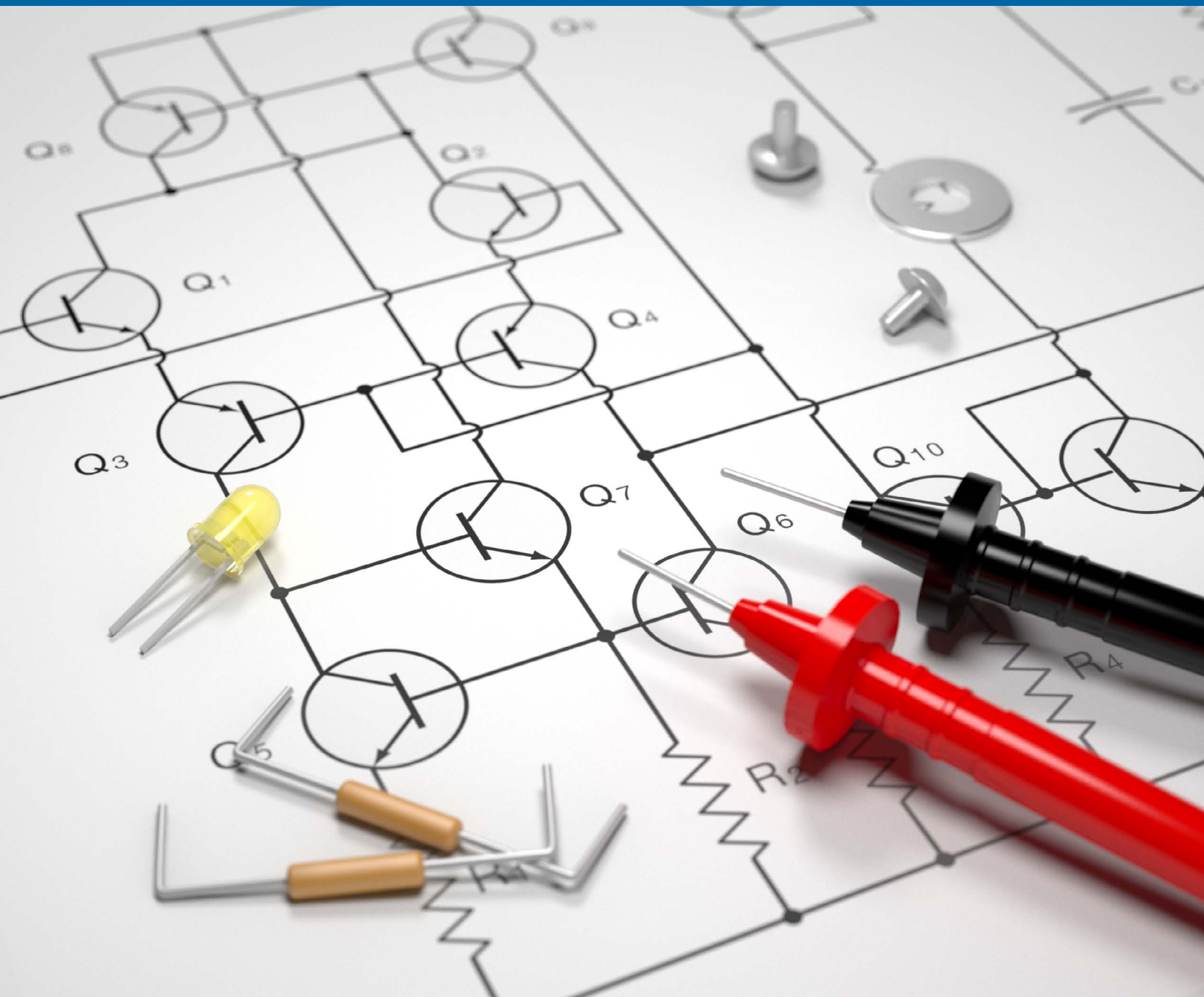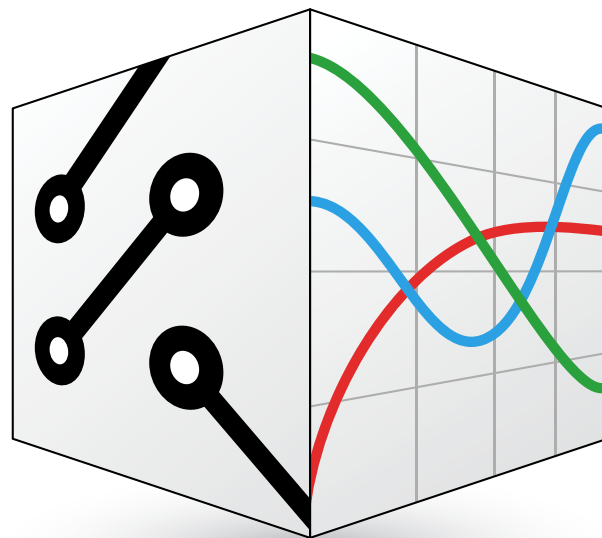2019 Edition

THE PRACTICING ELECTRONICS TECHNICIAN'S HANDBOOK

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PREFACE

Electronics and electromechanics are incredibly exciting and dynamic fields, but to be successful means having a thorough understanding of the foundational skills and concepts that make electricity so electrifying.

The Practicing Electronics Technician's Handbook was developed to be a compact collection of fundamental content for electronics and electromechanical technicians to refer to throughout their career. The handbook is broken down into three sections for easy reference: articles, key equations, and supplemental information, all aimed to help users understand the content and build the necessary skills to succeed in the field.

Covering everyday skills and topics such as areas of difficulty when working with linear DC network theorems, and math skills needed to solve simultaneous equations, the articles in the handbook clearly explain complex topics. Key equations included are commonly used equations that are divided by topic, such as solving for instantaneous voltage and average voltage. Additional topics are covered in the supplemental content section, with numerous diagrams included to help visualize theories.

We hope that this handbook leads to a better understanding of these topics, and becomes referenced resource for you.

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COMMON RULES FOR WEIGHTED NUMBER SYSTEMS

Technicians often encounter values expressed in binary, octal, or even the hexadecimal number systems. This article focuses on characteristics that are common to all of these number systems.

The first thing to understand is that these are all weighted number systems which use columns of digits. As with the decimal system, the names of these other number systems denote the base or "radix" of the system. The base of a number system can be described as the number of states that can be represented by a single digit or column. For instance, the base 10 "decimal" system can represent 10 distinct states in a single digit place holder using symbols 0 – 9. Each of these number systems behave the same way with respect to the weighting of the columns used to represent groups when expressing multi-digit values. As you add columns to the left of the least significant digit, you increase the exponent you are raising the radix to by one.

WHAT IS MEANT BY POSITION WEIGHTING?

	X^3	X^2	X^1	X^0
Binary (base 2)	8	4	2	1
Octal (base 8)	512	64	8	1
Decimal (base 10)	1000	100	10	1
Hexadecimal (base 16)	4096	256	16	1

When evaluating a value in a given number system, the above table illustrates the weight of the digits in each column for the given number system. We work with the decimal system daily, and it follows these rules as well. The decimal value 372, is evaluated as 3 groups of 100, 7 groups of 10, and 2 groups of 1. We apply this same general rule to all the above systems. For the octal value of 372, we would have 3 groups of 64, 7 groups of 8, and 2 groups of 1.

THE IMPACT OF SHIFTING DIGITS TO THE LEFT AND RIGHT

As a technician in the increasingly digital age, you may often come across the use of the binary or base 2 number system. As a consequence of the above stated nature of weighted number systems, shifting a given value to the left is the same as multiplying that value by the radix of the number system. Shifting a binary value to the left is the same as multiplying it by 2. Although most often used with binary values, this shifting as a form of multiplication is common to all weighted number systems. Conversely, if a binary value is shifted to the right, it is the same as dividing the value by 2 in the case of binary, or the radix of any other positional weighted number system. Again, we are already familiar with this fact, if not consciously, by our extensive usage of the decimal system in everyday base 10 calculations. It is important to remember that this same basic principal can easily be applied to octal or hexadecimal values as well despite our unfamiliarity with these special purpose number systems.

THE NUMBER OF AVAILABLE STATES FOR A GIVEN NUMBER OF DIGITS

Weighted number systems have other common properties. To calculate the total number of states that can be represented by a given number of digits in a particular number system, we simply raise the radix of the system, to the power of the number of digits we are using. The resulting value represents how many distinct states that are available with that many digits in that particular number system.

$$\text{radix}^{\text{number of digits}} = \text{Total Number Of States Available}$$

THE HIGHEST VALUE FOR A GIVEN NUMBER OF DIGITS

To calculate the highest value that can be represented by a given number of digits in a particular number system, we simply subtract one from the calculation for available states. This is due to the fact that in each system, "0" is one of the states represented.

$$\text{radix}^{\text{number of digits}} - 1 = \text{Highest Value That Can Be Represented}$$

Working with different weighted number systems may seem a bit intimidating until you remember that these alternate base number systems follow the same rules as the decimal number system which we work with every day.

HOW TO SOLVE SIMULTANEOUS EQUATIONS WITH MULTIPLE UNKNOWNS

Many technicians encounter difficulty in solving node or loop equations containing multiple unknown quantities. This article reviews a means of solving such equations to get loop currents or node voltages when performing linear DC network analysis. The two technician level methods for solving simultaneous equations having multiple unknowns used when dealing with two or three equations are "substitution" and "elimination". In order to solve for a given number of unknowns, we require that the same number of equations be provided. For instance, we would require two equations to solve for two unknown quantities. We would require three equations to solve for three unknown quantities, and so on.

USING THE SUBSTITUTION APPROACH TO SOLVE SIMULTANEOUS EQUATIONS

Solve for x, and y given these two equations containing the two unknown quantities.

Eq.1 $3x + 2 = 2y$

Eq.2 $8x - 4 = 4y$

We want to isolate the y term in one equation. By this we mean, we need an equation that states the value of a single y in terms of x.

Eq.1 $3x + 2 = 2y$

$y = (3x + 2) / 2$

Since we now have an expression for the value of y in terms of x, we will replace/substitute the y term in Eq.2 with this new expression we obtained above. This will leave us with only one unknown quantity, x, to solve for in Eq.2 instead of the two unknowns we had before.

Eq.2 $8x - 4 = 4y$

$8x - 4 = 4(3x + 2) / 2$

$8x - 4 = (12x + 8) / 2$

$8x - 4 = 6x + 4$

$8x = 6x + 4 + 4$

$8x - 6x = 4 + 4$

$2x = 8$

$x = 8/2$

x = 4

Having the value of x, we can use it in Eq.1 or Eq.2 to find the value of y. (Using Eq.1)

$3(4) + 2 = 2y$

$12 + 2 = 2y$

$14 = 2y$

$y = 14 / 2$

y = 7

USING THE ELIMINATION APPROACH TO SOLVE SIMULTANEOUS EQUATIONS

This approach can also be used to solve for the two unknowns in the same two equations.

Eq.1 $3x + 2 = 2y$

Eq.2 $8x - 4 = 4y$

This time, our objective is to find a factor to multiply one of the equations by which will allow us to sum the two equations and eliminate one of the unknowns. If we multiply both sides of Eq.1 by a factor of -2 and then sum the two equations, we will be left with an expression containing only one unknown. We selected -2 as the factor to multiply Eq.1 by so that the right hand side of Eq.1 when added to the right hand side of Eq.2 will result in the y term being eliminated from the resulting equation.

Eq.1 $3x + 2 = 2y$

$-2(3x + 2) = -2(2y)$

$-6x - 4 = -4y$

Now we will sum this new expression for Eq.1 with our original Eq.2. Adding the -4y from the right side of our new expression for Eq.1 to the 4y on the right hand side of Eq.2 will result in 0y, which effectively eliminates the y term from the resulting equation.

Eq.1 $-6x - 4 = -4y$ (modified Eq.1 by factor of -2)

Eq.2 $8x - 4 = 4y$

To sum these equations, add the terms from the left hand side of each equation together, and add the terms from the right hand side of the equations together as follows…..

$(-6x - 4) + (8x - 4) = (-4y) + (4y)$

$2x - 8 = 0$

$2x = 8$

$x = 8/2$

$x = 4$

We would now use the value of 4 for x in either of the two original equations to solve for the value of y. (Using Eq.2)

$8(4) - 4 = 4y$

$32 - 4 = 4y$

$28 = 4y$

$y = 28/4$

$y = 7$

In this last example, we eliminated the y term from the equations because it was an easily recognizable means of reducing the equation to a single unknown. We could have decided to eliminate the x variable instead, leaving an equation with y as the only unknown quantity.

Eq.1 $3x + 2 = 2y$

Eq.2 $8x - 4 = 4y$

In order to clear the x terms from the above equations, it will be necessary to apply a factor to both equations in order to create the situation we desire. If we multiply Eq.1 by 8 and Eq.2 by -3, the x terms become 24x and -24x respectively. These will cancel each other out when the two equations are summed.

Eq.1 $8(3x + 2) = 8(2y)$

Eq.1 $24x + 16 = 16y$

Eq.2 $-3(8x - 4) = -3(4y)$

Eq.2 $-24x + 12 = -12y$

Now we sum our two new equations to obtain an equation with a single variable. If we write the equations one on top of the other, we can simply sum vertically to arrive at our single variable equation.

Eq.1 $24x + 16 = 16y$

Eq.2 $-24x + 12 = -12y$

———————————————

$0x + 28 = 4y$

$4y = 28$

$y = 28/4$

$y = 7$

We would now use this known value of y in one of the original equations to solve for the value of x. (Use Eq.1)

$3x + 2 = 2(7)$

$3x + 2 = 14$

$3x = 14 - 2$

$3x = 12$

$x = 12/3$

$x = 4$

EXAMPLE

A practical example of how these techniques are applied is provided in the video animation on Loop Analysis. This example uses the Substitution and Elimination techniques to solve simultaneous KVL loop equations and is illustrated step by step.

THE SIGNIFICANCE OF CONDUCTOR RESISTANCE AND HOW TO CALCULATE IT

In this article, we will review the calculation required to determine the resistance of a given conductor. This often overlooked parameter can be important when trying to determine the appropriate wire diameter for a given application. It is also important to consider conductor resistance when examining application efficiency. Lower resistance means lower power dissipation by the conductor. Optimizing these two aspects of conductor resistance for your specific application can lead to significant reductions to implementation and operating costs. It is important to know the resistance offered by a given conductor as well as have an understanding of the extent to which that resistance impacts on the application and its operation. For this reason, we will review some relevant aspects of conductor resistance and briefly describe and discuss them.

WHAT FACTORS DETERMINE THE RESISTANCE OF A GIVEN CONDUCTOR?

There are three factors that determine the amount of resistance a given conductor will have. They are illustrated here, in the relationship used to calculate conductor resistance.

$$\text{Resistance} = \text{Resistivity} \times (\text{Length} / \text{Area})$$

$$R = \rho * (L / A)$$

R = resistance in ohms
ρ = material resistivity in ohms metres
L = conductor length in metres
A = cross-sectional area in square metres

We begin by acknowledging the obvious fact that the length of a conductor will contribute to its overall resistance. The longer the length of a given conductor, the more resistance that conductor will have. This can be clearly seen in the relationship provided above.

The material resistivity of the conductor plays a significant role in the overall resistance. This is because different materials for example gold or copper, offer different amounts of resistance to continuous current flow. Conductor materials are generally selected on a cost-benefit and suitability basis. The material resistivity of some of the most common conductors used today is listed below.

Material	Resistivity, ohms·m
Silver	1.64×10^{-8}
Copper	1.72×10^{-8}
Gold	2.45×10^{-8}
Aluminum	2.83×10^{-8}

The last significant factor that determines conductor resistance is the cross-sectional area of the given conductor. It is important to note the inverse relationship between the cross-sectional area of a conductor, and the conductor's resistance. The smaller the cross-sectional area of the conductor, the larger the resistance value of the conductor becomes. This means that although it may be cheaper to use smaller conductor sizes, there is a trade off with resistance.

IN WHAT WAYS CAN CONDUCTOR RESISTANCE BE SIGNIFICANT?

This relationship provides a means of determining conductor resistance which can be used to examine power losses that contribute to the overall efficiency of an application. This relationship can also be rearranged to solve for Area. This calculated value for cross-sectional area can then be used to provide the required wire diameter to meet specific application needs. As previously stated, these two considerations have impact on implementation and operating costs and are worth examining.

> **EXAMPLE**
>
> An example of the general relationship for calculating a conductors resistance to ascertain the minimum diameter and cross-sectional area is provided in the video animation Calculating Required Wire Diameter And Cross-sectional Area.

CONVERTING PARALLEL RL CIRCUITS TO THEIR "EASIER TO WORK WITH" SERIES EQUIVALENTS

Here, we look at a simple technique that can be used to simplify circuit analysis when working with series and parallel RL circuits. One of the issues encountered by technicians who are working with parallel RL circuits is the need to work with values that are the reciprocals of the more commonly used standard units. The use of conductance, susceptance, and admittance instead of resistance, reactance, and impedance, can often cause confusion or uncertainty when working with these lesser employed units. This conversion approach or technique can be especially helpful when working with circuits having multiple resistors and inductors in mixed series/parallel configurations. Reducing such a mixed topology network down to a few inductors and resistors in series greatly simplifies calculating overall resistance and inductance in a given circuit or network. In the series format, it is simply a matter of addition when calculating total inductive reactance, total resistance to get to overall impedance.

Below are the basic equations for creating a series representation of a given parallel RL circuit.
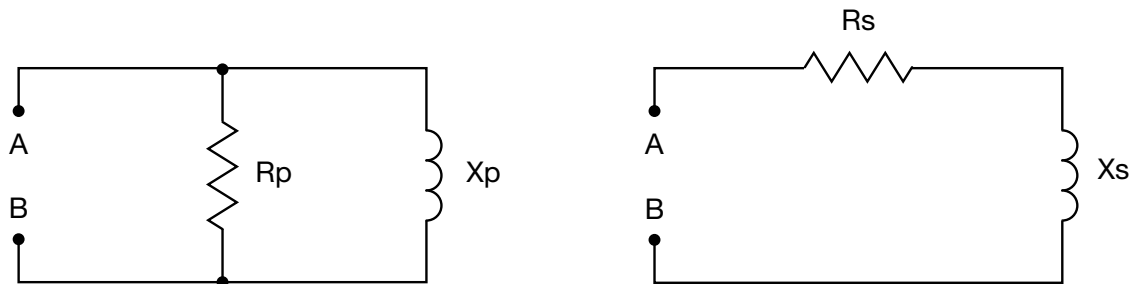
$$Rs = (Rp * Xp^2) / (Rp^2 + Xp^2)$$
$$Xs = (Xp * Rp^2) / (Rp^2 + Xp^2)$$

PERFORMING THE CONVERSION...

Step 1: Calculate the equivalent resistance value Rs

Step 2: Calculate the equivalent inductive reactance Xs

Step 3: Calculate the required inductor value that will provide the appropriate series inductive reactance for a given frequency. Use L = XL / (2 * Pi * freq) to obtain the inductor value.

Step 4: Redraw the circuit in a series configuration using the arrived at component values for the inductor and resistor.

Correctly employing the above steps will result in a series representation of a parallel RL circuit that behaves identically with respect to voltage, current, and the phase relationship between them. From the perspective of points A and B in the above, both circuits will result in identical behaviour.

Employing topology conversion techniques such as Parallel to Series RL circuit conversion, Delta-Wye conversions for resistor networks, or simple Source Transformations (converting current sources with parallel resistances to voltage sources with series resistances) is a common simplification tactic that can be extremely helpful in circuit reduction and analysis at a technician level. As a technician, the more tools you have at your disposal, the easier it will be to simplify and reduce complex circuits down to simple representations. This in turn will serve to reduce the chance of errors when performing technician level circuit analysis.

HOW TO CREATE CORRECT OHM'S LAW KCL BRANCH EQUATIONS FOR NODAL ANALYSIS

Nodal analysis is a means of determining the voltage present at a node of interest with respect to a specified reference point. Many technicians have difficulties creating valid Ohm's Law representations for the KCL (Kirchhoff's Current Law) node equations when trying to perform this type of circuit analysis. They often struggle with the concept that arbitrary branch current directions can be assigned at the start of the analysis, and the correct results can always be arrived at regardless of whether or not the branch current actually flows in the assumed direction.

The key to this analysis is to ensure that you state your current law equations for each node of interest in terms of your selected current direction. This sounds simple, however, this is the stage at which most errors occur when performing this type of analysis. Below is a straight forward approach that will always yield correct current law equations for independent nodes in any linear DC network. The most important thing to consider is how to define the unknown current which flows between the node of interest and the reference node. If this representation of branch current is incorrect, the entire analysis will be invalid. The correct application of Ohm's law in terms of the assumed current direction is essential to identifying node voltages and their polarities with respect to the specified reference node when performing this type of analysis. Below are the six scenarios that can exist when creating equations used to describe branch current flowing into or out of an independent node. Every branch in the linear DC network can be reduced to one of these six scenarios.

In **Figure 1-1a**, a known resistance is connected between two nodes in a network. We desire an equation that will define the current flowing through the resistor, in terms of the voltages present at the two nodes and the displayed direction of current flow. This current will allow us to define the voltage at node A.

Figure 1-1

Ref

(a)

Ref

(b)
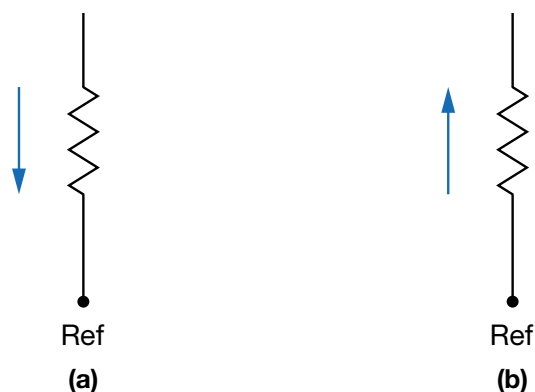
When current is flowing from node A towards the reference node as in Figure 1-1a, according to electron flow, node A must be at a lower voltage than the reference node. A current flowing in the direction shown can be expressed using Ohm's law as follows:

$$I = (VRef - VA) / R \quad \text{Eq. 1}$$

When current is flowing from the reference node towards node A as in Figure 1-1b, the reference node is at a lower voltage than node A. A current flowing in this direction can be expressed using Ohm's law as follows:

$$I = (VA - VRef) / R \quad \text{Eq. 2}$$

In **Figure 1-2a**, a voltage source appears between the node of interest and the reference node, its effect on the current flowing through the resistor must be taken into account. When examining the effect of the voltage source, you need to determine if the polarity of the voltage source adds to the current in the assumed direction, or does it oppose it. Electrons flow out of the negative terminal and into the positive terminal of a voltage source. If the direction of flow for the source agrees with the direction of flow that was assumed, the source would be adding (Vs / R) to the current already flowing between the nodes prior to the sources introduction. (See above)

Figure 1-2

(a)   (b)   (c)   (d)
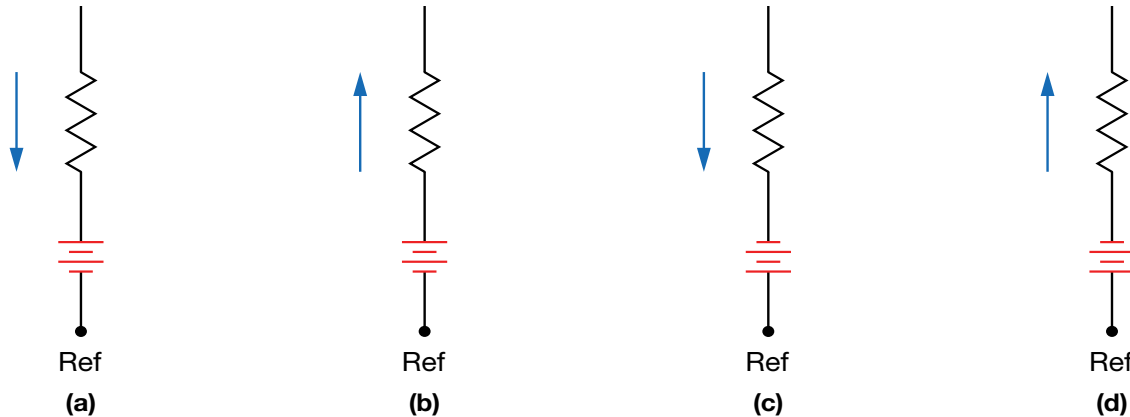
The expression for the current flowing in Figure 1-2a is similar to that in Figure 1-1a except that the effect of the voltage source on the current flowing through the resistor needs to be included in the expression. An easy way to visually determine the sign to use when accounting for the effects of the source (to add it or subtract it) is to apply the sign of the source terminal into which the current flows. In this example, the current flows into the positive terminal of the voltage source. This agrees with the assigned current direction and the current from the voltage source is therefore added to the expression for the current.

$$I = (VRef - VA) / R + Vs / R$$
$$I = (VRef - VA + Vs) / R \quad \text{Eq. 3}$$

The expression for Figure 1-2b is based on that in Figure 1-1b. Once again, the effect of a voltage source needs to be accounted for in the node voltage expression. This time, since the current enters the negative terminal of the voltage source, its contribution is subtracted from the expression for the current.

$$I = (VA – VRef) / R - Vs / R$$
$$I = (VA - VRef - Vs) / R \quad \text{Eq. 4}$$

Figure 1-2c is basically the same as Figure 1-2a except that the voltage source is connected in the opposite

direction. This means that the current is entering the negative terminal of the source and you must subtract its contribution from the expression for the current between the two nodes.

$$I = (VRef - VA) / R - Vs / R$$

$$I = (VRef - VA - Vs) / R \quad \text{Eq. 5}$$

Figure 1-2d is similar to Figure 1-2b but once again the voltage source is connected in the opposite direction. The current shown to be flowing, enters the positive terminal of the voltage source indicating that the contribution from the voltage source should be added.

$$I = (VA - VRef) / R + Vs / R$$

$$I = (VA - VRef + Vs) / R \quad \text{Eq. 6}$$

The previous equations, labelled 1 through 6, are essential to the proper application of nodal analysis to linear (resistive) DC networks. Any number of resistances and/or voltage sources between the node of interest and the reference node can be reduced to one of the six configurations illustrated in the above examples.

USING NODAL ANALYSIS TO SOLVE LINEAR DC NETWORKS

There are eight basic steps to follow when performing a Nodal Analysis on a linear DC network. With the aid of the six equations provided above, the steps outlined below will ensure that you arrive at the correct values when performing the analysis.

Step 1: Identify all nodes in the circuit.

Step 2: Select a reference node.

Step 3: Identify the independent nodes in the circuit. An independent node is a node whose voltage is determined by the size of the resistor and circuit configuration. Assign an arbitrary current direction for all currents entering or leaving the independent nodes in the network.

Step 4: Write the KCL equation for the currents entering or leaving each independent node in terms of the chosen current directions.

Step 5: Use Ohm's law to express each current listed in the KCL equations for the independent nodes keeping the assumed current direction in mind. Use the appropriate equation from the 6 equations outlined above paying close attention to the chosen direction of current flow.

Step 6: Express the KCL equations for the independent nodes using the Ohm's law representation obtained from step 5.

Step 7: Solve for the independent node voltages using the equations obtained from step 6. (Use the same approach outlined for Loop analysis when solving the multiple simultaneous equations.)

Step 8: Use the acquired node voltages with the Ohm's Law representations for branch current, to solve for the unknown independent node currents. A positive current value result means that the current flows in the direction arbitrarily chosen at the start of the analysis. If the branch current value is negative, it means that the current actually flows in the opposite direction than the assumed one.

THE UTILITY OF FINDING THE THEVENIN EQUIVALENT CIRCUIT

In this article, we will once again be working with a circuit reduction technique. This particular technique is quite useful for determining how changes in load conditions can impact on circuit performance. Until now, we have provided reduction techniques that are useful for fixed load circuit analysis. Thevenin's theorem can be used in cases where we want to see how load voltage, current and power are effected by changes in load resistance.

As an example of the utility of this theorem consider the testing of any power generation equipment. One of the key aspects of such a test exercise illustrates the usefulness of being able to make multiple calculations pertaining to varying load conditions easily. A resistive or unity power factor load bank is a device that is designed to provide scalable loads and is used during testing of power generation equipment. To calculate expected values under the relevant series of load conditions can be tedious. Thevenin's circuit reduction approach simplifies it. Not only can this approach be applied to larger scale power generation applications, it applies to something as simple as testing automotive batteries for high load usage during the turning over of the engine as opposed to other expected operating conditions.


HOW IS THIS USEFUL?

The theorem can be applied to create a simplified version of a linear DC network that consists of only a single source and series resistance which will behave identically to the linear DC network in terms of the load. As an example, this would drastically reduce the number of calculations required to obtain data in a situation where we want to know how a given network responds to 50%, 60%, 70%, 80% and 90% full load conditions. A somewhat complex traditional Loop or Nodal analysis would need to be repeated 5 times to make the data available for each load value. As an alternative, we can create a Thevenin Equivalent circuit consisting of a

single source and series resistance that will behave identically with respect to the load as the entire linear DC network would, and then do 5 very simple ohm's law level calculations to acquire load voltage (current, or power) under each load condition.

In this example, it is easy to see how the reduced circuit representation (bottom) can simplify our desired calculations for different loads even for a linear DC network as simple as the one used here which consists of only a single source and 4 resistors.
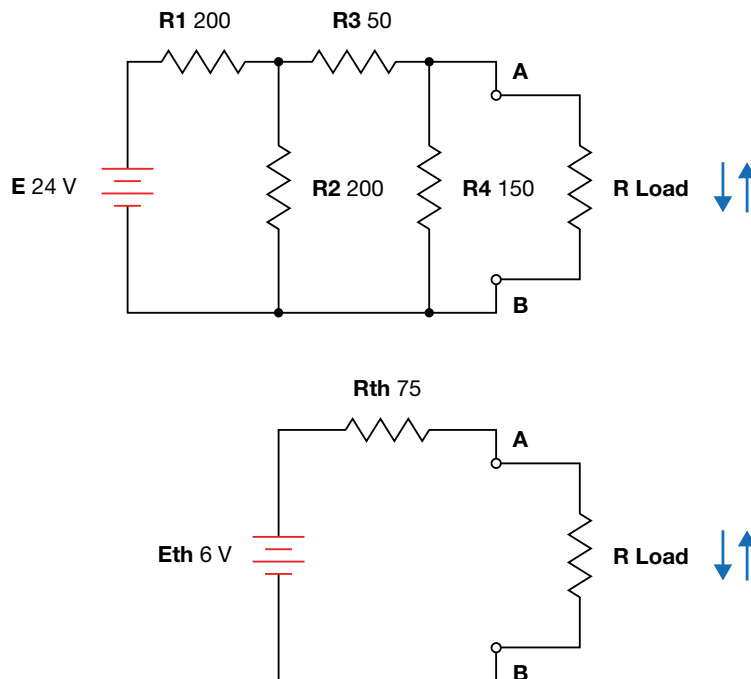
The original network (top) is quite simple, however, with Thevenin circuit reduction, the equivalent circuit (bottom) is much easier to work with when you need to know load voltage and load current for loads of 50 ohms, 60 ohms, 70 ohms, 80 ohms, and 90 ohms. With the reduced version, you can use V/R to find load current, and a simple voltage divider to calculate load voltage for each load resistance value. In contrast, if you use Loop or Nodal analysis, you would need to repeat those complex calculations over and over to get the desired data.

This powerful technique is not restricted to only simple single source linear DC networks. It can be used on multi-source, complex networks as well. The more complex your original linear DC network is, the more you simplify your life by creating the Thevenin Equivalent circuit representation of that network.

WHAT DOES THE THEOREM STATE?

A two-terminal linear DC network, consisting of any number of fixed value resistances and any number of fixed DC voltage and current sources, can be replaced by a single voltage source in series with a single resistance that will produce the same effects at the terminals.

HOW IS IT IMPLEMENTED?

Essentially, we redraw the circuit to provide a simplified version that behaves identically.

Step 1: Identify the portion of the network for which you require the Thevenin Equivalent circuit. Label the two terminals as points A and B and remove the portion not being included in the reduction. (ie. the load)

Step 2: Determine the Thevenin equivalent resistance (Rth) by short circuiting all voltage sources, and open circuiting all current sources. Once done, calculate the resistance that now appears between the two terminals labelled points A and B.

Step 3: Determine the Thevenin equivalent voltage (Eth) by returning all sources to their previous position and state, and calculating the voltage that would appear across the two terminals labelled points A and B.

Step 4: Draw the Thevenin Equivalent circuit using a single voltage source with a voltage value of Eth, and a single series resistance using a resistance value of Rth obtained above. Connect the previously removed portion of the circuit (the load) and make your simplified calculations for voltage, current, or power.

USING THE NATURAL LOG OR "LN" FUNCTION IN CIRCUIT ANALYSIS

The focus of this article is on Euler's number and the utility of the related natural logarithm or "ln" function as they pertain to technician level circuit analysis. Once we have discussed the nature of Euler's number and the related base "e" natural log function, we will move on to take a look at an example of their practical application for technicians when performing circuit analysis tasks.

WHAT IS EULER'S NUMBER?

Euler's number is also known as the exponential constant and is a non-terminating "irrational" number. It is derived from the following infinite power series:

$$e = 1 + (1/1!) + (1/2!) + (1/3!) + (1/4!) + (1/5!) + ...$$

$$e = 1 + (1/1) + (1/2) + (1/6) + (1/24) + (1/120) + ...$$

$$e = 2.718281828459 \text{ approx.}$$

This mathematical constant is widely used in instances where quantities of interest exhibit exponential growth or decay. For the practical technician, an everyday example of such a relationship would be the charging and discharging of capacitors and inductors in series RC and RL circuits with respect to time.

WHAT IS THE NATURAL LOGARITHM (LN) FUNCTION?

Logarithms in general allow you to operate on, or isolate, exponents used with various "base" values. A well-known example is the "Common" or "base 10" logarithm used by technicians for power calculations. The "ln" function is the base "e" natural logarithm function. The natural logarithm or "ln" of the value "e*" is equal to "x".

$$\ln (e^*) = x$$

A TYPICAL NATURAL LOG APPLICATION FOR TECHNICIANS

As with all logarithm functions, the "ln" function is very useful in instances where we wish to isolate or manipulate exponents used, in this instance, with base "e" values. An example of such an instance arises whenever we need to know the time it takes the voltage across a capacitor to reach a desired level during the capacitor charging curve. We begin with the commonly used relationship for calculating the voltage across the plates of a capacitor as it charges.

$$Vc = E * (1 - e^{-t/Tau})$$

Vc = Capacitor Voltage in volts
E = Applied DC Voltage in volts
e = Euler's Number (exponential constant)
t = Time in seconds
Tau = Time constant (R*C) in seconds

The equation defining capacitor voltage uses Euler's number. This is due to the fact that the capacitor charging curve exhibits exponential growth. We rearrange this relationship, isolating Euler's number and its exponent on one side of the equation, and everything else on the other side. Once we have isolated Euler's number and its exponent, we need to bring the exponent of "e" down to the main line so that we can operate on it as the variable we wish to isolate, "t" for time in seconds, is part of the exponent. This type of mathematical manipulation is accomplished by using logarithms. As we are dealing with a base "e" value, we apply the natural logarithm or "ln" function to both sides of the equation.

$$e^{-t/Tau} = 1 - Vc/E$$

$$\ln (e^{-t/Tau}) = \ln (1 - Vc/E)$$

Given that $\ln (e^{x}) = x$, the left side of the equation results in the desired "t" variable being moved to main line. It can then be isolated to solve for time given applied voltage and desired capacitor voltage level.

$$-t/Tau = \ln (1 - Vc/E)$$

$$t = -Tau * \ln (1 - Vc/E)$$

The above relationship provides the time it takes for the voltage on the plates of a capacitor to reach a specified value in a series RC circuit.

THE IMPORTANCE OF POWER FACTOR CORRECTION AND HOW IT CAN BE ACCOMPLISHED

This article will review the significance of power factor correction. As a technician, you may be responsible for monitoring and adjusting the power factor of your industrial operation. Many industrial applications involve induction motors or other equipment that results in supply voltage and supply current being out of phase. This is wasteful and expensive for power providers. In light of this fact, power companies will offer financial incentives by way of reduced rates to those customers who maintain a power factor as close to 1 as possible. Often, technicians will be charged with monitoring and/or correcting this "out of phase" relationship between supply voltage and current. It can be demonstrated that you can obtain the same real power dissipation (in Watts) with less current required if you maintain a power factor as close to 1 as possible. When voltage and current are in phase, the load appears purely resistive to the source and volt-amperes or VA are kept to a minimum. True power (Watts) has no VA component unlike apparent power. Power factor correction aims to bring the apparent power value (measured in VARs or volt-amp-reactive) as close as possible to the amount of true power you are using in Watts. This will result in less current being needed to provide the same amount of true power. Changes in plant equipment can often result in the need for power factor correction in order to maintain the benefits of in phase voltage and current and the resulting reduction to power costs.

We will work through an example of power factor correction by assessing the phase relationship of the supply voltage to the supply current. We will be calculating the amount of capacitance we need to add to our inductive load in order to bring the power factor back to 1. With all inductive loads, voltage is leading current and in order to bring these two parameters back into phase, we need to add some capacitive reactance to the circuit to offset the phase imbalance.
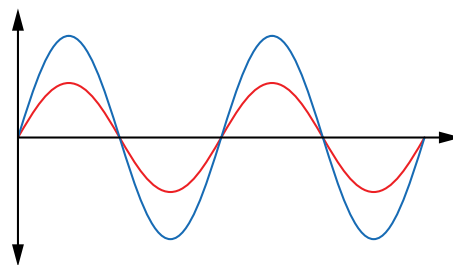
HOW DO WE CALCULATE POWER FACTOR?

Power Factor can be calculated by taking the cosine of the phase angle between the supplied voltage and the supplied current.

Power Factor = cos (theta)
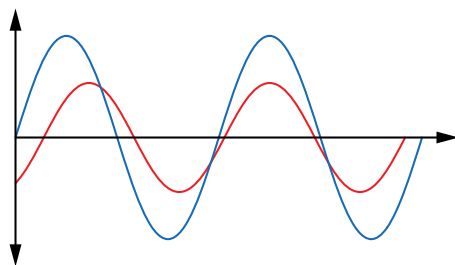
Voltage and current out of phase   **Voltage and current in phase**

When the voltage and current are in phase, the angle is equal to zero. The cosine of zero equals 1. Any difference between the phase of the voltage, and the phase of the current results in a non-zero phase angle resulting in a power factor of less than 1 as the cosine of any angle other than 0/360 will range from 0 to less than 1.

A second relationship describes this quantity (power factor) as the ratio of True Power in Watts, to Apparent Power in VA (volt-amperes): Power Factor = True Power / Apparent Power

HOW DO WE RESOLVE ANY EXISTING PHASE DIFFERENCE?

When the load is predominantly inductive in nature, in order to acquire a power factor of 1, we most often will introduce the correct amount of capacitive reactance to the load in order to bring supply voltage and supply current back into phase. This is accomplished by measuring the phase difference between the voltage and the current, and then using that value to calculate the inductive reactance in the load. Once you know that, you only need to calculate the required parallel capacitor value needed to make the load appear completely resistive to the source. Set XC = XL.

Step1: Calculate Z (total impedance)

Z = Erms / Irms

Step 2: Measure the phase angle (theta) between voltage and current

Theta (this example) = -37.8 degrees

Step 3: Calculate XL

XL = Z sin (theta)

Step 4: Use XL and supply frequency to calculate required capacitor value

We know that for the load to appear resistive, XL = XC

XC = XL

XL = 1 / 2*Pi*f*C

C = 1 / 2*Pi*f*XL

Step 5: Place a capacitor of the value calculated in step 4 in parallel with the load. This will cause the load to appear purely resistive as the inductive and capacitive inductances cancel each other out and the voltage and current from the source will now be in phase.

In practical terms, this procedure results in less current being required to provide the same real power to the load. This results in reduced operating costs for your industrial application by way of cheaper power rates from your utility company.

2 KEY EQUATIONS
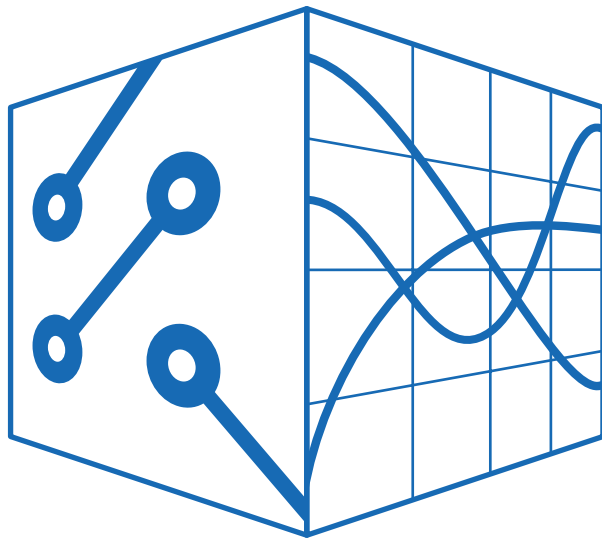
1. Current, Voltage & Resistance

Equation 1.1

$I = Q / t$

I = current in Amperes
Q = charge transferred, in Coulombs
t = time in Seconds

Equation 1.2

$E = W / Q$

E = potential difference in Volts
W = energy in Joules
Q = quantity of charge in Coulombs

Equation 1.3

$R = \rho * l / A$

R = resistance of material in Ohms
ρ = constant of proportionality in Ohms per Meter
l = length in Meters
A = cross-sectional area in Square Meters

Equation 1.4

A in circular mils $= d^2$

A = area in Circular Mils
d = diameter in Mils

Equation 1.5

$R_2 = R_1 * (1 + \alpha \Delta T)$

R_1 = original resistance in Ohms
R_2 = new resistance in Ohms
α = temperature co-efficient
$\Delta T = T_2 - T_1$ = temperature change in Degrees

2. Ohm's Law, Power & Energy

Equation 2.1

$R = E / I$

R = resistance in Ohms
E = potential difference in Volts
I = current in Amperes

Equation 2.2

$P = E * I$

P = power in Watts
E = potential difference in Volts
I = current in Amperes

3. Series Circuits

Equation 3.1

$R_t = R_1 + R_2 ..... + R_n$

R_t = equivalent total resistance in Ohms
R_1, R_2 = series resistor values in Ohms
R_n = resistance of last series resistance in Ohms

Equation 3.2

$VR_x = E (R_x / R_t)$

E = applied potential difference in Volts
VR_x = potential difference across series resistor in Volts
R_x = series resistor value in Ohms
R_t = total series resistance in Ohms

4. Parallel Circuits

Equation 4.1

$1 / R_{eq} = 1 / R_1 + 1 / R_2 .... + 1 / R_n$

R_{eq} = equivalent resistance of all parallel resistors in Ohms
R_1, R_2 = resistance of each parallel resistor in Ohms
R_n = resistance of last parallel resistor in Ohms

Equation 4.2

$I_1 = I_t * [R_2 / (R_1 + R_2)]$

I_t = total current flowing in Amperes
I_1 = current in the branch with R_1 in the parallel circuit in Amperes
R_1, R_2 = resistance of each of the two parallel resistors in Ohms

Equation 4.3

$$I_2 = I_t * [R_1 / (R_1 + R_2)]$$

I_t = total current flowing in Amperes
I_2 = current in the branch with R_2 in the parallel circuit in Amperes
R_1, R_2 = resistance of each of the two parallel resistors in Ohms

Equation 4.4

$$I_x = I_t * (R_t / R_x)$$

I_t = total current flowing in Amperes
I_x = current through the desired resistor in Amperes
R_x = resistance of the desired parallel resistor in Ohms
R_t = total resistance of the resistors in parallel in Ohms

5. Magnetism

Equation 5.1

$$B = \Phi / A$$

B = flux density in Teslas
Φ = total field flux in Webers
A = cross-sectional area in Square Meters

6. Magnetic Circuits

Equation 6.1

$$\mu = B / H$$

μ = permeability of a material in Henrys per Meter
B = flux density in Teslas
H = magnetic field strength in Ampere-turns per Meter

Equation 6.2

$$\mu r = \mu / \mu o$$

μr = Relative permeability of material
μ = Absolute permeability of material
μo = permeability of free space = $\pi * 4e\text{-}7$ Henrys per Meter

Equation 6.3

$$H_g = B_g / \mu_o$$

H_g = magnetic field strength of air gap in Ampere-turns per Meter
B_g = flux density of air gap in Teslas
μ_o = permeability of free space = $\pi * 4e\text{-}7$ Henrys per Meter

Equation 6.4

$$B = (F / l) * \mu$$

B = flux density in Teslas
F = magnetomotive force in Ampere-turns
l = length of material in Meters
μ = permeability of material in Henrys per Meter

7. Alternating Voltages and Currents

Equation 7.1

$$f = 1 / T$$

f = frequency in Hertz
T = period time in Seconds

Equation 7.2

$$\lambda = 300000000 / f$$

λ = wavelength in Meters
f = frequency in Hertz

Equation 7.3

$$e = E_P * \sin \theta$$

e = instantaneous voltage value in Volts
E_P = peak sine wave voltage in Volts
θ = phase angle in Degrees

Equation 7.4

$$e = E_P * \sin 2\pi ft$$

e = instantaneous voltage value in Volts
E_P = peak sine wave voltage in Volts
f = frequency in Hertz
t = time in Seconds

Equation 7.5

$$E_{ave} = E_P * (2 / \pi)$$

E_{ave} = average voltage value (½ cycle) in Volts
E_P = peak sine wave voltage in Volts

Equation 7.6

$$E_{rms} = E_P / \sqrt{2}$$

E_{rms} = root mean square (effective) voltage value
in Volts
E_P = peak sine wave voltage in Volts

8. Capacitance & Capacitors

Equation 8.1

$$C = Q / V$$

C = capacitance in Farads
Q = charge in Coulombs
V = potential difference in Volts

Equation 8.2

$$C = (\epsilon_r * \epsilon_o * A) / d$$

C = capacitance in Farads
ϵ_r = relative permittivity of material (dielectric
constant)
ϵ_o = absolute permittivity of vacuum
A = area of plates in Square Meters
d = distance between plates in Meters

Equation 8.3

$$\tau = R * C$$

τ = time constant in Seconds
R = resistance in Ohms
C = capacitance in Farads

Equation 8.4

$$Vc = E * (1 - e^{-t/\tau})$$

Vc = capacitor voltage at time t in Volts
E = supply voltage in Volts
e = exponential constant 2.71828
τ = time constant time in Seconds
t = desired time from charge commencing
in Seconds

Equation 8.5

$$Vc = E * e^{-t/\tau}$$

Vc = capacitor voltage at time t in Volts
E = supply voltage in Volts
e = exponential constant 2.71828
τ = time constant in Seconds
t = desired time from decay commencing in
Seconds

Equation 8.6

$$1/C_t = 1 / C_1 + 1/ C_2 \dots + 1/C_n$$

C_t = total series capacitance in Farads
C_1, C_2 = capacitance of each series capacitor
in Farads
C_n = capacitance of last series capacitor
in Farads

Equation 8.7

$$C_t = C_1 + C_2 \dots. + C_n$$

C_t = total capacitance in Farads
C_1, C_2 = capacitance of each parallel capacitor
in Farads
C_n = capacitance of last parallel capacitor
in Farads

9. Inductance & Inductors

Equation 9.1

$$L = (\mu * N^2 * A) / l$$

L = inductance in Henrys
μ = permeability of magnetic path
N = total number of turns of coil
A = area in square Meters
l = length of coil in Meters

Equation 9.2

$$L_t = L_1 + L_2 \dots.. + L_n$$

L_t = total inductance of series inductors in
Henrys
L_1, L_2 = inductance of each series inductor in
Henrys
L_n = inductance of last series inductor in Henrys

Equation 9.3

$1 / L_t = 1 / L_1 + 1 / L_2 \ldots + 1 / L_n$

L_t = total parallel inductance in Henrys
L_1, L_2 = inductance of each parallel inductor in
    Henrys
L_n = inductance of last inductor in parallel in
    Henrys

Equation 9.4

$L_t = (L_1 * L_2) / (L_1 + L_2)$

L_t = total inductance of two parallel inductors in
    Henrys
L_1, L_2 = inductance of each parallel inductor in
    Henrys

Equation 9.5

$L_t = [L_1 * L_2 * (1 - k^2)] / [L_1 + L_2 - 2 * k * \sqrt{(L_1 * L_2)}]$

L_t = total inductance of two parallel inductors
    with mutual inductance in Henrys
L_1, L_2 = inductance of each parallel inductor in
    Henrys
k = coefficient of coupling

Equation 9.6

$\tau = L / R$

τ = time constant time in Seconds
R = resistance in Ohms
L = inductance in Henrys

Equation 9.7

$I_L = (E / R) * (1 - e^{-t*(R/L)})$

I_L = inductor current in Amperes
E = supply voltage in Volts
e = exponential constant 2.71828
R = resistance in Ohms
L = inductance in Henrys
t = desired time from charge commencing in
    Seconds

Equation 9.8

$I_L = I * e^{-t/\tau}$

I_L = inductor current at time t in Amperes
I = current flowing in coil just prior to start of
    decay in Amperes
e = exponential constant 2.71828
τ = time constant time in Seconds
t = desired time from decay commencing in
    Seconds

10. Transformers

Equation 10.1

$E_P = 4.44 * \Phi_{pm} * f * N_P$

E_P = effective voltage induced into primary in
    Volts
Φ_{pm} = peak mutual flux in Webers
f = frequency of applied voltage in Hertz
N_P = number of turns in primary coil

Equation 10.2

$E_S = 4.44 * \Phi_{pm} * f * N_S$

E_S = effective voltage induced into secondary in
    Volts
Φ_{pm} = peak mutual flux in Webers
f = frequency of applied voltage in Hertz
N_S = number of turns in secondary coil

Equation 10.3

$E_P / E_S = N_P / N_S = I_S / I_P = a$

E_P = primary voltage in Volts
E_S = secondary voltage in Volts
N_P = number of turns in the primary coil
N_S = number of turns in the secondary coil
I_S = secondary current in Amperes
I_P = primary current in Amperes
a = transformation ratio

Equation 10.4

$R_P = a^2 * R_L$

R_P = reflected resistance at the primary in Ohms
a = transformation ratio
R_L = load resistance of secondary in Ohms

11. Alternating Current Circuits

Equation 11.1

$$e = I_m * R * \sin(\omega * t)$$

e = instantaneous voltage value in Volts
I_m = maximum current value in Amperes
R = circuit resistance in Ohms
ω = angular velocity in Radians per second
t = time in Seconds

Equation 11.2

$$X_L = 2 * \pi * f * L$$

X_L = inductive reactance in Ohms
f = frequency in Hertz
L = inductor inductance value in Henrys

Equation 11.3

$$X_{LT} = X_{L1} + X_{L2} + ... X_{LN}$$

X_{LT} = total series inductive reactance in Ohms
X_{L1}, X_{L2} = series inductive reactance
values in Ohms

Equation 11.4

$$1 / X_{LT} = 1 / X_{L1} + 1 / X_{L2} + ... 1 / X_{LN}$$

X_{LT} = total parallel inductive reactance in Ohms
X_{L1}, X_{L2} = parallel inductive reactance values in
Ohms

Equation 11.5

$$X_C = 1 / (2 * \pi * f * C)$$

X_L = capacitive reactance in Ohms
f = frequency in Hertz
C = capacitor capacitance in Farads

Equation 11.6

$$X_{CT} = X_{C1} + X_{C2} + ... X_{CN}$$

X_{CT} = total series capacitive reactance in Ohms
X_{C1}, X_{C2} = series capacitive reactance values
in Ohms

Equation 11.7

$$1 / X_{CT} = 1 / X_{C1} + 1 / X_{C2} + ... 1 / X_C N$$

X_{CT} = total parallel capacitive reactance in Ohms
X_{C1}, X_{C2} = parallel capacitive reactance values
for each in Ohms

Equation 11.8

$$Z = (E / I)$$

Z = impedance in Ohms
E = voltage in Volts
I = current in Amperes

Equation 11.9

$$Z = \sqrt{[R^2 + X^2]}$$

I = total impedance in Ohms
R = resistance in Ohms
X = net reactance in Ohms

Equation 11.10

$$\theta = \tan^{-1}(X / R)$$

θ = impedance phase angle in Degrees
R = resistance in Ohms
X = net reactance in Ohms

Equation 11.11

$$\theta = \sin^{-1}(X_L / Z) = \cos^{-1}(R / Z) = \tan^{-1}(X_L / R)$$

θ = impedance phase angle in Degrees
R = resistance in Ohms
Z = impedance in Ohms
X_L = inductive reactance in Ohms

Equation 11.12

$$X_L = Z \sin \theta$$

θ = impedance phase angle in Degrees
Z = impedance in Ohms
X_L = inductive reactance in Ohms

Equation 11.13

$R = Z \cos \theta$

θ = impedance phase angle in Degrees
Z = impedance in Ohms
R = resistance in Ohms

Equation 11.14

$X_L = R \tan \theta$

θ = impedance phase angle in Degrees
X_L = inductive reactance in Ohms
R = resistance in Ohms

Equation 11.15

$Z = (R * X_L) / \sqrt{(R^2 + X_L^2)}$ …and…

$\theta = \tan^{-1} (R / X_L)$

θ = impedance phase angle in Degrees
R = resistance in Ohms
Z = impedance in Ohms
X_L = inductive reactance in Ohms

Equation 11.16

$E = \sqrt{(V_R^2 + V_C^2)}$

E = applied voltage in Volts
V_R = voltage across the resistor in Volts
V_C = voltage across the capacitor in Volts

Equation 11.17

$-\theta = \sin^{-1} (X_C / Z) = \cos^{-1} (R / Z) = \tan^{-1} (X_C / R)$

θ = impedance phase angle in Degrees
R = resistance in Ohms
Z = impedance in Ohms
X_C = capacitive reactance in Ohms

Equation 11.18

$Z = (R * X_C) / \sqrt{(R^2 + X_C^2)}$

R = resistance in Ohms
Z = impedance in Ohms
X_C = capacitive reactance in Ohms

Equation 11.19

$-\theta = \tan^{-1} (R / X_C)$

θ = impedance phase angle in Degrees
R = resistance in Ohms
X_C = capacitive reactance in Ohms

Equation 11.20

$I_T = \sqrt{(I_R^2 + I_C^2)}$

I_T = total current in Amperes
I_R = current through the resistor in Amperes
I_C = current through the capacitor in Amperes

Equation 11.21

$\theta = \tan^{-1} (I_C / I_R)$

θ = current phase angle in Degrees
I_R = current through the resistor in Amperes
I_C = current through the capacitor in Amperes

Equation 11.22

$E = \sqrt{[V_R^2 + (V_L - V_C)^2]}$

E = applied voltage in Volts
V_R = voltage across the resistor in Volts
V_C = voltage across the capacitor in Volts
V_L = voltage across the inductor in Volts

Equation 11.23

$\theta = \tan^{-1} (V_L - V_C) / V_R$

θ = impedance phase angle in Degrees
V_R = voltage across the resistor in Volts
V_C = voltage across the capacitor in Volts
V_L = voltage across the inductor in Volts

Equation 11.24

$Z = \sqrt{(R^2 + X^2)}$ …..and….

$\theta = \tan^{-1} (X / R)$

θ = impedance phase angle in Degrees
R = resistance in Ohms
Z = impedance in Ohms
X = net reactance in Ohms

Equation 11.25

$I_T = \sqrt{(I_R^2 + I_X^2)}$

I_T = total current in Amperes
I_R = current through the resistor in Amperes
I_X = net current through the inductive element in Amperes

Equation 11.26

$\theta = \tan^{-1} (I_X / I_R)$

θ = current phase angle in Degrees
I_R = current through the resistor in Amperes
I_X = net current through the inductive element in Amperes

Equation 11.27

$P = E_{rms} * I_{rms} * \cos \theta$

P = True Power in an AC circuit in Watts
E_{rms} = rms voltage applies in Volts
I_{rms} = rms current in Amperes
θ = phase angle in Degrees

Equation 11.28

$S = E * I$

I = current in Amperes
E = voltage in Volts
S = apparent power in Volt-Amperes or VA

Equation 11.29

$PF = (E_{rms} * I_{rms} * \cos \theta) / (E_{rms} * I_{rms})$

$PF = \cos \theta$
PF = power factor
E_{rms} = rms voltage applies in Volts
I_{rms} = rms current in Amperes
θ = phase angle in Degrees

Equation 11.30

$PF = R / Z$

PF = power factor
R = circuit resistance in Ohms
Z = circuit impedance in Ohms

Equation 11.31

$Q = E_{rms} * I_{rms} * \sin \theta$

Q = reactive power Volt-Ampere-Reactive or VARs
E_{rms} = rms voltage applied in Volts
I_{rms} = rms current in Amperes

Equation 11.32

$S = \sqrt{(P^2 + Q^2)}$

S = apparent power in Volt-Amperes or VA
P = true power in Watts
Q = reactive power Volt-Ampere-Reactive or VARs

12. Resonance

Equation 12.1

$f_r = 1 / [2 * \pi * \sqrt{(L * C)}]$

f_r = series resonant frequency in Hertz
L = inductor inductance value in Henrys
C = capacitor capacitance value in Farads

Equation 12.2

$Q = (1 / Rs) * \sqrt{(L / C)}$

Q = quality factor or voltage magnification factor of series resonant circuit
R_S = series resistor resistance value in Ohms
L = inductor inductance value in Henrys
C = capacitor capacitance value in Farads

Equation 12.3

$BW = f_r / Q$

BW = band width in Hertz
f_r = resonant frequency in Hertz
Q = quality factor of resonant circuit

Equation 12.4

$Zr = (X_L * X_C) / R = L / (R * C)$

Zr = impedance of parallel resonant circuit in Ohms
X_L = inductive reactance in Ohms
X_C = capacitive reactance in Ohms
L = parallel inductor inductance value in Henrys
R = parallel resistor resistance value in Ohms
C = parallel capacitor capacitance value in Farads

Equation 12.5

$dB = 10 \log_{10} (Pout / Pin)$

dB = decibels, provides power gain
Pout = output power in Watts
Pin = input power in Watts
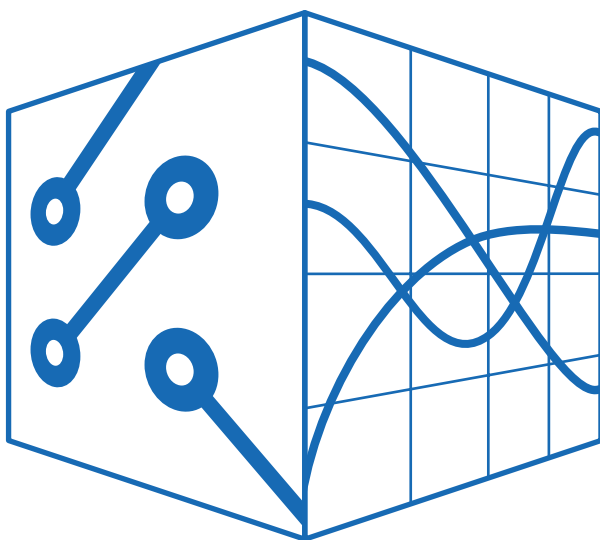
Equation 12.6

$dB = 20 \log_{10} (Vout / Vin)$

dB = decibels, provides voltage gain
Vout = output voltage in Volts
Vin = input voltage in Volts

3 SUPPLEMENTAL CONTENT

NOTATION

SCIENTIFIC NOTATION

Scientific Notation allows you to express very large and very small numbers in an efficient way. In Scientific Notation, a number between 1 and 10 is multiplied by a power of ten.

For example, it allows you to express the number

82300 like this: 8.23×10^4

The power of ten tells you how many places the decimal moves. Here, the decimal moves 4 places.

	EXAMPLE	
0.045	=	4.5×10^{-2}
8730	=	8.73×10^{3}
0.00748	=	7.48×10^{-3}
691	=	6.91×10^{2}

CONVERTING FRACTIONS

Scientific Notation is useful for working with fractions. Count how many digits you need to move the decimal to the right so that only one significant digit remains to the left of the decimal place.

Since you moved the decimal place from the left to the right the power of ten is negative!

EXAMPLE

0.0015   = 1.5×10^{-3}

The exponent has a negative power because we moved the decimal three places to the right.

CONVERTING WHOLE NUMBERS

For fractions, the decimal moves to the right. When you convert a whole number to Scientific Notation, the decimal moves to the left.

When the decimal place moves to the left, it is important to remember that the power of ten is positive.

EXAMPLE

12345   = 1.2345×10^{4}

The power to ten is positive since we moved the decimal to the left.

SCIENTIFIC NOTATION INTO A REGULAR NUMBER

Let's look at the opposite.

To convert Scientific Notation into a regular number you are simply carrying out multiplication. The power of ten tells you the number of places the decimal will move.

For example, to convert 7.821×10^4 into a regular number simply multiply 7.821 x 10 000 = 78 210.

Here, the decimal moves 4 places when you multiply by 10 000.

	EXAMPLE	
4.5×10^{-2}	=	0.045
8.73×10^{3}	=	8730
7.48×10^{-3}	=	0.00748
6.91×10^{2}	=	691

WHY WE NEED TO USE SCIENTIFIC NOTATION

Calculations require standard measures. The system of standard measures we use is called SI units.

For example, when we talk about distance we use meters. Meters are a standard SI unit. When we talk about mass we use kilograms and so on. Now, what if we want to use a quantity that is extremely large or small in our calculations?

Scientific Notation provides a way of expressing them efficiently.

ENGINEERING NOTATION

Engineering notation is similar to scientific notation except that the exponent must be a multiple of three (3, 6,9,12 and so on). To convert a number to engineering notation, you move the decimal place in groups of 3 until the base number is between 1 to 999. The number of places you moved the decimal now becomes the exponent of ten for the number.

For example:

Number	Scientific Notation	Engineering Notation
0.00075	7.5×10^{-4}	750×10^{-6}
890000	8.9×10^{5}	890×10^{3}
8730	8.73×10^{3}	8.73×10^{3}
691	6.91×10^{2}	691

WHY WE NEED TO USE ENGINEERING NOTATION

For example, the distance from Toronto to Kingston is about 3×10^{5} m or equivalently 300×10^{3} . Remember the metric system?

10^{3} can also be expressed as kilometers. Now, most people immediately know how much 300 km is but it takes a little more work to visualize 3×10^{5} m.

> **EXAMPLE**
>
> The Sun is 1980 billion billion billion kilograms. That's 198 followed by 28 Zeros! Scientific Notation can express this number more efficiently as 1.98×10^{30}.

> **EXAMPLE**
>
> Since 1×10^{3}m is equal to 1 km, 23,000m is equal to 23×10^{3}m which is equal to 23 km.

3×10^{2} km
3×10^{5} m
Kingston
Toronto
Lake Ontario
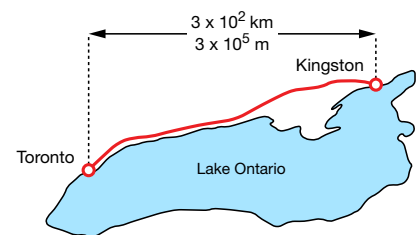
Every substance in the universe is electrically charged.

Substances are either:

Positively charged
(excess protons)
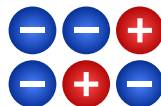
Negatively charged
(excess electrons)
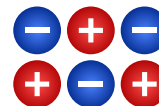
Neutrally charged
(equal protons and electrons)

Neutral substances have a balance of positive and negative charges.

SI UNIT FOR CHARGE

The coulomb (C) is the standard international (SI) unit for charge.

The coulomb is named after French scientist Charles Coulomb, whose work greatly advanced the study of electricity and magnetism.

What does one coulomb of charge mean?

Let's look at coulombs in practical terms: A typical lightning bolt contains about 20 to 30 C of charge. An electron has a charge of -1.60 x $C10^{-19}$. Thus, 1 C of charge contains 6.24 x 10^{18} electrons.

Indeed, 1 C is an enormous amount of charge!

INTERACTION OF CHARGES

How do charges interact with each other?

- Charges with the same electrical sign repel each other.
- Charges with opposite electrical signs attract each other.

What causes a positive charge to attract a negative charge and repel a positive charge? The answer leads to the concept of the electric field.

ELECTROSTATIC LINES OF FORCE

All charges have an electric field around them. An electric field can be represented by electrostatic lines of force.

Remember:

- The electric field strength increases as the amount of charge increases.

- The electric field strength decreases as the distance from the charge increases.
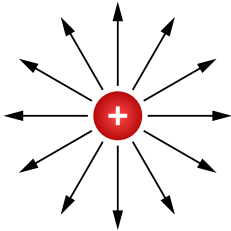
For a positive charge the electric field (lines of force) points outwards in all directions from the charge.
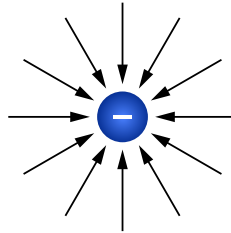
For a negative charge the field (lines of force) points inwards in all directions towards the charge.

ELECTRIC FIELD

Now we can answer the question:

"What causes a positive charge to attract a negative charge and to repel a positive charge?"

The answer is that even though the two charges are not touching, each is exposed to the electric field of the other.

- Positive charges move in the direction of the electric field

- Negative charges move in a direction opposite to the field

WHEN POSITIVE AND NEGATIVE CHARGES ARE PLACED TOGETHER:
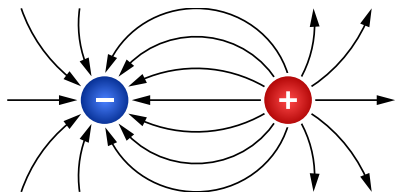
The positive charge tends to move toward the negative charge (field of the negative charge points inwards)

The negative charge tends to move towards the positive charge (field for the positive charge points outward
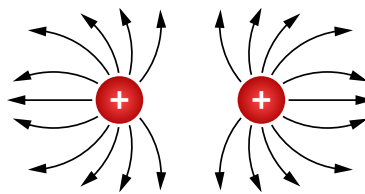
When two positive charges are placed together each of them will move away from the other because the electric field for each is outward

THE LAW OF CONSERVATION CHARGE

The Law of Conservation of Charge states that electric charges within a system cannot be created or destroyed. Charge is only transferred from one object to another.

Consider an example: Someone runs across a carpet to open a door.

Slippers, rubbing against the carpet, pick up extra electrons from the carpet.

The girl is negatively charged. The carpet is positively charged, since it has lost electrons.

What is the result of this system?
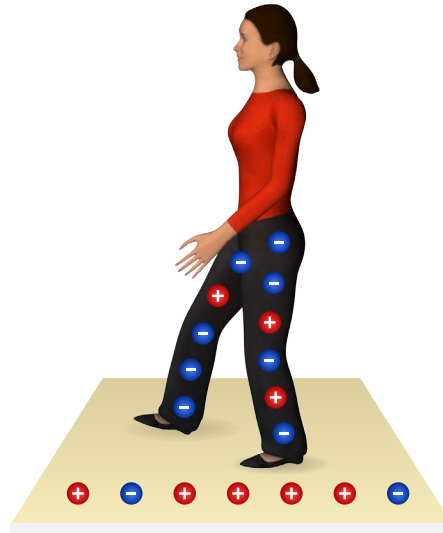
WHEN SHE REACHES FOR THE METAL DOORKNOB:
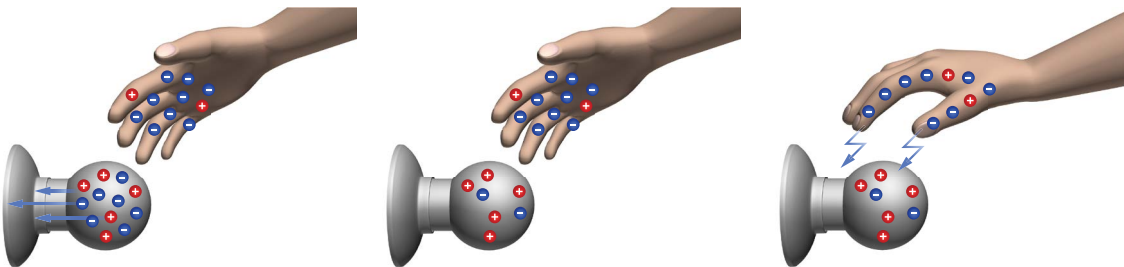
Free electrons from the knob are initially repelled by her negatively charged body.

The doorknob becomes deficient in negative electron charge.

The excess electrons from the girl become attracted to the doorknob (opposite charges attract). The charges jump from her hand to the doorknob, creating a spark!

Significantly, the total charge within this system (the room) remains constant. Charge is simply transferred from carpet to person and then to the doorknob.

WHY WE NEED TO KNOW ABOUT CHARGES

Understanding charges and how they interact is essential to understanding current.

RESISTANCE

PRACTICAL EXAMPLE

You arrive home after a long day of work. You open the door and turn on the light. Nothing happens! The light bulb has burned out.

To understand what happens when light bulbs burn out requires understanding the concept of electrical resistance.

RESISTANCE

Resistance is defined as the property of a device or a circuit that opposes the movement of current through it.

Measuring the resistance requires applying voltage to a circuit. Then measure the current passing through it.

Resistance is measures in ohms (Ω). By definition, when 1 volt is applied, a circuit's resistance equals 1 ohm if 1 ampere of current flows.

Let's look at ohms of resistance in practical terms:

- A typical television cable has a resistance of 50Ω to 75Ω

- The human body has a resistance of 10kΩ.

- A good insulator has a resistance of over 1MΩ.

HIGH VERSUS LOW RESISTANCE

The higher an object's resistance, the less current it conducts. The lower an objects resistance, the more current it conducts.

High Resistance

Insulating material on electrical wires typically has an extremely high resistance. This high resistance prevents dangerous current flow.

Low Resistance

Electrical wires, however, have a very low resistance. Electrical wires are designed to conduct high currents.

CALCULATION

The resistance of an object can be determined by dividing the value of the voltage by that of the current.

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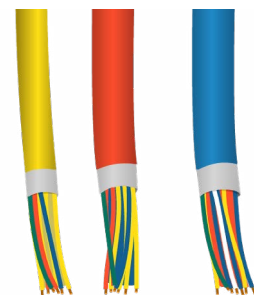
Electrical Wires

RESISTANCE AND LENGTH

A material's resistance depends on several things:

- Length
- Cross-sectional area
- Material and
- Temperature

Given a length of copper wire with a fixed cross-sectional area and temperature:

- A longer length of the same wire contains more material for electrons to pass through and therefore has more resistance.

- A shorter length of the same wire contains less material for the electrons to pass through and therefore has less resistance.

Changing the type of material (i.e. from copper to aluminum) will also alter the resistance.
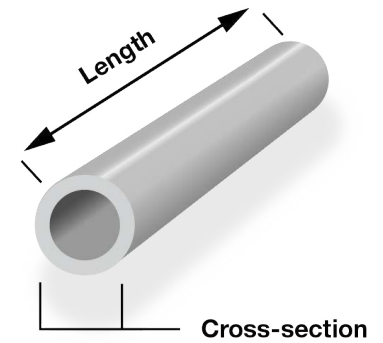
Cross-section

RESISTANCE AND CROSS-SECTIONAL AREA

An object's resistance depends on its cross-sectional area. More cross-sectional area allows more electrons to flow through the object at the same time.

More electrons passing through an object (it has more current) means the object's resistance is lower.

Less cross-sectional area means fewer electrons can flow through the object at the same time. Less cross-sectional area, then, means the object's resistance is higher.

Standard copper wire

Coaxial cable

CROSS-SECTIONAL AREA – AN EXAMPLE

Consider the analogy of water flow through a pipe:

Given the fixed water pressure, a large pipe allows more water to pass through it in a given period of time than a small pipe.

Given a fixed length, materials and temperature, a large wire (larger cross-sectional area) allows more electrons to pass through it than a small wire (smaller cross-sectional area).
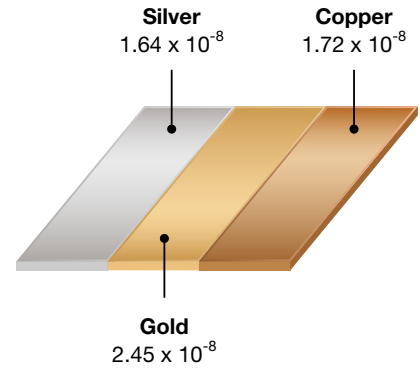
Large pipe
Large cross-section

Small pipe
Small cross-section

Silver
1.64×10^{-8}

Copper
1.72×10^{-8}

Gold
2.45×10^{-8}

RESISTANCE AND MATERIAL

An object's resistance also depends on what it is made of. Some materials, due to their atomic structure, allow more electrons to flow than others.

RESISTANCE & TEMPERATURE

An object's resistance also depends on its temperature.

Higher Temperature

As an object's temperature increases:

- The vibration of atoms increases.

- Increased vibration increases the likelihood that electrons collide with atoms.

- More collision means it's more difficult for electrons to flow.

- Vibration due to heat, therefore, means greater resistance.

Lower Temperature

The cooler the object is:

- There is less vibration of atoms

- Electrons are less likely to collide with atoms.

- Less collision means it's easier for electrons to flow.

- With less vibration, cooler objects, therefore, have less resistance.
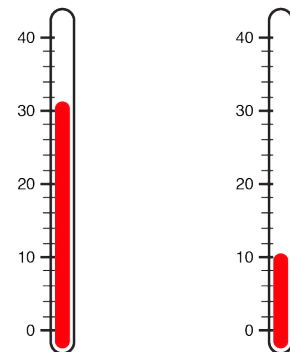
RESISTIVITY

Resistivity is defined as the resistance of a conductor having unit length and unit cross-sectional area. The unit for resistivity is $\Omega \times m$.

Remember: Resistance is a property of an object. Resistivity is a property of a material.

When comparing various conductors, it is better to focus on resistivity rather than resistance. After all, a conductor's resistance depends on its length and cross-sectional area.

While a conductor's resistivity does not. An objects resistance can be determined by:

- Multiplying the resistivity of the material of which the object is composed (ρ)

- By the length of the object (l)

- And dividing that product by the cross-sectional area (A)

Where:

R = resistance of material in ohms

l = length of current path through the conductor in meters

A = cross-section area of conductor, in meters squared

ρ = the resistivity of the material

$$R = \rho \times \frac{l}{A}$$

WHY THE LIGHT BULB BURNS OUT

Understanding resistance and variables that affect resistance allows us to solve the case of the burned-out light bulb.

- Assuming an incandescent light bulb, the light bulb works by using electricity to heat a metal filament. The heat energy in the filament produces light.

- In order for the filament to produce light it is heated to a very high temperature.

- This is achieved by supplying a constant 110V voltage across two terminals of a light bulb.

However:

- Due to the heat the metal filament evaporates over time.

- Evaporation causes the cross-sectional area of the filament to decrease.

- This decrease in cross-sectional area increases the filaments resistance.

- The increased resistance causes more heating action between the electrons and the filament.

- Increased heat, in turn, again increases the evaporation rate of the filament.

This cycle continues until part of the filament completely evaporates.

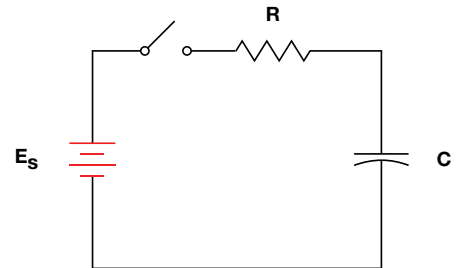- The incandescent light bulb burns out when the filament breaks.

RC CIRCUITS

RC CIRCUITS

RC means resistor-capacitor.

The simplest form of an RC circuit consists of:

- capacitor
- resistor
- voltage source

TRANSIENT STATE

Consider driving a car:

- When you press on the gas, the car accelerates.
- When you step on the brakes, the car slows down.
- However, you cannot start or stop the car instantly. The car must first speed up or slow down.

A car cannot move at 40 km/h at one instant and 20 km/h the next. The motion must be continuous. When the car is accelerating or decelerating, it is in a period of transition.

The period of transition is called a transient state.

TRANSIENT STATE – RC CIRCUITS

The concept of the transient state applies to RC circuits.

In RC circuits, voltage across a capacitor must be continuous.

When a switch is turned ON, for example, the voltage applied to the RC circuit will instantly jump from 0V to 12V. When the switch is turned off the voltage applied to the RC circuit will instantly fall from 12V to 0.

The voltage won't jump, however, at the terminals of the capacitor in an RC circuit. Like the car, there must be a transition period during which a capacitor charges or discharges.

This period is called the transient state.

RC Circuit

Charging of Capacitor
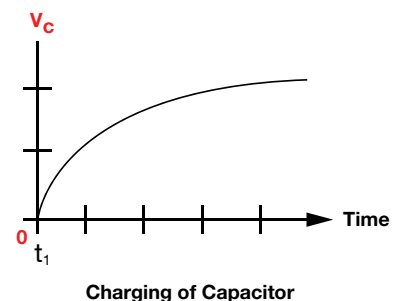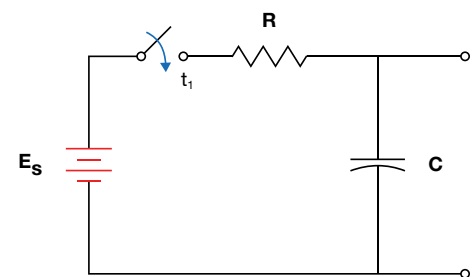
TIME CONSTANT

In car racing, 0-100 km/h is used for determining a car's acceleration.

A similar comparison is used for charge and discharge in RC circuits.

Time elapsed after switching is given in terms of multiples of time constants, or τ (tau).

> At 1 time constant or 1 tau often a capacitor has started to charge through a resistor, the voltage on the capacitor has increased by **1-e^{-1}** (approximately 0.67 of the applied voltage).

EXAMPLE

Time (Constant)	Charged, $1-e^{-t/\tau}$ (% of final value)	Discharged, $e^{-t/\tau}$ (% of initial value)
1τ	63%	37%
2τ	87%	14%
3τ	95%	5.0%
4τ	98%	1.8%
5τ	99%	0.67%

Note: When the charging time elapsed exceeds 5 time constants, then the voltage is more than 1% of the initial value for discharging. (0.9933, to be precise. See table above.)

After 5 time constants, the voltage and current have approximated their final values for charging.

- Voltage and current values from time of switching to 5 time constants (tau) are known as the transient response.

- Voltage and current values after 5 time constants (tau) are known as the steady state response.

TRANSIENT RESPONSE

To calculate the transient response of an RC circuit:

1. Find the time constant. Remembering $\tau = RC$.

2a. If the capacitor is charging, use $V_C = E(1-e^{-t/\tau})$, where E is the voltage applied to the RC circuit.

2b. If the capacitor is discharging, use $V_C = Ee^{-t/\tau}$, where E is the initial voltage across the capacitor.

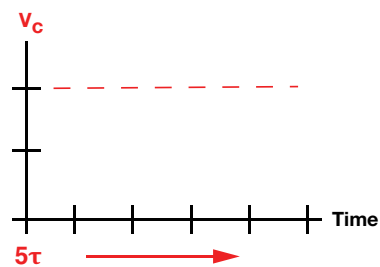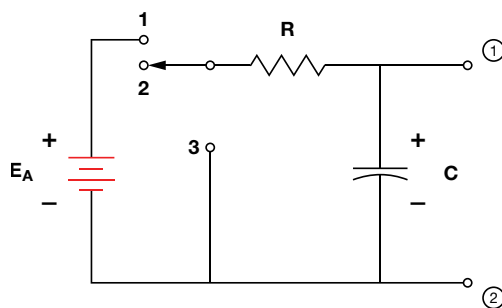3. Once Vc is found, the transient current in the circuit can be determined.
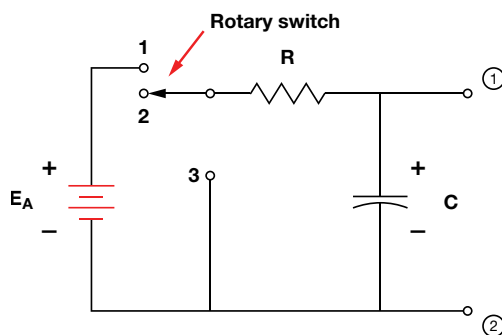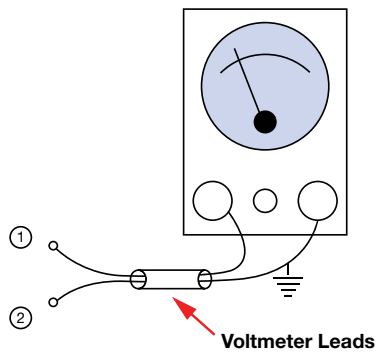

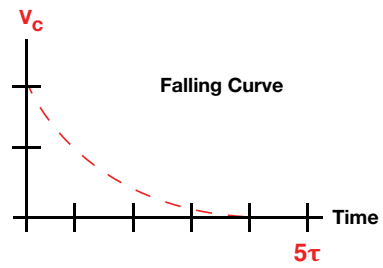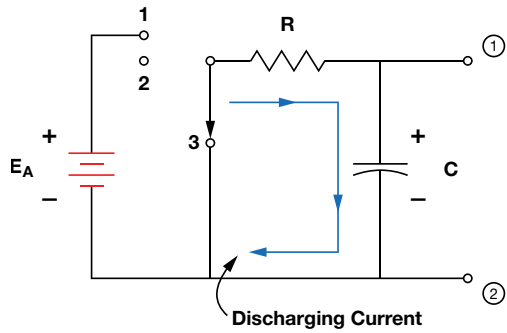R and C not connected to E_A (open circuit).

$V_C = 0V$.

The switch is connected to position #1. The charging actions of the capacitor begins.
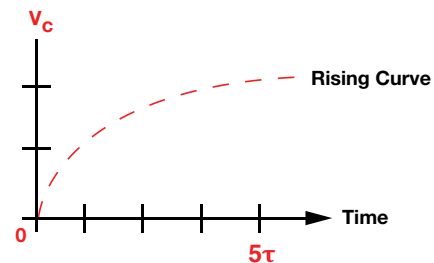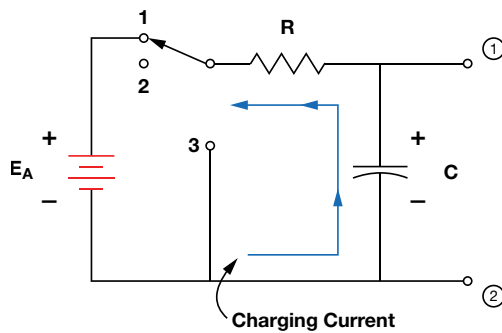
If the switch is connected to position #2 after 5τ the voltage V_C will remain at $V_C = EA$ indefinitely.

Discharging Current

Falling Curve

V_C

Time

5τ

Voltmeter Leads

If switch is connected to position #3, the charged capacitor will discharge through R. After 5τ the voltage on the capacitor will have dropped to zero for all practical purposes.

V_C

Time

0τ 5τ 10τ 15τ 20τ
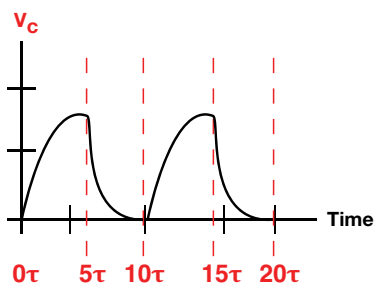
After two cycles of moving through switch positions this is what the waveform will look like.

THE PRACTICING ELECTRONICS TECHNICIAN'S HANDBOOK - 2019 EDITION

The Practicing Electronics Technician's Handbook serves as a useful tool to technicians who are in training and in the workforce. It is a text designed to provide guidance by illustrating important concepts, key equations, and supplemental content that is relevant to the field.

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