Induced voltage (Volts)
N = Number of turns of wire
$\frac{d\Phi}{dt}$ = Rate of change of magnetic flux (Webers per second)

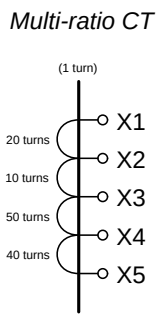
To generate a larger voltage, therefore, a current transformer must develop a faster-changing magnetic flux in its core. If the voltage in question is sinusoidal at a constant frequency, the magnetic flux also traces a sinusoidal function over time, the voltage peaks coinciding with the steepest points on the flux waveform, and the voltage "zero" points coinciding with the peaks on the flux waveform where the rate-of-change of magnetic flux over time is zero:



[7] An illustrative example to consider is the venerable Westinghouse model CO-11 overcurrent relay, exhibiting a burden of 1.07 Volt-Amperes at a CT secondary current of 5 Amperes with a 5-Ampere tap setting. By contrast, an SEL-551 digital overcurrent relay exhibits only 0.16 Volt-Amperes of burden at the same CT current of 5 Amperes: nearly *seven times less* burden than the electromechanical relay. The reason for this stark disparity in burden values is the design of each relay: the electromechanical relay demands power from the CT to spin an aluminum disk against the restraining forces of a spring and a drag magnet, while the electronic relay receives operating power from a separate source (station power) and only requires that the CT drive the input of an analog-to-digital converter (ADC) circuit.

Imposing a larger burden on a CT (i.e. more impedance the current must drive through) means the CT must develop a larger sinusoidal voltage for any given amount of measured line current. This equates to a flux waveform with a faster-changing rate of rise and fall, which in turn means a higher-peak flux waveform (assuming a sinusoidal shape). The problem with this at some point is that the required magnetic flux reaches such high peak values that the ferrous[8] core of the CT begins to saturate with magnetism, at which point the CT ceases to behave in a linear fashion and will no longer faithfully reproduce the shape and magnitude of the power line current waveform. In simple terms, if we place too much burden on a CT it will begin to output a distorted signal no longer faithfully representing line current.

The fact that a CT's maximum AC voltage output depends on the magnetic saturation limit of its ferrous core becomes particularly relevant to *multi-ratio* CTs where the secondary winding is provided with more than two "taps". Multi-ratio current transformers are commonly found as the permanently mounted CTs in the bushings of power transformers, giving the end-user freedom in configuring their metering and protection circuits. Consider this distribution transformer bushing 600:5 CT with a C800 accuracy class rating:



Current ratio	Taps
50:5	X2-X3
100:5	X1-X2
150:5	X1-X3
200:5	X4-X5
250:5	X3-X4
300:5	X2-X4
400:5	X1-X4
450:5	X3-X5
500:5	X2-X5
600:5	X1-X5

This CT's "C800" classification is based on its ability to source a maximum of 800 Volts to a burden *when all of its secondary turns are in use*. That is to say, its rating is "C800" only when connected to taps X1 and X5 for the full 600:5 ratio. If someone happens to connect to taps X1-X3 instead, using only 30 turns of wire in the CT's secondary instead of all 120 turns, this CT will be limited to sourcing 200 Volts to a burden before saturating: the same magnitude of magnetic flux that could generate 800 Volts across 120 turns of wire can only induce one-quarter as much voltage across one-quarter the number of turns, in accordance with Faraday's Law of Electromagnetic Induction ($V = N\frac{d\Phi}{dt}$). Thus, the CT must be treated as a "C200" unit when wired for a 150:5 ratio.

[8] Iron and iron alloys ("ferrous") reach a point of maximum magnetization where all the magnetic "domains" in a sample are oriented in the same direction, leaving no more left to orient. Once a sample of ferrous material has thus "saturated", it is of no further benefit to the establishment of a magnetic field. Increases in magnetic force will still produce additional lines of magnetic flux, but not at the rate experienced when the material was not saturated. In other words, a magnetically saturated inductor or transformer core essentially behaves like an air-core inductor or transformer for all additional current values beyond full saturation.

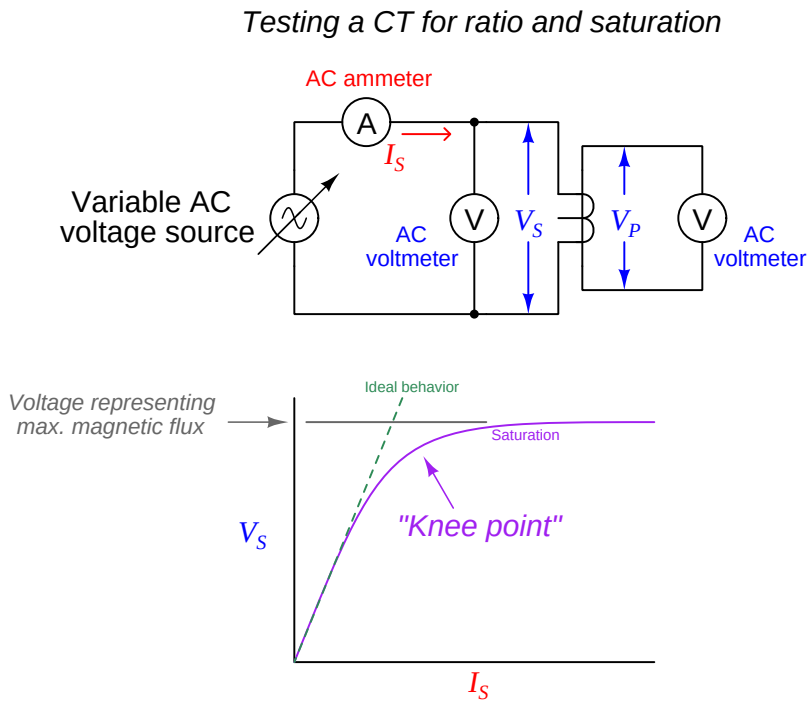
The presence of any direct current in AC power line conductors poses a problem for current transformers which may only be understood in terms of magnetic flux in the CT core. Any direct current (DC) in a power line passing through a CT biases the CT's magnetic field by some amount, making CT saturate more easily in one half-cycle of the AC than the other. Direct currents never sustain indefinitely in AC power systems, but are often present as transient pulses during certain fault conditions. Even so, transient DC currents will leave CT cores with some residual magnetic bias predisposing them to saturation in future fault conditions. The ability of a CT core to retain some magnetic flux over time is called *remanence*.

Remanence in a transformer core is an undesirable property. It may be mitigated by designing the core with a air gap (rather than making the core as an unbroken path of ferrous metal), but this compromises other desirable properties such as saturation limits (i.e. maximum output voltage). Some industry experts advise CTs be demagnetized by maintenance personnel as part of the repair work following a high-current fault, in order to ensure optimum performance when the system is returned to service. Demagnetization consists of passing a large AC current through the CT and then slowly reducing the magnitude of that AC current to zero Amperes. The gradual reduction of alternating magnetic field strength from full to zero tends to randomize the magnetic domains in the ferrous core, returning it to an unmagnetized state.

Whatever the cause, CT saturation can be a significant problem for protective relay circuits because these relays must reliably operate under all manner of transient overcurrent events. The more current through the primary of a CT, the more current it should output to the protective relay. For any given amount of relay burden (relay input impedance), a greater current signal translates into a greater voltage drop and therefore a greater demand for the CT to output a driving voltage. Thus, CT saturation is more likely to occur during overcurrent events when we most need the CT to function properly. Anyone tasked with selecting an appropriate current transformer for a protective relaying application must therefore carefully consider the maximum expected value of overcurrent for system faults, ensuring the CT(s) will do their job while driving the burdens imposed by the relays.

2.6.4 Current transformer testing

Current transformers may be bench-tested for turns ratio and saturation[9] by applying a variable AC voltage to the secondary winding while monitoring secondary current and primary voltage with meters. For common "window" style CTs, the primary winding is a single wire threaded through its center hole. An ideal current transformer would present a constant impedance to the AC voltage source and a constant voltage ratio from input to output. A real current transformer will exhibit less and less impedance as voltage is increased past its saturation threshold:



An ideal CT (with no saturation) would trace a straight line. The bent shape reveals the effects of magnetic saturation, where there is so much magnetism in the CT's core that additional current only yields miniscule increases in magnetic flux (revealed by voltage drop).

Of course, a CT is never *powered* by its secondary winding when installed and operating. The purpose of powering a CT "backwards" as shown is to avoid having to drive very high currents through the primary of the CT. If high-current test equipment is available, however, such a *primary injection test* is actually the most realistic way to test a CT.

[9] In the electric power industry this is commonly referred to as a "rat/sat" test.

The following table shows actual voltage and current values taken during a secondary excitation test on a C400 class relay CT with a 2000:5 ratio. The source voltage was increased from zero to approximately 600 Volts AC at 60 Hz for the test while secondary voltage drop and primary voltage were measured using AC voltmeters. Around 575 Volts a "buzzing" sound could be heard coming from the CT – an audible effect of magnetic saturation. Calculated values of secondary winding impedance and turns ratio are also shown in this table:

I_S	V_S	V_P	$Z_S = V_S \div I_S$	Ratio $= V_S \div V_P$
0.0308 A	75.14 V	0.1788 V	2.44 kΩ	420.2
0.0322 A	100.03 V	0.2406 V	3.11 kΩ	415.8
0.0375 A	150.11 V	0.3661 V	4.00 kΩ	410.0
0.0492 A	301.5 V	0.7492 V	6.13 kΩ	402.4
0.0589 A	403.8 V	1.0086 V	6.86 kΩ	400.4
0.0720 A	500.7 V	1.2397 V	6.95 kΩ	403.9
0.0883 A	548.7 V	1.3619 V	6.21 kΩ	402.9
0.1134 A	575.2 V	1.4269 V	5.07 kΩ	403.1
0.1259 A	582.0 V	1.4449 V	4.62 kΩ	402.8
0.1596 A	591.3 V	1.4665 V	3.70 kΩ	403.2
0.2038 A	600.1 V	1.4911 V	2.94 kΩ	402.5

As you can see from this table, the calculated secondary winding impedance Z_S begins to drop dramatically as the secondary voltage exceeds 500 Volts (near the "knee" point of the curve). The calculated turns ratio appears remarkably stable – close to the ideal value of 400 for a 2000:5 CT – but one must remember this ratio is calculated on the basis of *voltage* and not current. Since this test does not compare primary and secondary currents, we cannot see the effects saturation would have on this CT's current-sensing ability. In other words, this test reveals when saturation begins to take place, but it does not necessarily reveal how the CT's current ratio is affected by saturation.

What makes the difference between a 2000:5 ratio CT with a relay classification of C400 and a 2000:5 ratio CT with a relay classification of C800 is not the number of turns in the CT's secondary winding (N)[10] but rather the amount of ferrous metal in the CT's core. The C800 transformer, in order to develop upwards of 800 Volts to satisfy relay burden, must be able to sustain twice as much magnetic flux in its core than the C400 transformer, and this requires a magnetic core in the C800 transformer with (at least) twice as much flux-carrying capacity. All other factors being equal, the higher the burden capacity of a CT, the larger and heavier it must be due to the girth of its magnetic core.

[10] If you think carefully about this, you realize that the number of turns of wire in either CT must be identical, because there is only one "turn" of wire passing through the center of either CT. In order to achieve a 2000:5 ratio, you must have 400 turns of wire wrapped around the toroidal ferrous core per the 1 "turn" of wire passing through the center of that core.

2.6.5 Current transformer circuit wire resistance

The burden experienced by an operating current transformer is the total series impedance of the measuring circuit, consisting of the sum of the receiving instrument's input impedance, the total wire impedance, and the internal secondary winding impedance of the CT itself. Legacy electromechanical relays, with their "operate" coils driven by CT currents, posed significant burden. Since the burden imposed by an electromechanical relay stems from the operation of a wire coil, this burden impedance is a complex quantity having both real (resistive) and imaginary (reactive) components. Modern digital relays with analog-to-digital converters at their inputs generally pose purely resistive burdens to their CTs, and those burden values are generally much less than the burdens imposed by electromechanical relays.

A significant source of burden in any CT circuit is the resistance of the wire carrying the CT's output current to and from the receiving instrument. It is quite common for the total "loop" distance of a CT circuit to be several hundred feet or more if the CTs are located in remote areas of a facility and the protective relays are located in a central control room. For this reason an important aspect of protective relay system design is wire size (gauge), in order to ensure the total circuit resistance does not exceed the CT's burden rating.

Larger-gauge wire has less resistance per unit length than smaller-gauge wire, all other factors being equal. A useful formula for approximating the resistance of copper wire is shown here:

$$R_{1000ft} = e^{0.232G - 2.32}$$

Where,

R_{1000ft} = Approximate wire resistance in Ohms per 1000 feet of wire length

G = American Wire Gauge (AWG) number of the wire

AWG wire sizes, like most "gauge" scales, is inverse: a larger number represents a thinner wire. This is why the formula predicts a smaller R value for a larger G value. An easy example value to plug into this formula is the number 10 representing #10 AWG wire, a common conductor size for CT secondary circuits:

$$R_{1000ft} = e^{(0.232)(10) - 2.32}$$

$$R_{1000ft} = e^{2.32 - 2.32}$$

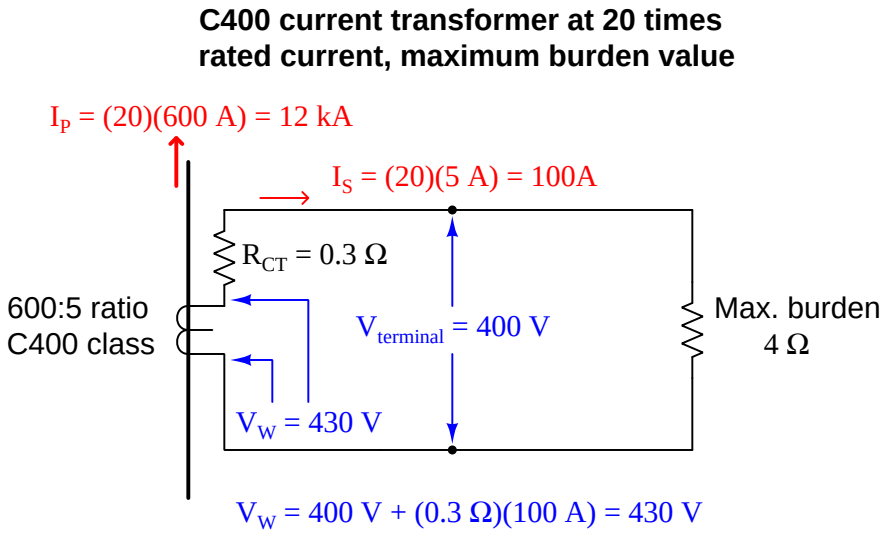
$$R_{1000ft} = e^{0} = 1\,\Omega \text{ per } 1000 \text{ feet}$$

Bear in mind that this result of 1 Ohm[11] wire resistance per 1000 feet of length applies to the *total circuit length*, not the distance between the CT and the receiving instrument. A complete CT secondary electrical circuit of course requires *two* conductors, and so 1000 feet of wire will be needed to cover 500 feet of distance between the CT and the instrument. Some sources cite #12 AWG wire as the minimum gauge to use for CT secondary circuits regardless of wire length.

[11] Calculations based on the specific resistance of copper at 20 ^{o}C place 10 AWG wire at 0.9989 Ohms per 1000 feet. $R = \frac{\rho l}{A}$

2.6.6 Example: CT circuit wire sizing, simple

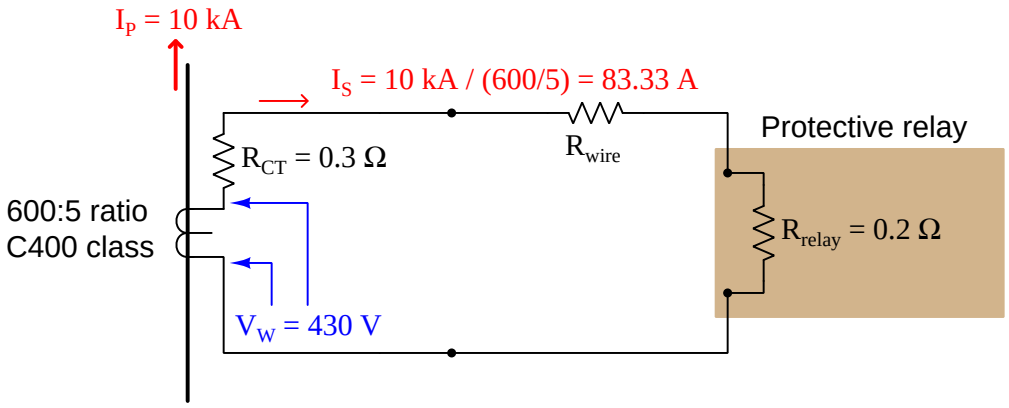
A practical example will help illustrate how wire resistance plays a role in CT circuit performance. Let us begin by considering a C400 accuracy class current transformer to be used in a protective relay circuit, the CT itself possessing a measured secondary winding resistance of 0.3 Ω with a 600:5 turns ratio. By definition, a C400 current transformer is one capable of generating 400 Volts at its terminals while supplying 20 times its rated current to a burden. This means the maximum burden value is 4 Ohms, since that is the impedance which will drop 400 Volts at a secondary current of 100 Amperes (20 times the CT's nominal output rating of 5 Amperes):



Although the CT has a C400 class rating which means 400 Volts (maximum) produced at its terminals, the winding must actually be able to produce more than 400 Volts in order to overcome the voltage drop of its own internal winding resistance. In this case, with a winding resistance of 0.3 Ohms carrying 100 Amperes of current (worst-case), the winding voltage must be 430 Volts in order to deliver 400 Volts at the terminals. This value of 430 Volts, at 60 Hz with a sinusoidal current waveform, represents the maximum amount of magnetic flux this CT's core can handle while maintaining a current ratio within ± 10% of its 600:5 rating. Thus, 430 Volts (inside the CT) is our limiting factor for the CT's winding at *any* current value.

This step of calculating the CT's maximum internal winding voltage is not merely an illustration of how a CT's "C" class rating is defined. Rather, this is an essential step in any analysis of CT circuit burden because we must know the maximum winding potential the CT is limited to. One might be tempted to skip this step and simply use 400 Volts as the maximum terminal voltage during a fault condition, but doing so will lead to minor errors in a simple case such as this, and much more significant errors in other cases where we must de-rate the CT's winding voltage for reasons described later in this section.

Suppose this CT will be used to supply current to a protective relay presenting a purely resistive burden of 0.2 Ohms. A system study reveals maximum symmetrical fault current to be 10,000 Amperes, which is just below the 20× rated primary current for the CT. Here is what the circuit will look like during this fault condition with the CT producing its maximum (internal) voltage of 430 Volts:



The CT's internal voltage limit of 430 Volts still holds true, because this is a function of its core's magnetic flux capacity and not line current. With a power system fault current of 10,000 Amperes, this CT will only output 83.33 Amperes rather than the 100 Amperes used to define its C400 classification. The maximum total circuit resistance is easily predicted by Ohm's Law, with 430 Volts (limited by the CT's magnetic core) pushing 83.33 Amperes (limited by the system fault current):

$$R_{total} = \frac{V_W}{I_{fault}} = \frac{430 \text{ V}}{83.33 \text{ A}} = 5.16\,\Omega$$

Since we know the total resistance in this series circuit is the sum of CT winding resistance, wire resistance, and relay burden, we may easily calculate maximum wire resistance by subtraction:

$$R_{total} = R_{CT} + R_{wire} + R_{relay}$$

$$R_{wire} = R_{total} - (R_{CT} + R_{relay})$$

$$R_{wire} = 5.16\,\Omega - (0.3\,\Omega + 0.2\,\Omega) = 4.66\,\Omega$$

Thus, we are allowed to have up to 4.66 Ω of total wire resistance in this CT circuit while remaining within the CT's ratings. Assuming the use of 12 gauge copper wire:

$$R_{1000ft} = e^{(0.232)(12)-2.32} = 1.59\,\Omega \text{ per } 1000 \text{ feet}$$

$$\frac{4.66\,\Omega}{1.59\,\Omega/1000 \text{ ft}} = 2.93 \times 1000 \text{ ft} = 2930 \text{ ft}$$

Of course, this is *total* conductor length, which means for a two-conductor cable between the CT and the protective relay the maximum distance will be half as much: 1465 feet.

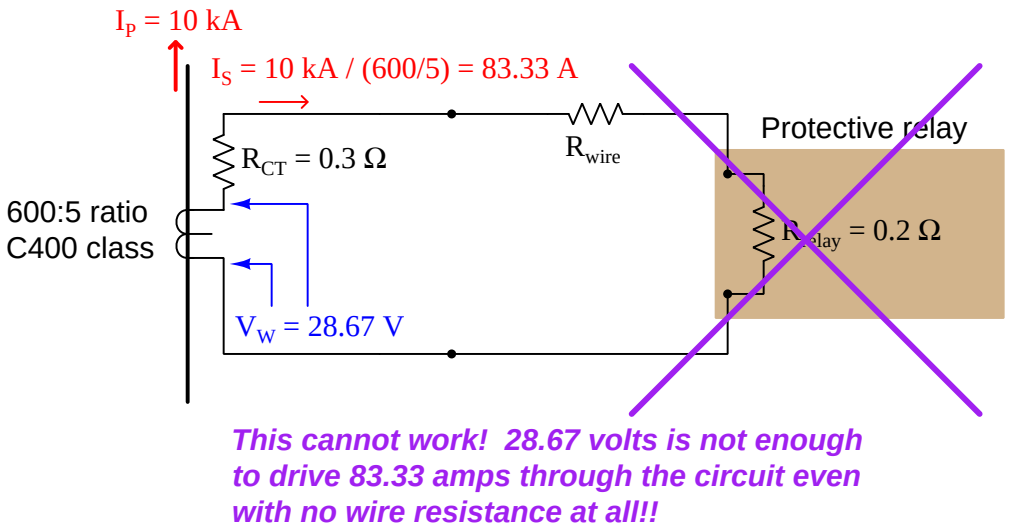
2.6.7 Example: CT circuit wire sizing, with DC considered

The previous scenario assumes purely AC fault current. Real faults may contain significant DC components for short periods of time, the duration of these DC transients being related to the $\frac{L}{R}$ time constant of the power circuit. As previously mentioned, direct current tends to magnetize the ferrous core of a CT, predisposing it to magnetic saturation. Thus, a CT under these conditions will not be able to generate the full AC voltage possible during a controlled bench test (e.g. a C400 current transformer under these conditions will not be able to live up to its 400-volt terminal rating). A simple way to compensate for this effect is to de-rate the CT's winding voltage by a factor equal to $1 + \frac{X}{R}$, the ratio $\frac{X}{R}$ being the reactance-to-resistance ratio of the power system at the point of measurement. De-rating the transformer provides a margin of safety for our calculations, anticipating that a fair amount of the CT's magnetic core capacity may be consumed by DC magnetization during certain faults, leaving less magnetic "headroom" to generate an AC voltage.

Let's re-do our calculations assuming the power system being protected now has an $\frac{X}{R}$ ratio of 14. This means our C400 current transformer (with a maximum internal winding potential of 430 Volts) must be "de-rated" to a maximum winding voltage of:

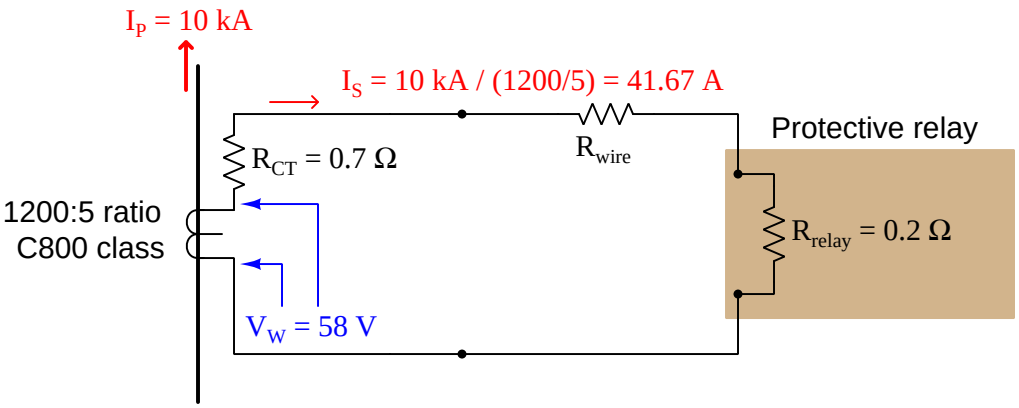
$$\frac{430 \text{ V}}{1 + \frac{X}{R}} = \frac{430 \text{ V}}{1 + 14} = 28.67 \text{ V}$$

If we apply this de-rated winding voltage to the same CT circuit, we find it is insufficient to drive 83.33 Amperes through the relay:



With 0.5 Ω of combined CT and relay resistance (and no wire resistance), a winding voltage of 28.67 Volts could only drive 57.33 Amperes which is far less than we need. Clearly this CT will not be able to perform under fault conditions where DC transients push it closer to magnetic saturation.

Upgrading the CT to a different model having a higher accuracy class (C800) and a larger current step-down ratio (1200:5) will improve matters. Assuming an internal winding resistance of 0.7 Ohms for this new CT, we may calculate its maximum internal winding voltage as follows: if this CT is rated to supply 800 Volts at its terminals at 100 Amperes secondary current through 0.7 Ohms of internal resistance, it must mean the CT's secondary winding internally generates 70 Volts more than the 800 Volts at its terminals, or 870 Volts under purely AC conditions. With our power system's $\frac{X}{R}$ ratio of 14 to account for DC transients, this means we must de-rate the CT's internal winding voltage from 870 Volts to 15 times less, or 58 Volts. Applying this new CT to the previous fault scenario:



Calculating the allowable total circuit resistance given the new CT's improved voltage:

$$R_{total} = \frac{V_W}{I_{fault}} = \frac{58 \text{ V}}{41.67 \text{ A}} = 1.392\,\Omega$$

Once again, we may calculate maximum wire resistance by subtracting all other resistances from the maximum total circuit resistance:

$$R_{wire} = R_{total} - (R_{CT} + R_{relay})$$

$$R_{wire} = 1.392\,\Omega - (0.7\,\Omega + 0.2\,\Omega) = 0.492\,\Omega$$

Thus, we are allowed to have up to 0.492 Ω of wire resistance in this circuit while remaining within the CT's ratings. Using 10 AWG copper wire (exhibiting 1 Ohm per 1000 feet), this allows us a total conductor length of 492 feet, which is 246 feet of distance between the CT terminals and the relay terminals.

Chapter 3

Historical References

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

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

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

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

3.1 Early instrument transformer safety

A fascinating historical reference on protective relay systems is Victor Todd's *Protective Relays – their theory, design, and practical operation* published in 1922. One quotation in particular discusses the hazards of open-circuiting an operating current transformer (CT):

> **Opening of Secondary.** – The secondary circuit of a current transformer should never be opened while the primary is carrying current. If it is necessary to disconnect instruments the secondary should first be short-circuited. If the secondary circuit is opened, a difference of potential is developed between terminals which is dangerous to anyone coming into contact with the meters or leads. The cause of this high voltage is that with open secondary circuit all of the primary ampere-turns are effective in producing flux in the core, whereas normally but a very small portion of the total perform this function. The danger is magnified by the fact that the wave form of this secondary voltage is peaked, producing a high-maximum value. A high flux produced in this way may also permanently change the magnetic condition of the core so that the accuracy of the transformer will be impaired. [page 122]

As we see, the danger is not only of a personal sort, but also that the CT could be damaged by permanent magnetization of its iron core should it be open-circuited under load.

Chapter 4

Derivations and Technical References

This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

4.1 Electrical safety

A subject of extreme importance to all electrical practitioners is electrical *safety*, with Ohm's and Joule's Laws being excellent starting points for a discussion on that topic. Here we examine the human body as an electrical *load*: electrical charge carriers passing through the resistance of the body from an external source relinquish some of their energy in the same way charge carriers lose energy passing through any other resistance. The rate of energy dissipation (i.e. *power*) through the body's resistance is predicted by Joule's Law, $P = I^2R$. The total amount of energy delivered to a body by an electric current is a function of that power dissipation rate multiplied by the amount of time current flowed[1].

Electrical energy poses two distinctly different threats to any living body: the first threat is forced activation of the body's nervous system by electric current passing through nerve cells, and the second threat is burning from the thermal power dissipated in flesh and bone. Both threats are direct functions of the amount of energy delivered to the body, with the first effect (called *electric shock*) beginning at lower levels of current than the second effect.

Electric shock – not to be confused with the general condition of *circulatory shock* characterized by reduced blood circulation in the body – first manifests as a tingling sensation, then as pain with greater electric current intensity. At a certain threshold value, the current will be sufficient to override voluntary muscle control. At higher levels of current, breathing will become difficult or may cease due to paralysis of the diaphragm muscles within the chest. At even higher levels of current, the heart (itself a muscle of the body) will either fall into an arrhythmic beat pattern or cease beating altogether. *All of these effects will occur at current levels significantly less than one Ampere.*

Some of the most detailed data we possess on the effects of electric shock come from the research of University of California Berkeley Professor Charles Dalziel, who in the year 1961 published a report entitled "Deleterious Effects of Electric Shock". Dalziel performed electric shock experiments on human volunteers, subjecting both males and females to varying degrees of electric current, both direct (DC) and alternating (AC), for the purpose of determining thresholds of sensation, pain, and loss of muscular control.

Table II of Dalziel's' report (shown on page 24) is partially[2] reproduced in the following table. The headings "M" and "F" refer to male and female subjects, respectively. Tests conducted using direct current[3] are labeled "DC" while tests conducted using alternating current[4] are labeled with

[1] Putting units of measurement to this concept, the amount of energy in *Joules* is equal to average power in *Joules per second* multiplied by time in *seconds*, with the unit of "seconds" canceling out. For brief exposures to electricity, such as lightning strikes, the most important measurement with regard to safety is the total energy delivered to the body. The same is true for deliberate applications of electricity to the body, for example cardiac defibrillators, where the machine's setting is calibrated in Joules of energy delivered per impulse.

[2] The original Table II contained a column of data representing thresholds for women at 10 kHz alternating current, but these were estimations and not actual data. Extrapolating from the other data points where women tended to exhibit the same effects as men at approximately $\frac{2}{3}$ the current, Dalziel writes, *"Tests on women were not made on frequencies other than 60 cycles, but if it is assumed that the response for women would be similar, values for women can be estimated at two-thirds of the corresponding value for men."* Readers should note that I have taken editorial liberties with the description of bodily effects, for no reason other than formatting.

[3] Direct current, or DC, refers to a continuous flow of electric charge carriers in one direction only.

[4] Alternating current, or AC, refers to an electric current that periodically switches direction, the period of that

frequency values expressed in the unit of Hertz (Hz) or cycles per second. All data points are expressed in *milliAmperes* (mA), one milliAmpere being $\frac{1}{1000}$ of an Ampere:

Bodily effect	**DC, M**	**DC, F**	**60 Hz, M**	**60 Hz, F**	**10 kHz, M**
Slight sensation felt on hand	1 mA	0.6 mA	0.4 mA	0.3 mA	7 mA
Median perception threshold	5.2 mA	3.5 mA	1.1 mA	0.7 mA	12 mA
Shock, with no loss of muscular control	9 mA	6 mA	1.8 mA	1.2 mA	17 mA
Pain, with 50% of subjects losing muscular control	62 mA	41 mA	9 mA	6 mA	55 mA
Pain, labored breathing, 99.5% of subjects losing muscular control	90 mA	60 mA	23 mA	15 mA	94 mA

For rather obvious reasons no human tests were conducted to the point of cardiac fibrillation. Dalziel's report does, however, provide data collected on a variety of animals (pigs, sheep, calves, dogs, cats, guinea pigs, rabbits) which were anesthetized and then administered large amounts of electric current until their hearts malfunctioned. From this admittedly limited data, Dalziel extrapolated the values to obtain 500 mA ($\frac{1}{2}$ Ampere) of direct current and 100 mA ($\frac{1}{10}$ Ampere) of alternating current as thresholds for "possible" human heart fibrillation following a three-second electric shock.

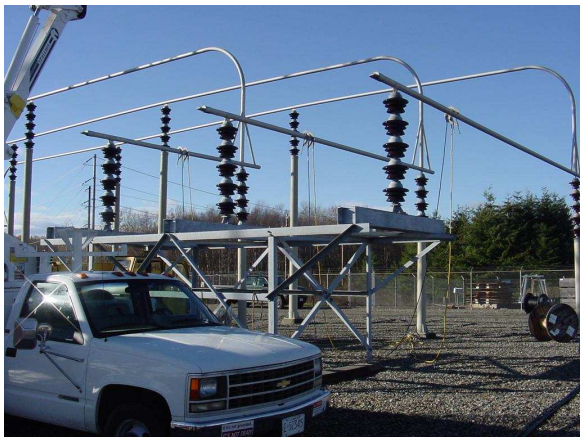
All gruesome details aside, the lesson to be learned here is very plain: *very little electric current is necessary to induce painful and even life-threatening effects on the human body!* These danger thresholds are all substantially less than the amount of current most power conductors are rated to handle, and less than the ratings of fuses and circuit breakers designed to protect conductors from overheating.

switching measured in cycles per second or Hertz. In North America, the standard AC grid power frequency is 60 cycles per second, or 60 Hz. The second AC frequency used in Dalziel's experiments is 10 kHz, which is 10 *kilo*-Hertz, or 10000 cycles per second.

The first line of defense against electrical shock is to place as much electrical resistance between your body and the circuit's conductors as is practical, as a means of impeding the flow of electric current to and through your body. Turning "off" any disconnecting switches between the circuit and its energy source is a simple means to do this, essentially inserting an air gap between the circuit and its normal source of power. This allows all points within the circuit to achieve an equipotential state, which may then be made equipotential to your body by connection to Earth ground (where you are standing). If there is no voltage present (i.e. no difference in the potential energy levels of electric charge carriers at different points), then there should be no possibility of dissipating electrical energy into your body.

Once all electrical energy sources have been disconnected from the circuit you intend to work on, an additional safety measure is to *bond* that circuit's power conductors to Earth ground. This step forces the power conductors to be *electrically common* with Earth, and therefore guarantees a condition of equipotentiality with the Earth. Line workers who install and maintain electric power line conductors do this as a standard part of their operating procedure: attaching temporary grounding cables between the power conductors and Earth after opening all disconnect switches normally connecting those lines to electrical sources. This extra step of bonding the power conductors ensures no stray sources[5] of electrical energy may pose a threat.

The following photograph shows a work site at a 230 kV (230,000 Volt!) electrical substation, where electricians are busy performing maintenance work on a high-voltage component. In addition to opening large switches (called *disconnects*) to isolate this new component from any source of voltage, they have *bonded* the high-voltage conductors to each other and to Earth ground by means of temporary wire cables. The cables on this work site happen to be yellow in color, and may be seen hanging down from C-shaped clamps attached to three horizontal metal tubes called *busbars* which serve as conductors for electricity in this substation:



[5] Examples include electrostatic or magnetic "coupling" with adjacent energized power lines, nearby lightning strikes, etc.

Obviously, such measures are quite necessary on high-voltage systems such as substation busbars – there simply is no safe way to work on energized conductors at this voltage level. However, in lower-voltage circuits it is often necessary to take electrical measurements and make certain adjustments while the circuit is in an energized state. If the circuit in question cannot be "killed" by disconnection of its power source and therefore must be worked on "live", the next best protective measure is to layer insulating material on your body where contact might otherwise be made to permit an electric current through it. This means wearing insulating gloves and shoes, at minimum. The principle behind this technique is Ohm's Law: for any given amount of voltage (V), current (I) will be inversely proportional to the total resistance (R) of the circuit pathway. Layering electrically insulating material over your body's possible points of contact (e.g. hands, feet) increases the total resistance of the circuit pathway, and therefore minimizes the amount of current that may flow in the event of physical contact between two points where a substantial voltage exists.

Lastly, in order to minimize the risk of electric current passing through one's chest (where the heart and diaphragm muscles are located), a wise habit when working on energized circuits is to place one hand in a pocket so that only one hand is in use. This will not only prevent arm-to-arm passage of electric current, but it also minimizes the number of potential points of contact with bare skin. Electrical practitioners commonly refer to this as the *One-Hand Rule*. Ideally, the best hand to place in a pocket is the left hand, because this is the side of the body where the heart is most vulnerable.

It is worth noting that the danger from electric shock is best quantified in terms of current, not voltage, since it is electric current that activates nerve cells. The amount of current passing through a victim's body from an applied voltage is a function of Ohm's Law ($I = \frac{V}{R}$), and since resistance (R) varies greatly with skin dryness and layering provided by shoes and clothing, it is difficult to predict how much voltage poses a shock hazard. A generally accepted threshold of danger is 30 Volts, but this assumes direct contact with dry skin. Moist skin, perspiration, cuts or punctures, and other factors reducing body resistance may greatly reduce the voltage threshold for shock hazard! Another factor is the general health of the victim prior to receiving the electric shock. A preexisting cardiac condition will likely predispose that individual to harm resulting from an electric shock.

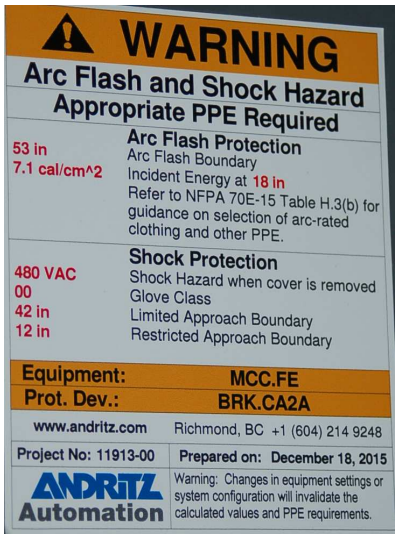
Burns produced by electricity passing through the body may manifest on the skin, at the point of contact with an electrical conductor (such as a wire), or in severe cases may extend to internal organs. Comparing internal flesh with skin, dry human skin tends to exhibit much greater levels of electrical resistance than the internal organs which are wet. This is why electricity causes skin-surface burns before causing internal organ burns: for any given amount of electric current passing through different resistances, power dissipated by that current will be greatest wherever the electrical resistance is greatest. Mathematically stated, P is maximized where R is greatest, given any value of (I), in accordance with Joule's Law (I^2R).

Another mechanism of electrically-caused burns is *arc flash*: the heating of air by the passage of electric current through it (rather than through the body). Under normal conditions air is an extremely good insulator of electricity, with no free charge carriers available to sustain an electric current. However, when sufficient voltage causes the electrons in air molecules to separate from their respective atoms, the negatively-charged electrons and positively-charged ions constitute charge carriers, and will form an electric current called either a *spark* or an *arc*. This current heats the air molecules by dissipating power as described by Joule's Law ($P = I^2R$), with I being the magnitude of current traveling through the ionized air and R being the resistance of the arc path.

The amount of resistance exhibited by a high-temperature arc is surprisingly low, typically less than one Ohm across the entire length of the arc. With such low resistance, Ohm's Law predicts relatively high current values for even modest voltages ($I = \frac{V}{R}$), resulting in high power levels. Even if the amount of energy released by each charge carrier moving through the arc is small, the fact that a great many charge carriers are moving through the arc each second means that the total amount of energy dissipated may be phenomenally large. This is why arcs forming in high-voltage electric power systems may reach temperatures of tens of thousands of degrees[6]!

In the United States of America, a widely respected standard document for electrical hazards and protection is the National Fire Protection Association (NFPA) standard 70E. This document rates both electric shock and arc flash hazards for electric power circuits based on voltage and current capabilities, as well as specifies best practices for protection against those hazards.

An example of NFPA 70E standards applied to an industrial installation is the following pair of photographs showing warning labels affixed to metal-clad electrical switchgear (i.e. metal cabinets housing large circuit breakers). Each label cites both arc flash and electric shock hazards, including *boundary* distances within which greater hazards exist:



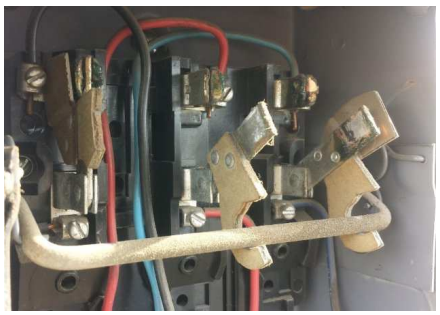
The first line of defense against arc flash is the same as for electric shock: *de-energize the circuit* so there will be no electrical energy present to harm you. The procedure for de-energizing includes placing a warning *tag* as well as a secure *lock* on any main disconnecting switches or circuit breakers to ensure power does not get accidently applied to the circuit while people are in harm's way. This is referred to in industry as *lock-out, tag-out*, or *LOTO*.

[6]The NFPA 70E electrical safety standard (Informative Annex K) cites temperatures as high as 35,000 degrees Fahrenheit in arc flash events, and states that such events are lethal at distances up to 10 feet (3.05 meters). It is worth noting that electric arc temperatures are limited only by the rate of power dissipated in the arc. Unlike chemically-driven combustion events, where temperature is limited by the rate at which the various chemical reactants are able to combine, no such limiting factor exists with electric arcs: the more power dissipated in the arc, the hotter it will become. These temperatures involved with electric power faults can be so high that they *vaporize* the metal wires!

Generally accepted lock-out, tag-out procedures for electrical equipment include (but are not limited to) the following steps:

1. Turn equipment off using regular on/off switch to interrupt load current
2. Open all disconnect switches and/or circuit breakers feeding electrical power to the equipment
3. Visually confirm (if possible) that *all* poles of the disconnecting switch(es) are open
4. Attempt to re-start equipment as your first confirmation that power is indeed shut off
5. Attach locks and tags to prevent disconnecting switches from being re-closed; if no lockable disconnect means exists, you must open and tag *two* or more redundant disconnects!
6. Confirm proper operation of voltage meter against a known source
7. Test for dangerous voltage between all relevant conductors, especially those you could bodily contact, including between pairs of phase conductors in a polyphase system as well as between each phase conductor and earth ground
8. Confirm (again) proper operation of voltage meter against a known source

Such a lengthy procedure may seem paranoid, but there is good reason for all these steps. Remember that *all safety standards and procedures are written in blood:* in other words, every one of them exists because either someone got hurt or came close to getting hurt by not taking appropriate precautions. One example of the latter is the following photograph generously shared by Jim Lyon[7] who discovered a failed three-phase disconnect switch during a routine LOTO procedure:



As you can see in this photograph, one of the linkages between the disconnecting switch pole and the actuating lever has broken, allowing one phase to remain closed while the other two opened as they should. Such a failure would neither be apparent to the operator of that switch nor by anyone's external inspection of it, but would be revealed by proper voltage testing (phase-to-ground) on that faulted phase conductor. Had Mr. Lyon simply trusted the switch handle's "off" position as proof of a zero-energy state, he could have been electrocuted touching the un-opened conductor "downstream" of the switch.

[7] Mr. Lyon granted me permission to include his safety-related photographs in my open-source writings during an exchange on the professional social-media website `LinkedIn`.

Another important note with regard to electrical safety and LOTO is the proper function of your test equipment. Multimeters and test leads are not just tools for precision measurement, but are life-saving indicators of dangerous voltage. I have personally witnessed multiple instances of failed multimeter test leads, where one or more leads failed open such that the meter could not reliably register the presence of voltage. This is why good LOTO procedure always includes verification of the meter both *before and after* checking for dangerous voltages at the system conductors.

In cases where de-energization is not possible or not practical, special "arc-flash rated" clothing may be worn to protect your skin against the high temperatures of arc flash should an arc flash occur. Arc flash suits cover all skin surfaces, and are rated according to the number of calories[8] of heat the fabric may sustain without disintegrating. The following photograph shows a pair of arc flash suits hanging on a wall ready for electricians to use while working on circuit breakers at an electric power generating station:

The blue-colored hood covers the worker's head and neck, while the grey-colored jumpsuit covers the rest of the worker's body.

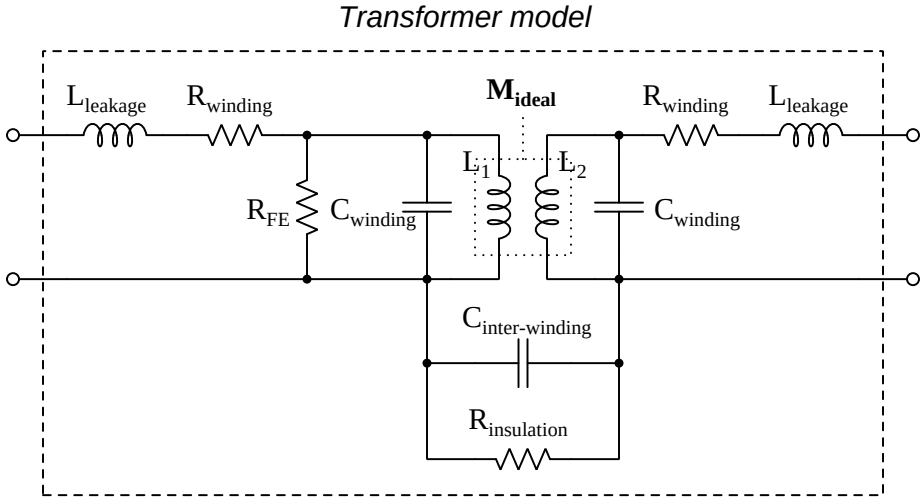
[8] A *calorie* is simply another unit of energy measurement. The unit-conversion equivalence is 4.187 Joules per calorie.

The hazards of electrical arcs are not limited to bodily burns. Given sufficient arc power, the explosive expansion of hot air and the shrapnel created by disintegrating hardware represents its own unique hazard, known as *arc blast*. As an *electrically-driven* explosion[9], arc blast is limited only by the available power of the fault, and can in fact be more violent than a chemical explosion. No suit can ensure safety against arc blast, and so the only reasonable precaution is maintaining a safe distance beyond the blast radius.

[9]The concussive effects of an arc blast originate from the rapid expansion of air and vaporized metal, producing intense sound waves and blast pressures. Extremely bright light, as well as high temperatures caused by convection of super-heated air and by radiation of infrared light from the arc are capable of creating third-degree burns on unprotected skin.

4.2 Transformer parasitics

An ideal transformer couples electrical energy from its primary winding to its secondary winding(s) with no energy loss (i.e. dissipation) and with no additional impedance standing in the way of that energy transfer. When unloaded, an ideal transformer draws no current whatsoever from its connected source. Real transformers, however, fall quite short of these ideal characteristics. The following diagram models some of the parasitic effects observed in real transformers:



Each of the transformer's windings have resistance owing to the specific resistance of the metal making up those wire windings, this winding resistance effectively being in series with each winding. Additionally, each winding has *leakage inductance* which is the result of magnetic flux that does not couple between the two windings but instead merely stores and releases energy like the self-inductance of a single inductor. Together, winding resistance and leakage inductance contribute to the *impedance* of the transformer, limiting its ability to seamlessly transfer energy from primary to secondary circuits.

We also see each winding suffering from capacitance, resulting from the insulation between adjacent turns of wire. The presence of this parasitic capacitance, something found in every inductor as well as in transformers, means the primary and secondary windings are able to *self-resonate* at certain frequencies. Note also that there is capacitance coupling between the primary and secondary windings, which means no transformer can ever *perfectly* isolate the primary and secondary circuits from each other.

Lastly we have a resistance shown in the model as R_{FE} representing dissipative losses in the iron core material from effects such as hysteresis and magnetostriction. This is often referred to as *iron loss* (as opposed to the *copper loss* of winding resistance).

Next we will explore common mechanisms for each of these effects.

4.2.1 Parasitic resistance in transformers

Winding resistance depends on the size and composition of wire used to make each winding. Using low-resistivity metal and wire of sufficiently large gauge are really the only ways to minimize this parasitic effect. Using a transformer with over-sized wire (i.e. a transformer having current ratings in excess of the currents expected in your application) is one way to reduce this parasitic effect using commonly-available transformers.

So-called "iron loss" resistance is based on magnetic effects, primarily the hysteresis curve for the iron alloy. Modern silicon-steel alloys formulated for transformer applications enjoy very narrow B-H hysteresis curves which in turn translate to low levels of energy dissipation as the core magnetizes in one polarity, de-magnetizes, and re-magnetizes in the other polarity with each cycle of the energizing AC. Using a transformer with an over-sized magnetic core has the result of dispersing the magnetic flux over a larger cross-sectional area, resulting in less magnetic flux density (B) with all other factors being equal. One way to specify a transformer with an over-sized magnetic core is to select one with a higher voltage rating than your application strictly needs, as peak magnetic flux density for any given AC frequency is a function of the peak voltage experienced by each winding. If frequency is not variable, then the cycle time (period) of the AC waveform will likewise be fixed, and since total magnetic flux in any inductor is the integral of voltage and time (i.e. the *Volt-second product*) it means a transformer with a higher voltage rating must possess a larger magnetic core.

4.2.2 Leakage inductance in transformers

Leakage inductance, another contributing factor of transformer impedance, results from some of the core's magnetic flux not coupling perfectly between primary and secondary windings. Core shape and material choice affect this parameter, with toroidal transformer cores generally performing better than cores having abrupt corners.

4.2.3 Parasitic capacitance in transformers

Capacitance unavoidably exists between adjacent turns of wire in any inductor, and also between adjacent turns of primary and secondary windings in a transformer. Reducing turn-to-turn parasitic capacitance within any single winding requires those turns be spaced farther apart from each other, or wound in different patterns, or with an insulating material having a lower dielectric permittivity.

Primary-to-secondary winding capacitance can be mitigated to a large extent by placing an electrostatic *shield* between the two windings of the transformer and connecting that shield conductor to Earth ground. This works precisely the same way as wrapping a foil or braided shield conductor around a multi-conductor cable in order to shield those conductors from electric fields external to the cable. In this case, the shielding stops electric flux lines from linking from one winding to another. Shielded-winding transformers are more expensive to manufacture than their unshielded counterparts.

Another mitigation technique for primary-to-secondary parasitic capacitance is to use a *split-bobbin* transformer where the primary and secondary windings do not overlap each other, but rather are placed at different locations around the magnetic "circuit" formed by the iron core. This increases the separation distance between these two windings without significantly affecting other performance parameters of the transformer, but of course has the effect of increasing the over-all size of the transformer.

4.2.4 Excitation and magnetization currents

As described at the beginning of this section, an ideal transformer draws no current whatsoever from its energizing source. This, however, is possible only by meeting two idealized conditions:

- The primary winding inductance must be infinite
- Magnetic core losses must be zero (i.e. a lossless core)

An infinite primary winding inductance is simply impossible to achieve in any real transformer, though we may approach this ideal by building transformers whose primary inductance values are quite large. Large primary inductance means large values of inductive reactance ($X_L = 2\pi fL$), and so the larger the winding's inductance is the less *magnetization current* it will need to draw from an AC voltage source to create a rate-of-change of magnetic flux in the core sufficient to balance the applied source voltage as per Faraday's Law of Electromagnetic Induction ($V = N\frac{d\phi}{dt}$).

A lossless core material is similarly impossible to achieve in most real transformers, as all ferromagnetic materials invariably dissipate at least *some* energy when magnetized and demagnetized, and air/vacuum-core transformers become impractically large for typical AC power system frequencies (in order to achieve large amounts of inductance, as necessitated above).

Referencing our transformer model showing various parasitic and ideal effects, magnetization current is that amount of current drawn by ideal primary inductance L_1 when the secondary is unloaded (i.e. open-circuited). This, combined with the current drawn from the AC voltage source as a result of the iron losses (R_{FE}), is called *excitation current*. Thus, $I_{excite} = I_{L_1} + I_{R_{FE}}$ which is a phasor current sum, I_{L_1} lagging the applied voltage by 90^o and $I_{R_{FE}}$ being in-phase with the applied voltage. If the excitation current is measured using an instrument such as an oscilloscope capable of comparing phase angles between the measured current and the applied voltage, magnetization current will be the imaginary portion of the excitation current while core-loss current will be the real portion.

4.2.5 Transformer testing

The following list shows typical tests for transformers at the time of manufacture:

- **DC winding resistances** – the simplest of these to measure, using a multimeter
- **Winding inductances/impedances** – performed by exciting one winding with an AC source and comparing voltage/current, typically using either an LCR meter or an impedance analyzer
- **Equivalent winding resistances** – based on the ratio of AC voltage to AC current (only the portions of each in-phase with each other) representing winding resistance as well as energy losses in the magnetic core
- **Turns ratio** – performed by exciting one winding with an AC current source and measuring another winding's short-circuited current using an AC ammeter
- **Phase shift** – performed by exciting one winding with an AC current source and measuring the relative phase shift of another winding's induced voltage
- **Winding polarity/phase-shift** – performed by exciting one winding with an AC voltage and measuring another winding's induced voltage, an oscilloscope used to compare the phases of each voltage
- **Core saturation** – performed by exciting one winding with a sinusoidal AC current and measuring another winding's induced voltage until a non-sinusoidal waveshape is detected, or more crudely by determining when the induced voltage no longer increases proportionately to increased excitation current
- **Excitation current** – performed by exciting one winding with an AC voltage and measuring current drawn by that winding
- **Insulation resistance** – performed with a "Hi-Pot" (high-potential) insulation tester, generally connecting one terminal to both ends of one winding and the other tester terminal to both ends of another winding, this infers insulation resistance by applying (typically) several thousand Volts DC while measuring the small current passing through the stressed insulation

A more thorough battery of tests used during transformer design development might include the following:

- **Linearity** – turns ratio testing performed at several different amounts of excitation current, checking to see how consistent the effective turns ratio is over a wide range
- **BH loop** – performed by exciting one winding with an AC voltage and measuring the voltage induced in another winding, that induced voltage representing the rate-of-change of magnetic flux which may be mathematically integrated to infer the amount of magnetic flux, those two variables being plotted using an oscilloscope's X-Y mode much like "curve tracing" for a semiconductor component ; often performed at different temperatures to fully characterize the magnetic properties of the core material
- **High-voltage impulse** – similar to an insulation resistance test, this uses a high-voltage DC pulse applied across one winding to stress turn-to-turn insulation resistance

- **Volt-second** – performed by applying a DC voltage pulse to one winding while measuring current through it, the ideal response being a linear-ramping current whose magnitude is proportional to the Volt-second product of the applied pulse
- **Overload** – subjecting a winding to dramatic overcurrent to thermally and mechanically stress the transformer as it might be in an overloaded power system scenario
- **External magnetic field rejection** – subjecting the entire transformer to an external (alternating) magnetic field and measuring any voltage induced across any winding, usually tested with the magnetic field applied across different physical axes
- **Vibration** – not an electrical test per se, but a useful stressor when followed by repeated electrical tests to ensure electrical/magnetic properties have not substantially changed following the vibration

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

Electromagnetism

Electromagnetic induction

Faraday's Law of electromagnetic induction

Transformer

Primary winding

Secondary winding

Turns ratio

Winding tap

Potential transformer (PT)

Current transformer (CT)

Grounding

Polyphase

Open

Short

Ground loop

Burden

Apparent power

Magnetic flux

Impedance

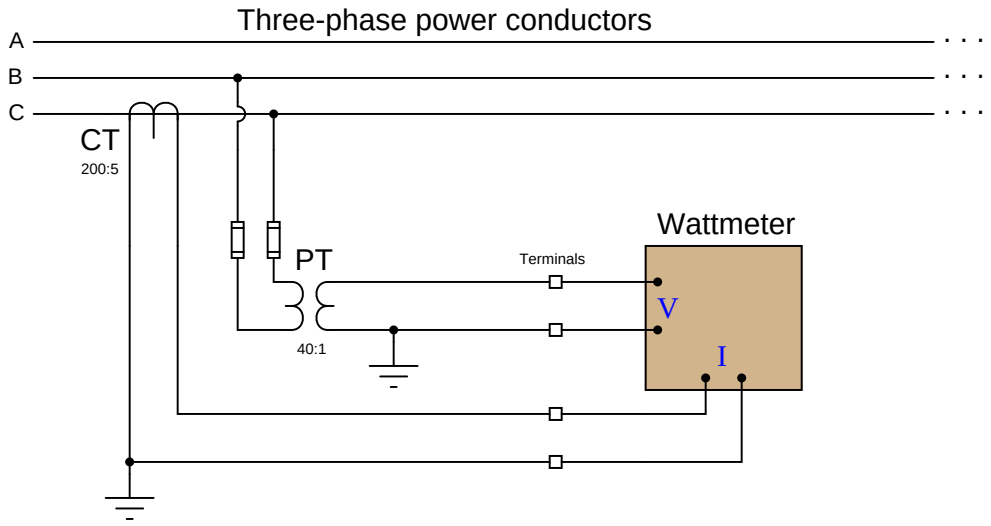
Remanence

Wire gauge

Class rating

5.1.3 Wattmeter transformers

This wattmeter measures power on one phase of a three-phase power system by sensing both line voltage and line current through instrument transformers:



What would you have to do in order to check the calibration of this wattmeter? Specifically, devise a step-by-step procedure that you could give to another technician telling them what they would have to do in order to simulate precise amounts of electrical power to the wattmeter's input, keeping safety in mind as the first priority. Note: you are not allowed to shut power off in the three-phase system to do your test – it must be done "live."

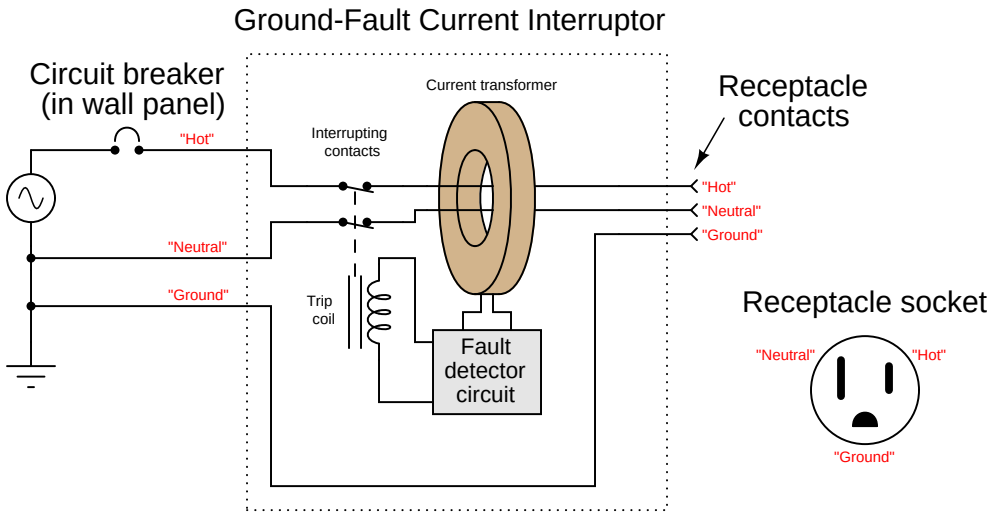
Challenges

- An important safety rule to apply when working with live circuit is the "one-hand rule." Explain what this rule is, and how it is applied to a scenario such as this.
- When loosening the screws on a terminal block to remove wires for the PT signal, should you remove the wires from the left-hand side of the terminals (as shown in the diagram) or from the right-hand side, or does this matter at all?
- The task of disconnecting a wattmeter from live instrument transformers presents significant hazard. Devise a way to make this procedure safer, using special "test switches" installed on the signal wires at the time of construction, so that a technician may simply throw the switches' levers to isolate the wattmeter instead of putting a screwdriver on "live" terminals and removing wires from terminal blocks.
- Suppose the PT's output signal were 113.6 Volts RMS, and the CT's output signal were 2.9 Amperes RMS. How much power does this represent flowing through the three-phase lines?

- Why are both instrument transformers' secondary circuits grounded?
- Suppose the potential transformer has a reliability rating of 0.9995 and the current transformer has a reliability rating of 0.9998. Calculate the probability that the wattmeter will receive good information from which to calculate power.

5.1.4 GFCI

A *Ground Fault Current Interruptor*, or *GFCI*, is a special type of AC power receptacle required by the National Electrical Code (NFPA 70) for residential installations near water or any areas that may become wet. The basic idea behind a GFCI is represented in this simplified schematic diagram:



A GFCI receptacle uses a single current transformer (CT) to measure the *difference* in electric current through the "hot" and "neutral" conductors of any electrical appliance plugged into the receptacle. If even a slight difference is detected, the interruptor contacts open, stopping power to the appliance.

Explain how a single CT is able to detect a difference in current between two conductors. Also, explain how a difference in current would ever arise between the "hot" and "neutral" conductors of an appliance. Finally, explain how you could test the proper operation of a GFCI by introducing a real ground fault.

Challenges

- Ground fault current interruption is required by code in residential and commercial installations where the possibility of a wet surface exists. Explain why ground/floor moisture is a factor for consideration here.

5.1.5 PT and CT magnetic flux levels

All transformers regardless of type or application function on the same basic principle: current passing through one coil produces a magnetic field experienced by the other coil(s), inducing voltage in the other coil(s) as predicted by Faraday's Law of Electromagnetic Induction:

$$V = N\frac{d\Phi}{dt}$$

Where,

V = Induced voltage across the coil, in Volts
N = Number of "turns" or "wraps" in the coil
$\frac{d\Phi}{dt}$ = Rate-of-change of magnetic flux, in Webers per second

Voltage is therefore a function of how *quickly* magnetic flux rises or falls in strength within the core of a transformer. Magnetic flux, in turn, is a function of how much voltage has been across the coil and for how long:

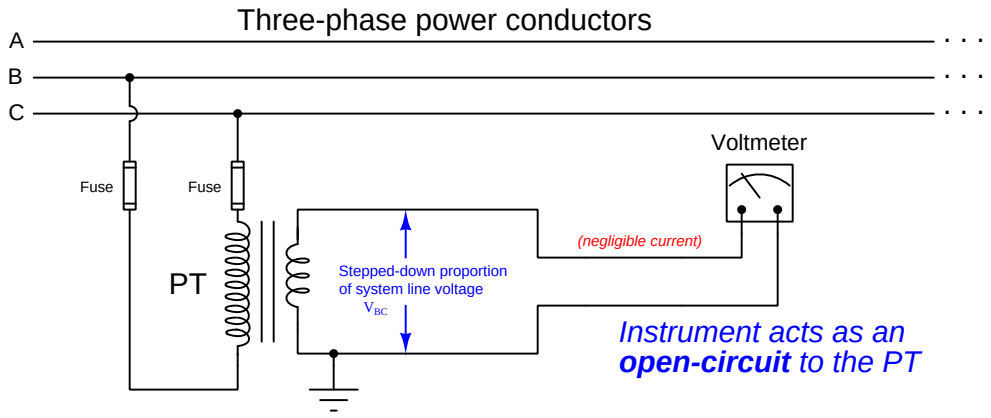
$$\Phi = \frac{1}{N}\int_0^T V\,dt + \Phi_0$$

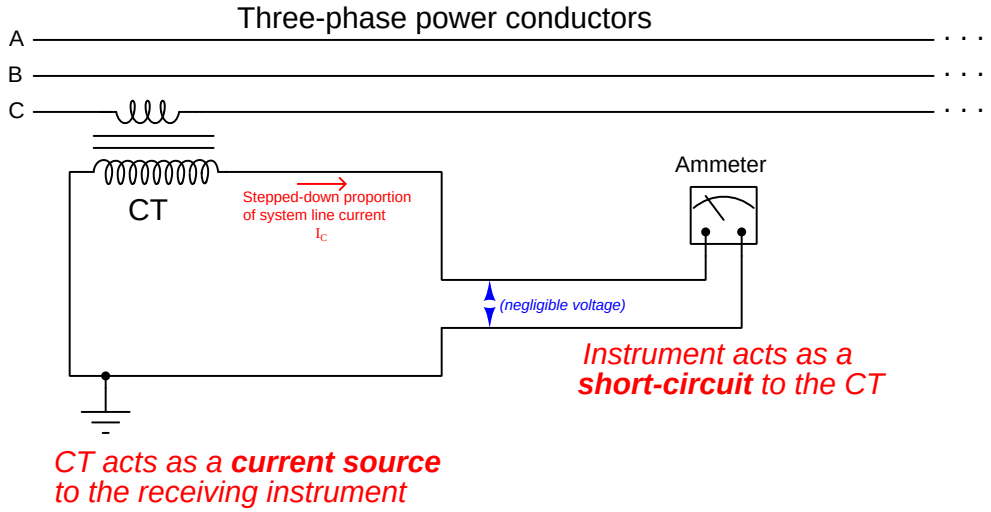
Where,

Φ = Total magnetic flux accumulated in the core, in Webers
N = Number of "turns" or "wraps" in the coil
V = Induced voltage across the coil, in Volts
T = The amount of time over which magnetic flux accumulates, in seconds
Φ_0 = Original magnetic flux present in the core at time = 0, in Webers

Simply put, the more voltage exists across a coil, the more magnetic flux accumulates within that coil's core. Also, the more *time* that voltage exists across a coil, the more magnetic flux accumulates within the core. In any transformer powered by alternating current (AC), this total amount of flux generally builds to some maximum level, decays to zero, builds to a symmetrical negative (maximum) level, decays back to zero, and then builds to a positive level again.

Compare the amount of magnetic flux you would expect there to be within the iron cores of a PT and of a CT operating under ideal conditions (i.e. PT driving a voltmeter and CT driving an ammeter):





Challenges

- What circuit conditions might prompt a PT's core flux to increase to the point of saturation?
- What circuit conditions might prompt a CT's core flux to increased to the point of saturation?

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	

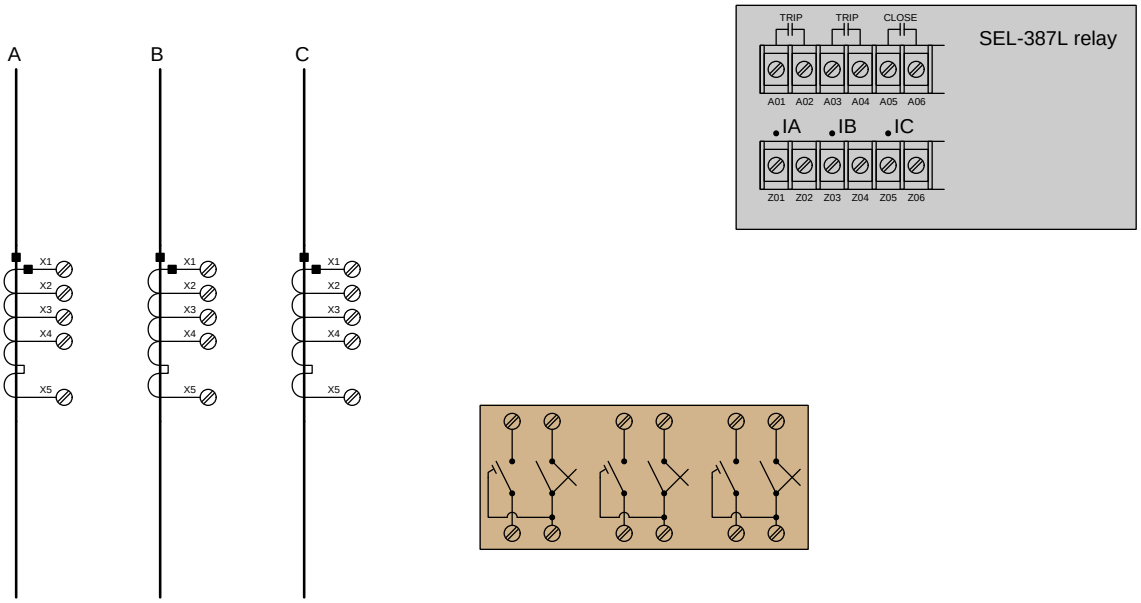
Note how the square-root term (y) is calculated in cell `C1`, and the denominator term (z) in cell `C2`. This makes the two final formulae (in cells `B1` and `B2`) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly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

Sketch wire connections to complete wiring between this SEL-387L differential current relay and a set of three line CTs. Note that only a few of the available terminals on the SEL-387L relay are shown, and that the line CTs are *multi-ratio current transformers* with different "taps" to choose from:



Assume we wish to have the CT ratios be 1200:5 each. The number of CT secondary winding turns between adjacent terminals are as follows:

Terminals	**Turns**
X1 – X2	80
X2 – X3	160
X3 – X4	60
X4 – X5	100

Challenges

- Since we only need two terminals on the secondary of each CT, should the other (unused) terminals be shorted together for safety? Why or why not?

5.2.4 CT circuit voltages

Suppose an 800:5 current transformer is connected to a protective relay presenting a purely resistive burden of 0.7 Ohms. The wire used to connect the CT to the relay is 12 gauge copper, 1500 feet total circuit length (i.e. 750 feet cable length for a 2-conductor cable).

From this information, determine both the voltage dropped across the relay's terminals at a fault current value of 4.5 kA (power line current), as well as the voltage dropped across the CT's terminals at that same current.

$V_{relay} =$

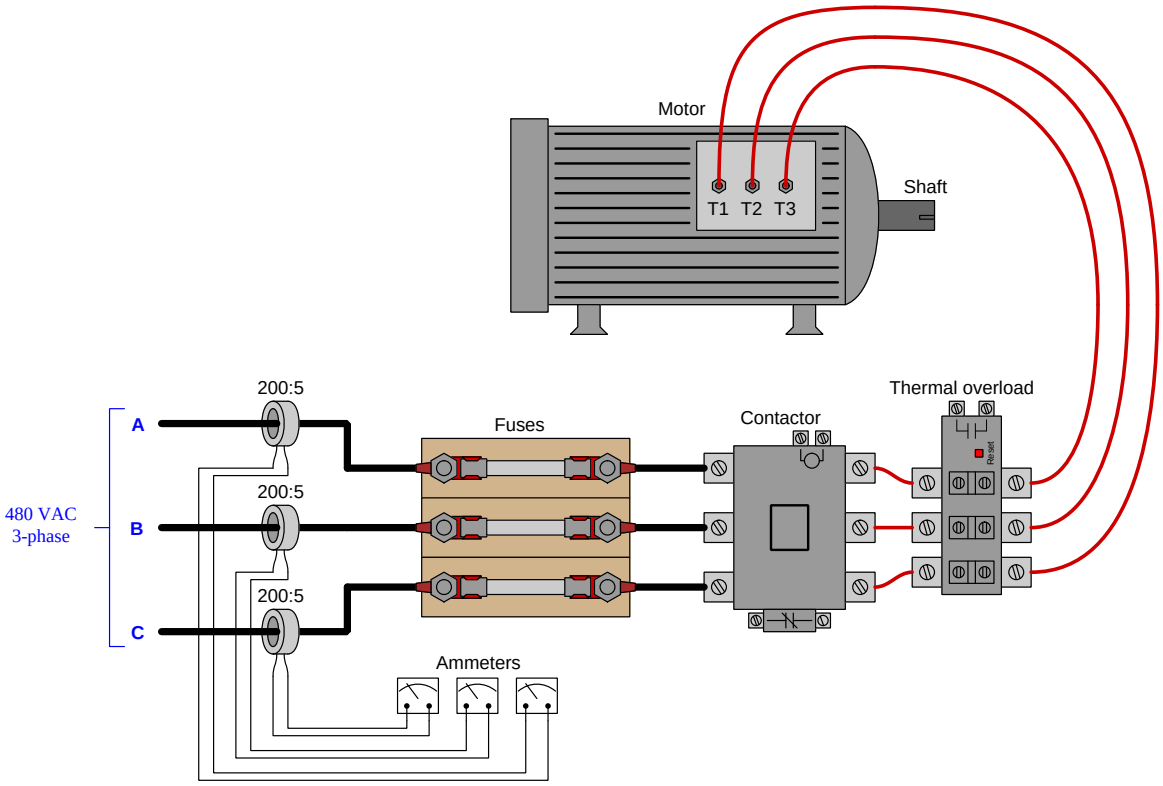
$V_{CT-terminals} =$

Challenges

- The Fluke brand 80-series digital multimeters are advertised as exhibiting 1.8 mV/mA of burden when measuring current in the low range (up to 400 mA maximum), and 0.03 V/A burden when measuring current in the high range (up to 10 Amperes maximum). How do these specifications compare to the burden of the protective relay in this question's scenario? Would a Fluke 80-series DMM present a lesser or greater burden to the CT than the specified relay? Would you recommend using a digital multimeter to interpret current from the CT in this application?

5.2.5 Motor line currents

Calculate the current measured by each ammeter assuming the motor's power consumption is 95 kW with a perfect power factor (1), the phase rotation is CBA, and $V_A = 277\angle -20^o$. Be sure to express each current value in polar form:



Ammeter "A" current =

Ammeter "B" current =

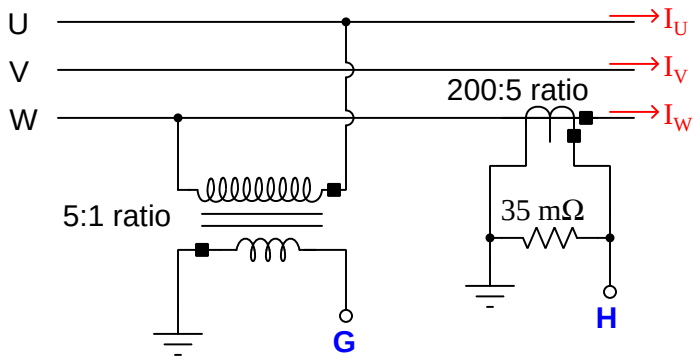
Ammeter "C" current =

Challenges

- What advantage is there in using CTs to measure the motor's current this way, rather than line-connected ammeters?
- Incorporate proper Earth grounding into the CT circuits shown.

5.2.6 Transformer-isolated voltage calculations

Calculate the V_G and V_H in this circuit, expressing both answers in polar form. Assume a balanced three-phase system with UVW phase rotation, where $V_U = 277$ Volts $\angle -15^o$ and $I_W = 83$ Amperes $\angle 100^o$:



$V_G =$

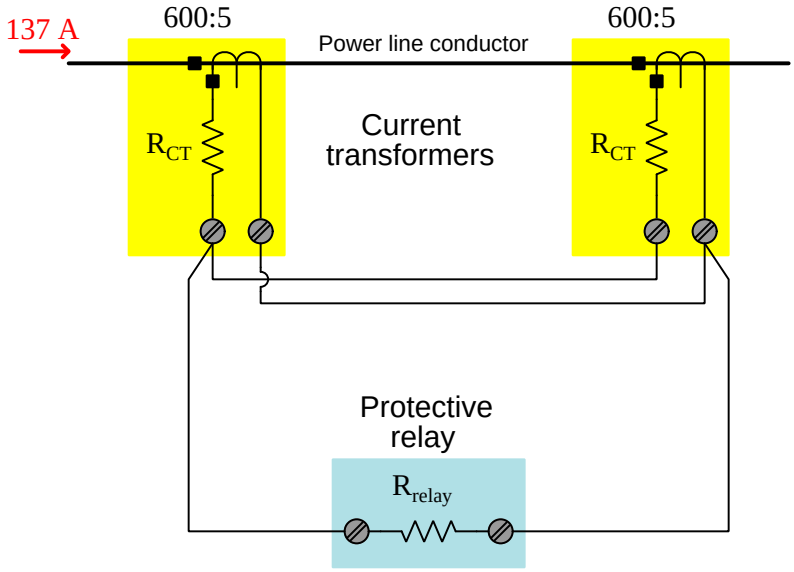
$V_H =$

Challenges

- Annotate this circuit with voltage polarity marks (+, −) and current arrows.

5.2.7 Paralleled CTs

Suppose a pair of current transformers with 600:5 ratios are parallel-connected to feed their output signals to a protective relay as shown in this schematic diagram:



- $R_{CT} = 0.5\ \Omega$ (this is the internal resistance of each CT's secondary winding)
- $R_{relay} = 1.8\ \Omega$

Calculate the following voltage drops in this current transformer circuit, from the given information:

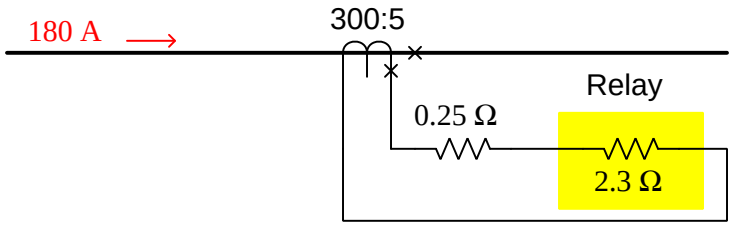
- $V_{relay} =$
- Voltage output at each CT's terminals =
- Voltage generated by each CT's secondary winding (before any R_{CT} losses) =

Challenges

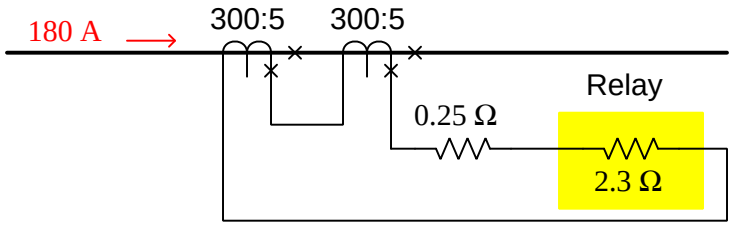
- Why might one wish to connect two CTs in parallel with each other?

5.2.8 Series-connected CTs

Calculate all currents and voltages in this current transformer (CT) circuit:



Now, calculate all currents and voltages in this current transformer circuit, with two identical CTs connected in series:



Finally, sketch the direction of current through each CT assuming the direction shown by the 180 Ampere arrow at one particular instant in time.

Challenges

- Why might one wish to connect two CTs in series with each other?

5.2.9 Polarizing coil current

Every AC meter connected to an instrument transformer presents a *burden* to that transformer, whether it be a PT or a CT. The greater a relay's burden, the more power is demanded from the instrument transformer and the less accurate the system will tend to be. For this reason, burden is a very important parameter to consider when wiring a protective relay system.

The datasheet for a General Electric model CEB52 "distance" protective relay (ANSI/IEEE code 21) shows the burden for its "polarizing coil" PT input to be $1540 - j162$ ohms. Calculate the current through this coil when the PT's output signal is 103 Volts $\angle -6^o$.

Challenges

- What would the *ideal* burden be for this particular relay, so as to present the lightest load possible to the PT?

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.

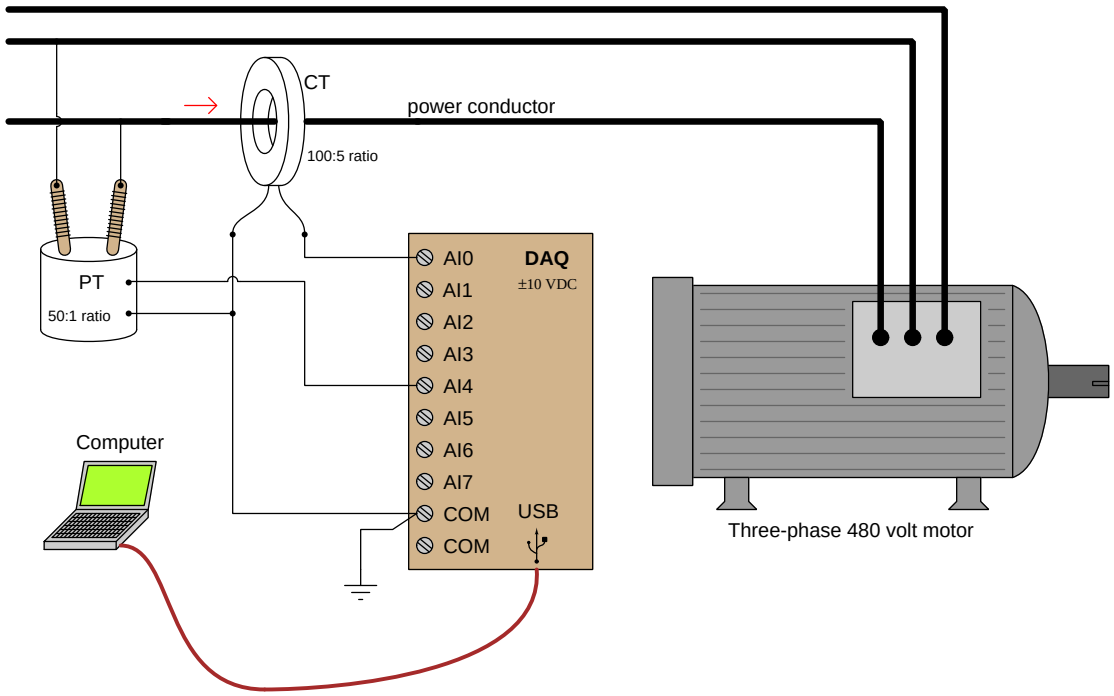
You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far 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 Damaged data acquisition system

A technician connects a DAQ (Data Acquisition) module to one phase of a 480 VAC three-phase electric motor in order to measure and record that motor's voltage and current simultaneously on a laptop computer. The DAQ functions as a high-speed analog-to-digital converter unit with eight voltage-sensing input channels (`AI0` through `AI7`), allowing the computer to display and record a time-based graph of motor voltage and motor current over time. In essence, this DAQ acts as a digital voltmeter with eight measurement channels, each of those channels having its own "red" test lead while all channels share a common "black" test lead (the two redundant `COM` terminals).

Knowing that the phase-to-phase voltage of approximately 480 Volts and the line current of approximately 25 Amperes will be far too great for the DAQ to directly measure, the technician uses *instrument transformers* (a "PT" potential transformer and a "CT" current transformer) to step these voltages and currents to more reasonable values:



Unfortunately, as soon as the motor is energized, the DAQ disappears in a bright flash of light and cloud of smoke. The destruction also propagated to the PC the DAQ was connected to (through the USB cable)! What went wrong, and how should the technician correct his mistake? Assume we must use the same model of DAQ unit having the same ± 10 Volt input limits.

Challenges

- Identify some practical tests the technician could have done prior to connecting the instrument transformers to the DAQ unit, to ensure that DAQ would not be damaged.

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 December 2025 – added more comments in the Tutorial chapter on instrument transformer burden, and corrected some typographical errors.

2 December 2025 – added more instructor notes to the "Transformer-isolated voltage calculations" Quantitative Reasoning question.

17 February 2025 – added a new Technical References section on transformer parasitics.

18 December 2024 – added a photograph to the "Instrument transformer test switches" section of the Tutorial chapter showing a CT test probe inserted into an opened CT test switch, modified an existing photograph, and added some more explanatory text to that section.

16 November 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.

6 December 2023 – added more instructor notes to the "Transformer-isolated voltage calculations" Quantitative Reasoning question.

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

8 December 2021 – emphasized the use of *meters* for saturation testing of CTs in the Tutorial.

9 July 2021 – replaced some TeX-style italicizing markup with LaTeX-style.

8 May 2021 – commented out or deleted empty chapters.

27 April 2021 – 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. Also corrected an error in the instructor notes.

25 April 2021 – changed title of a Quantitative Reasoning question from "CT wiring to a relay" to "Multi-ratio CT wiring"

17 April 2021 – added questions, and also split the "Instrument transformer test switches" section into two sections, with the new section devoted to terminal blocks.

1 January 2019 – added a Technical Reference section on electrical safety.

5 November 2018 – retitled Historical References section(s) so as to not be redundant to the "Historical References" chapter.

September 2018 – renamed "Derivations and Technical References" chapter to "Historical References".

July 2018 – document first created.

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