



ELECTRICAL THEORY/TECHNOLOGY PLC CONCEPTS BASIC ELECTRONICS

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PURPOSE OF THIS GUIDE

This “Study Guide” is designed to provide the electrical troubleshooter with a review of, and the mechanical troubleshooter with an introduction of, basic electrical skills needed for him/her to safely and more efficiently carry out their duties in the plant environment. After successful completion, the troubleshooter can improve their understanding of DC, AC, three phase circuits, Relays, Contactors, PLC, Electronics, and other related technology.

MATH

To review the mathematics related to electrical theory and the application of that theory to electrical equipment.

APPLIED ELECTRICAL THEORY

To improve the understanding and application of electrical theory related to the principles of operation of manufacturing equipment.

1. Draw and solve for circuit parameters such as resistance, voltage, current, and power in:
 - D.C. series circuits
 - D.C. parallel circuits
 - D.C. complex series/parallel circuits
2. Understand the properties of magnetism and how they relate to electromagnetic concepts as applied to contactors, relays, generators, motors, and transformers
3. Explain the generation of an A.C. sinewave using the associated terms
4. Draw and solve for circuit parameters such as resistance, inductance, inductive reactance, capacitance, capacitive reactance, impedance, voltage, current, and power in:
 - A.C. series resistive circuits
 - A.C. series inductive circuits
 - A.C. series capacitive circuits
 - A.C. series combination RLC circuits
5. Draw transformers, explain the operating principle, and solve problems using voltage, current, and turns relationships
6. Understand three phase concepts:
 - Advantages and disadvantages
 - Waveform generation
 - Calculations for Wye and Delta circuits
7. Understand three phase motor concepts:
 - Squirrel Cage motors
 - Wound Motors
 - American motor connections
 - European motor connections

ELECTRICAL SCHEMATICS

To improve the understanding of the different types of electrical drawings and the use of electrical drawings associated with trouble-shooting procedures.

1. Recognize the standard electrical schematic symbols
2. Relate symbols to the actual device
3. Use symbols and basic drawing techniques to draw valid circuits from word descriptions
4. Use electrical schematics to determine operating cycles for machines
5. Use electrical schematics to analyze conventional machine faults such as open circuits, ground faults, and short circuits

TROUBLE-SHOOTING PROCEDURES

To improve the understanding of safe, simple, and logical trouble-shooting procedures on conventional relay controlled machines.

1. Have become familiar with and practiced appropriate safety procedures during trouble-shooting
2. Be able to locate and repair open circuit faults using a safe, efficient procedure
3. Be able to locate and repair ground faults and short circuits using a safe, efficient procedure

EQUIPMENT TECHNOLOGY

To improve the understanding of the operating principle of industrial input and output devices, protection devices, ac motors, dc motors, motor brakes and other associated electrical control devices.

1. Understand and be able to explain the operating principles of conventional electrical components such as push buttons, limit switches, fuses, overcurrent relays, electro-magnetic relays, and contactors
2. Become familiar with the proper use and care of multimeters, amprobes and megohm-meters



MATH

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BASIC MATH RULES

ADDITION AND SUBTRACTION

- A. To add two numbers of the same sign, add their absolute values and attach the common sign.
- B. To add two numbers of opposite signs, subtract the smaller absolute value from the larger absolute value and attach the sign of the larger.
- C. To subtract signed numbers, change the sign of the number to be subtracted (subtrahend) and add as in (A) or (B) above.

MULTIPLICATION AND DIVISION

- A. To multiply two signed numbers, multiply their absolute values and attach a positive if they have like signs, a negative if they have unlike signs.
- B. To divide two signed numbers, use rule (A) above, dividing instead of multiplying.

Examples:

A. Addition

- 1. $-9 + (-5) = -14$
- 2. $-9 + 5 = -4$
- 3. $3.65 + (-1.27) = 2.38$

B. Multiplication

- 1. $(-9) \times (-5) = 45$
- 2. $(-9) \times 5 = -45$
- 3. $2.80 \times (-1.25) = -3.5$

C. Division

- 1. $(-24) \div 3 = -8$
- 2. $(-9) \div (-3/2) = 6$
- 3. $1.6 \div (-0.4) = -4$

COMMON FRACTIONS

BASIC CONCEPTS

FRACTIONS AND MEASUREMENT

The need for greater precision in measurement led to the concept of fractions. For example, "the thickness is $\frac{3}{4}$ in." is a more precise statement than "the thickness is between 0 and 1 in." In the first measurement, the space between the inch marks on the scale was likely subdivided into quarters; on the second scale, there were no subdivisions. In the metric system, the subdivisions are multiples of 10 and all measurements are expressed as *decimal* fractions. In the British system, the subdivisions are *not* multiples of 10 and the measurements are usually recorded as common fractions. The universal use of the metric system would greatly simplify the making and recording of measurements. However, common fractions would still be necessary for algebraic operations.

TERMS

Fraction: Numbers of the form $\frac{3}{4}$, $\frac{1}{2}$, $\frac{6}{5}$ are called fractions. The line separating the two integers indicates division.

Numerator: (or dividend) is the integer above the fraction line.

Denominator: (or divisor) is the integer below the fraction line. The denominator in a measurement may show the number of subdivisions in a unit.

Common fraction: a fraction whose denominator is numbers other than 10, 100, 1000, etc. Other names for it are: simple fraction and vulgar fraction.

Examples:

$$\frac{1}{125}, \frac{2}{7}, \frac{15}{32}$$

Decimal fraction: a fraction whose denominator has some power of 10.

Mixed number: is a combination of an integer and a fraction.

Example:

The mixed number $3\frac{2}{5}$ indicates the addition of $3 + \frac{2}{5}$

Improper Fraction: Not in lowest terms

Example: $\frac{9}{2}$

BASIC PRINCIPLE

A fundamental principle used in work with fractions is: *If both the numerator and denominator of a fraction are multiplied or divided by the same non-zero number, the value of the fraction is unchanged.* Another way of expressing this rule is: If a fraction is multiplied by 1, the value of the fraction remains unchanged.

Example:

$$\frac{2}{3} = \frac{2 \cdot 2}{3 \cdot 2} = \frac{4}{6}$$

$$\frac{2}{3} = \frac{2 \cdot 5}{3 \cdot 5} = \frac{10}{15}$$

$$\frac{2}{3} = \frac{2 \cdot 6}{3 \cdot 6} = \frac{12}{18}$$

The numerator and denominator of the fraction $\frac{2}{3}$ were multiplied by 2, 5, and 6 respectively. The fractions $\frac{2}{3}$, $\frac{4}{6}$, $\frac{10}{15}$, $\frac{12}{18}$ are equal and are said to be in *equivalent forms*. It can be seen that in the above example the change of a fraction to an equivalent form implies that the fraction was multiplied by 1. Thus the multipliers $\frac{2}{2}$, $\frac{5}{5}$, $\frac{6}{6}$ of the fraction $\frac{2}{3}$ in this case are each equal to 1.

REDUCTION TO LOWEST TERMS

The basic principle given on the previous page allows us to simplify fractions by dividing out any factors which the numerator and denominator of a fraction may have in common. When this has been done, the fraction is in reduced form, or reduced to its lowest terms. This is a simpler and more convenient form for fractional answers. The process of reduction is also called cancellation.

Example:

$$\text{Since } \frac{18}{30} = \frac{2 \cdot 3 \cdot 3}{2 \cdot 3 \cdot 5}, \text{ the numerator and denominator}$$

can be divided by the common factors 2 and 3.

The resulting fraction is $\frac{3}{5}$, which is the reduced

form of the fraction $\frac{18}{30}$.

Factoring

The process of factoring is very useful in operations involving fractions. If an integer greater than 1 is not divisible by any positive integer except itself and 1, the number is said to be prime. Thus, 2, 3, 5, 7, etc., are prime numbers, the number 2 being the only even prime number.

If a number is expressed as the product of certain of its divisors, these divisors are known as factors of the representation. The prime factors of small numbers are easily found by inspection. Thus, the prime factors of 30 are 2, 3, 5. The following example illustrates a system which can be used to find the prime factors of a large number.

Example: Find the prime factors of 1386.

Try to divide 1386 by each of the small prime numbers, beginning with 2. Thus, $1386 / 2 = 693$. Since 693 is not divisible by 2, try 3 as a divisor: $693 \div 3 = 231$. Try 3 again: $231 \div 3 = 77$. Try 3 again; it is not a divisor of 77, and neither is 5. However, 7 is a divisor, for $77 \div 7 = 11$. The factorization is complete since 11 is a prime number. Thus, $1386 = 2 \cdot 3 \cdot 3 \cdot 7 \cdot 11$. The results of the successive divisions might be kept in a compact table shown below.

Dividends	1386	693	231	77	11
Factors	2	3	3	7	11

The following divisibility rules simplify factoring:

Rule 1. A number is divisible by 2 if its last digit is even.

Example: The numbers 64, 132, 390 are each exactly divisible by 2.

Rule 2. A number is divisible by 3 if the sum of its digits is divisible by 3.

Example: Consider the numbers 270, 321, 498. The sums 9, 6, 21 of the digits are divisible by 3.

Rule 3. A number is divisible by 5 if its last digit is 5 or zero.

Example: The numbers 75, 135, 980 are each divisible by 5.

Rule 4. A number is divisible by 9 if the sum of its digits is divisible by 9.

Example: The numbers 432, 1386, and 4977 are exactly divisible by 9 since the sums of their digits are 9, 18, 27, and these are divisible by 9.

OPERATIONS WITH FRACTIONS

ADDITION OF FRACTIONS

To add fractions, which have a common denominator, add their numerators and keep the same common denominator.

Example: Determine the sum of: $\frac{1}{4} + \frac{5}{4} + \frac{3}{4}$.

Adding the numerators, $1 + 5 + 3 = 9$.

Keeping the same common denominator 4,

the desired result is $\frac{9}{4}$ or $2\frac{1}{4}$.

To add fractions with unlike denominators, determine the least common denominator. Express each fraction in equivalent form with the **LCD**. Then perform the addition.

Example: Determine the sum of: $\frac{1}{2} + \frac{3}{4} + \frac{2}{8}$. The LCD is 8.

The sum with the fractions in equivalent form is $\frac{4}{8} + \frac{6}{8} + \frac{2}{8}$.

Adding the numerators and keeping the same LCD,

the result is $\frac{12}{8}$ or $\frac{3}{2}$ or $1\frac{1}{2}$.

To add mixed numbers calculate the sum of the integers separately from the sum of the fractions. Then add the two sums.

Example: Add the mixed numbers $7 \frac{1}{6}$ and $2 \frac{3}{4}$.

First we add the integers: $7 + 2 = 9$.

Adding the fractions, we get $\frac{1}{6} + \frac{3}{4} = \frac{2}{12} + \frac{9}{12} = \frac{11}{12}$.

Combining the two sums, the answer we obtain is $9 \frac{11}{12}$.

SUBTRACTION OF FRACTIONS

As with addition, before two fractions can be subtracted they must have a common denominator.

Example: Subtract $\frac{2}{3}$ from $\frac{3}{4}$. The LCD is 12.

The subtraction with the fractions in equivalent

form gives: $\frac{3 \cdot 3}{4 \cdot 3} - \frac{2 \cdot 4}{3 \cdot 4} = \frac{9}{12} - \frac{8}{12} = \frac{1}{12}$

Example: Perform the operation $7 \frac{1}{5} - 4 \frac{5}{10}$.

The LCD of the fractions is 10.

The desired difference can be expressed as $7 \frac{2}{10} - 4 \frac{5}{10}$.

But $\frac{5}{10}$ is larger than $\frac{2}{10}$. Therefore, borrowing 1 or $\frac{10}{10}$

from 7 and adding it to $\frac{2}{10}$, and performing the operation,

we obtain: $6 \frac{12}{10} - 4 \frac{5}{10} = 2 \frac{7}{10}$.

MULTIPLICATION OF FRACTIONS

To multiply two or more fractions, multiply their numerators to obtain the numerator of the product. Multiply the denominators to obtain the denominator of the product.

Example: Multiply $\frac{3}{7} \times \frac{2}{5}$.

The desired product is $\frac{3 \times 2}{7 \times 5} = \frac{6}{35}$.

The calculations are greatly simplified, and the product put in its lowest terms, by cancellation of common factors.

Example: Determine the product $\frac{2}{5} \times \frac{10}{3} \times \frac{6}{7}$.

Express all the numerators and denominators in factored form,

cancel the common factors, and carry out the multiplication

of the remaining factors. The result is:

$$\frac{2}{\cancel{5}} \times \frac{2 \cdot \cancel{5}}{\cancel{3}} \times \frac{2 \cdot \cancel{3}}{7} = \frac{8}{7} = 1 \frac{1}{7}.$$

Note: The \dot{x} is used to show the numbers being cancelled.

Every integer can be written as a fraction with 1 as a denominator, since an integer divided by 1 is equal to the integer. Thus, to multiply an integer by a fraction, multiply the numerator of the fraction by the integer and retain the denominator of the given fraction.

Example: Determine $\frac{3}{5} \times 6$.

Applying the rule, $\frac{3}{5} \times \frac{6}{1} = \frac{3 \times 6}{5 \times 1} = \frac{18}{5} = 3 \frac{3}{5}$.

To multiply mixed numbers, convert them first into fractions and then apply the rule for multiplication of fractions.

Example: Multiply $1 \frac{3}{4}$ by $3 \frac{1}{7}$.

Converting $1 \frac{3}{4}$ and $3 \frac{1}{7}$ to common fractions,

$$\text{we get } 1 \frac{3}{4} = \frac{4}{4} + \frac{3}{4} = \frac{7}{4} \text{ and } 3 \frac{1}{7} = \frac{21}{7} + \frac{1}{7} = \frac{22}{7}.$$

Now in fractional form $\frac{7}{4} \times \frac{22}{7}$

Express in factored form $\frac{\cancel{7}}{2 \cdot \cancel{2}} \times \frac{\cancel{2} \cdot 11}{\cancel{7}}$. Cancel out 7 and 2.

The result is $\frac{11}{2}$ or $5 \frac{1}{2}$.

DIVISION OF FRACTIONS

To divide one fraction by another, invert the divisor and multiply the fractions.

Example: $\frac{3}{5} \div \frac{4}{7} \Rightarrow$ invert the divisor $\frac{4}{7}$ to $\frac{7}{4} \Rightarrow$

Now multiply $\frac{3}{5} \times \frac{7}{4} = \frac{3 \times 7}{5 \times 2 \times 2} = \frac{21}{20} \Rightarrow$

Notice nothing cancelled and the result is $\frac{21}{20}$

To divide mixed numbers, convert them first to fractions as before and apply the rule for division.

DIVISION BY ZERO

It is important to emphasize the following reminder: **Division by 0 is impossible.** Therefore, a fraction cannot have 0 as a denominator.

RECIPROCAL

The reciprocal of a number is 1 divided by the number. It follows from the definition that the product of a number and its reciprocal is 1. The reciprocal of zero is not defined.

Example: *The reciprocal of 25 is $\frac{1}{25}$ or 0.04.*

Conversely, the reciprocal, of 0.04 is $\frac{1}{0.04}$ or 25.

CONVERSION OF COMMON FRACTIONS INTO DECIMAL FRACTIONS

To convert a common fraction into a decimal equivalent form, divide the numerator by the denominator.

Example: *Convert $\frac{7}{16}$ into a decimal fraction.*

Since 16 is larger than 7, there will be no digits except 0 to the left of the decimal point in the quotient. Then performing the division, 0 is adjoined to 7 to give 70, which is larger than 16.

Proceeding as with integers, the decimal equivalent of $\frac{7}{16}$ is 0.4375.

PRACTICE PROBLEMS

1. Solve:

$$\frac{9}{64} - \frac{1}{16} =$$

2. Solve:

$$12 \frac{7}{8} \div 4 \frac{2}{3} =$$

3. Solve:

$$1 \frac{3}{4} + 5 \frac{1}{6} =$$

4. Solve:

$$\frac{4}{9} \times \frac{8}{12} =$$

5. Solve:

$$\frac{8}{4} + \frac{3}{32} =$$

6. Solve:

$$0.5 \div \frac{1}{4} =$$

FUNDAMENTAL RULES OF ALGEBRA

Commutative Law of Addition

$$a + b = b + a$$

$$9 + 1 = 1 + 9$$

Associative Law of Addition

$$a + (b + c) = (a + b) + c$$

$$4 + (3 + 2) = (4 + 3) + 2$$

Commutative Law of Multiplication

$$ab = ba$$

$$6 \times 7 = 7 \times 6$$

Associative Law of Multiplication

$$a(bc) = (ab)c$$

$$4(5 \times 2) = (4 \times 5)2$$

Distributive Law

$$a(b + c) = ab + ac$$

$$2(3 + 9) = 2 \times 3 + 2 \times 9$$

SOLVING EQUATIONS AND FORMULAS

An arithmetic equation such as $3 + 2 = 5$ means that the number named on the left ($3 + 2$) is the same as the number named on the right (5).

An algebraic equation, such as $x + 3 = 7$, is a statement that the sum of some number x and 3 is equal to 7. If we choose the correct value for x , then the number $x + 3$ will be equal to 7. x is a *variable*, a symbol that stands for a number in an equation, a blank space to be filled. Many numbers might be put in the space, but only one makes the equation a true statement.

Find the missing numbers in the following arithmetic equations:

a) $37 + \underline{\hspace{2cm}} = 58$

b) $\underline{\hspace{2cm}} - 15 = 29$

c) $4 \times \underline{\hspace{2cm}} = 52$

d) $28 \div \underline{\hspace{2cm}} = 4$

We could have written these equations as

a) $37 + A = 58$

b) $B - 15 = 29$

c) $4 \times C = 52$

d) $28 \div D = 4$

Of course any letters would do in place of A, B, C, and D in these algebraic equations.

How did you solve these equations? You probably eye-balled them and then mentally juggled the other information in the equation until you had found a number that made the equation true. Solving algebraic equations is very similar except that we can't "eyeball" it entirely. We need certain and systematic ways of solving the equation that will produce the correct answer quickly every time.

Each value of the *variable* that makes an equation true is called a *solution* of the equation. For example, the solution of $x + 3 = 7$ is $x = 4$.

Check: $(4) + 3 = 7$

Another **example:** The solution of $2x - 9 = 18 - 7x$ is $x = 3$

Check: $2(3) - 9 = 18 - 7(3)$
 $6 - 9 = 18 - 21$
 $-3 = -3$

Check: $x - 4 = 2$

$$6 - 4 = 2$$

$$2 = 2$$

Use these balancing operations to solve the equations below:

a) $8 + x = 14$

b) $x - 4 = 10$

c) $12 + x = 27$

d) $x + 6 = 2$

Solving many simple algebraic equations involves both kinds of operations: addition/subtraction and multiplication/division. For example,

Solve: $2x + 6 = 14$

We want to change this equation to an equivalent equation with only x or terms that include x on the left, so subtract 6 from both sides.

$$2x + 6 - 6 = 14 - 6 \text{ Combine like terms.}$$

$$2x = 8$$

Now change this to an equivalent equation with only x on the left by dividing both sides by 2.

$$2x \div 2 = 8 \div 2$$

$$2x \div 2 = x \text{ and } 8 \div 2 = 4$$

$$x = 4$$

Use these balancing operations to solve the equations below:

a) $3x - 7 = 11$

b) $7x + 2 = 51$

c) $x - 6 = 3x$

d) $12 - 2x = 4 - x$

e) $17x = 0$

f) $3 + 2x = 17$

g) $5y + 3 = 28$

h) $(x - 2) - (4 - 2x) = 12$

Transposing Equations

To transpose an equation or formula so as to solve for a different unknown means to rewrite the formula as an equivalent formula with that letter isolated on the left of the equals sign.

For example, the area of the triangle is given by the formula

$$A = \frac{BH}{2}$$

where A is the area, B is the length of the base, and H is the height.

Solving for the base B gives the equivalent formula

$$B = \frac{2A}{H}$$

Solving for the height H gives the equivalent formula

$$H = \frac{2A}{B}$$

Solving formulas is a very important practical application of algebra. Very often a formula is not written in the form that is most useful. To use it you may need to rewrite the formula, solving it for the letter whose value you need to calculate.

To solve a formula, use the same balancing operations that you used to solve equations. You may add or subtract the same quantity on both sides of the formula and you may multiply or divide both sides of the formula by the same non-zero quantity.

For example, to solve the formula

$$S = \frac{R + P}{2} \quad \text{for } R$$

First, multiply both sides of the equation by 2.

$$2 \cdot S = 2 \cdot \left(\frac{R + P}{2}\right)$$

The 2's on the right cancel.

$$2S = R + P$$

Second, subtract **P** from both sides of the equation.

$$2S - P = R + P - P$$

The P's on the right cancel.

$$2S - P = R$$

This formula can be reversed to read.

$$R = 2S - P$$

We have solved the formula for **R**.

Remember, when using the multiplication/division rule, you must multiply or divide *all* of both sides of the formula by the same quantity. Practice solving formulas with the following problems:

a) $V = \frac{3K}{T}$ for K

b) $Q = I - R + T$ for R

c) $V = \pi R^2 H - AB$ for H

d) $P = \frac{T}{A - B}$ for A

e) $P = 2A + 3B$ for A

f) $E = MC^2$ for M

g)
$$S = \frac{A - RT}{I - R} \text{ for } A$$

h)
$$S = \frac{1}{2}gt^2 \text{ for } g$$

i)
$$P = I^2 R \text{ for } R$$

j)
$$I = \frac{V}{R + a} \text{ for } R$$

k)
$$A = \frac{2V - W}{R} \text{ for } V$$

l)
$$F = \frac{9C}{5} + 32 \text{ for } C$$

m)
$$A = \frac{\pi R^2 S}{360} \text{ for } S$$

n)
$$P = \frac{t^2 dN}{3.78} \text{ for } d$$

o)
$$C = \frac{AD}{A + 12} \text{ for } D$$

p)
$$V = \frac{\pi LT^2}{6} + 2 \text{ for } L$$

Factoring and Adding/Removing Parentheses

Parentheses are used to group or isolate terms in an expression for special consideration. When two or more terms are enclosed in parentheses they are to be treated as a single quantity. A *term* is an expression in a quantity which is isolated by plus or minus signs.

Removal of Parentheses - Parentheses preceded by a plus sign can be removed without changing any signs. Parentheses preceded by a minus sign can be removed only if all the enclosed signs are changed.

Example: **A + (B + C - D) is the same as A + B + C - D**
 A - (B + C - D) is the same as A - B - C + D

Parentheses Preceded by a Factor - These can be handled two ways.

- a) By performing all operations within the parentheses first and then multiplying.

Example: $A(4 + 5)$
 $A(9)$
 $9A$

- b) Or multiplying each term within the parentheses by the factor.

Example: $A(4 + 5)$
 $4A + 5A$
 $9A$

The result is the same as above.

Factoring - In the expression $A(B + C - D)$, each term with the parentheses must be multiplied by the factor A with the result being

$A(B + C - D)$
 $AB + AC - AD$

Conversely, if a series of terms have a common quantity, that quantity can be factored out.

Example: $AB + AC - AD$ the factor A is common

$A(B + C - D)$ result of factoring out A

Example: $4AB + 4AX - 4AY$ factors 4 and A are common

$4A(B + X - Y)$ result of factoring out $4A$

Using Square Roots in Solving Equations

The equations you have learned to solve so far are all *linear* equations. The variable appears only to the first power with no x^2 or x^3 terms appearing in the equations. Terms that are raised to a power greater than one can also be solved using the balancing operations from the previous lessons. As an example, let's solve the following equation.

$$c^2 = a^2 + b^2 \quad \text{for } c$$

First, we have to take the square root of both sides.

$$\sqrt{c^2} = \sqrt{a^2 + b^2}$$

The square root of C^2 is C , and the result is

$$c = \sqrt{a^2 + b^2}$$

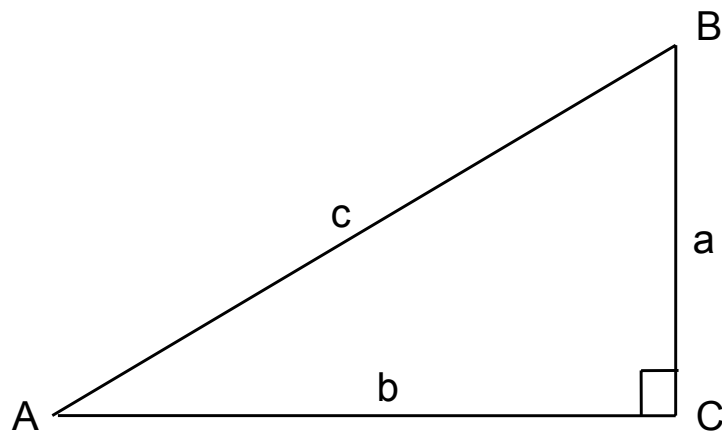
TRIANGLE TRIGONOMETRY

The word *trigonometry* means simply "triangle measurement". We know that the ancient Egyptian engineers and architects of 4000 years ago used practical trigonometry in building the pyramids. By 140 B.C. the Greek mathematician Hipparchus had made trigonometry a part of formal mathematics and taught it as astronomy. We will look at only the simple practical trigonometry used in electrical applications.

A *triangle* is a polygon having three sides. In this course, the electrical applications will only need to refer to a *right triangle*. A right triangle contains a 90° angle. The sum of the remaining two angles is 90° . Two of the sides are perpendicular to each other. The longest side of a right triangle is always the side opposite to the right angle. This side is called the *hypotenuse* of the triangle.

Labeling of Sides and Angles

The following figure indicates the conventional method for designating sides and angles:



Side **a** is the altitude of the triangle.

Side **b** is the base of the triangle.

Side **c** is the hypotenuse of the triangle.

* Note that each angle has the same letter designation as the opposite side. When the angle is unknown Greek letters are used to represent these angles. A common Greek letter used for angles is θ (**theta**).

Pythagorean Theorem

The Pythagorean theorem is a rule or formula that allows us to calculate the length of one side of a right triangle when we are given the lengths of the other two sides. Although the formula is named after the ancient Greek mathematician Pythagoras, it was known to Babylonian engineers and surveyors more than a thousand years before Pythagoras lived.

Pythagorean Theorem - For any right triangle, the square of the hypotenuse is equal to the sum of the squares of the other two sides.

$$c^2 = a^2 + b^2$$

Trigonometric Functions

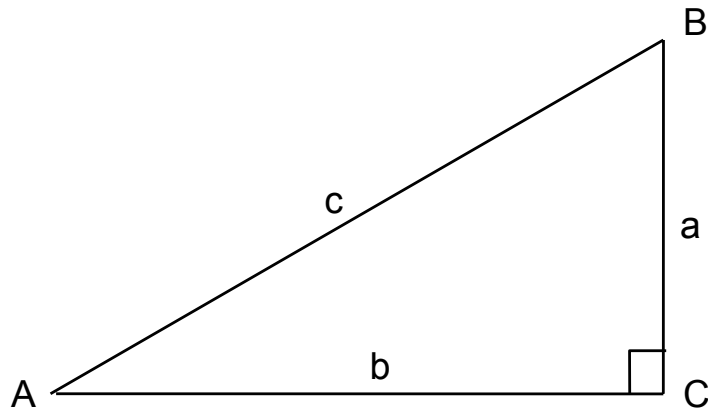
We have observed the relationship of the side lengths of a right triangle based upon the Pythagorean Theorem. There is also a relationship between the ratio of the opposite side to the hypotenuse for a fixed angle. The ratio will always be constant regardless the unit of measure of the sides. The same applies to the ratio of the adjacent side to the hypotenuse and the ratio of the opposite side to the adjacent side.

These ratios are useful in solving right triangles and certain other scientific calculations. These ratios are called *trigonometric functions*. Using the labeling techniques from the previous page, these functions are shown as follows:

$$\text{sine } \angle \theta = \frac{\text{Opposite Side}}{\text{Hypotenuse}}$$

$$\text{cosine } \angle \theta = \frac{\text{Adjacent Side}}{\text{Hypotenuse}}$$

$$\text{tangent } \angle \theta = \frac{\text{Opposite Side}}{\text{Adjacent Side}}$$



The sine of angle A is written:

$$\text{sine } \angle A = \frac{O}{H} = \frac{a}{c}$$

The cosine of angle A is written:

$$\text{cosine } \angle A = \frac{A}{H} = \frac{b}{c}$$

The tangent of angle A is written:

$$\text{tangent } \angle A = \frac{O}{A} = \frac{a}{b}$$

ADDITION AND SUBTRACTION USING SCIENTIFIC NOTATION

Before adding or subtracting two numbers expressed in scientific notation, their powers of 10 must be equal.

Example: **Add:** $1.63 \times 10^4 + 2.8 \times 10^3$

Convert to: $16.3 \times 10^3 + 2.8 \times 10^3 = 19.1 \times 10^3$

or: $1.63 \times 10^4 + .28 \times 10^4 = 1.91 \times 10^4$

MULTIPLICATION AND DIVISION USING SCIENTIFIC NOTATION

To multiply two numbers expressed in scientific notation, multiply their decimal numbers together first, then add their exponents. If the decimal number is greater than 9 after the multiplication, move the decimal point and compensate the exponent to express in scientific notation.

$$8.4 \times 10^3 \times 2.2 \times 10^2 = 18.48 \times 10^5 = 1.848 \times 10^6$$

To divide two numbers expressed in scientific notation, divide separately their decimal numbers and subtract their exponents.

$$8.4 \times 10^3 \div 2.0 \times 10^2 = 4.2 \times 10^1$$

POWERS OF TEN NOTATION USING ENGINEERING UNITS

Powers of ten notation follows the same rules for addition, subtraction, multiplication, and division as scientific notation. The only difference is that the resultant for powers of ten does not have to be expressed with only 1 digit to the left of the decimal point. When using engineering units for calculations, this is very important. Below is a table for engineering units expressed in powers of ten:

<u>Power</u>	<u>Decimal Number</u>	<u>Prefix</u>	<u>Abbreviation</u>	
1×10^9	1,000,000,000		Giga	(G)
1×10^6	1,000,000		Mega	(M)
1×10^3	1,000		Kilo	(K)
1×10^0	1		Unity	
1×10^{-3}	.001	Milli		(m)
1×10^{-6}	.000,001	Micro		(μ)
1×10^{-9}	.000,000,001		Nano	(n)
1×10^{-12}	.000,000,000,001	Pico		(p)

Example: $V = I \times R$
 $1.2 \text{ Kvolts} = 200 \text{ mAmps} \times 6 \text{ KW}$

APPROXIMATE NUMBERS AND SIGNIFICANT DIGITS

When we perform calculations on numbers, we must consider the accuracy of these numbers, since this affects the accuracy of the results obtained. Most of the numbers involved in technical work are approximate, having been arrived at through some process of measurement. However, certain other numbers are exact, having been arrived at through some definition (1 hour = 60 minutes) or counting process (cured tires counted). We can determine whether or not a number is approximate or exact if we know how the number was determined.

Most numbers used in the calculations for this course will be approximate. In calculations using approximate numbers, the position of the decimal point as well as the number of significant digits is important. What are significant digits? Except for the left-most zeros, all digits are considered to be **significant digits**.

The last significant digit of an approximate number is known not to be completely accurate. It has usually been determined by estimation of **rounding off**. However, we do know that it is at most in error by one-half of a unit in its place value.

The principle of rounding off a number is to write the closest approximation, with the last significant digit in a specified position, or with a specified number of significant digits.

Let's specify this process of rounding off as follows: If we want a certain number of significant digits, we examine the digit in the next place to the right. If this digit is **less than 5**, we accept the digit in the last place. If the next digit is **5 or greater**, we increase the digit in the last place by 1, and this resulting digit becomes the final significant digit of the approximation.

The answers on the assessment are taken to the fourth digit and round back to three places right of the decimal. Please utilize this format during this class.



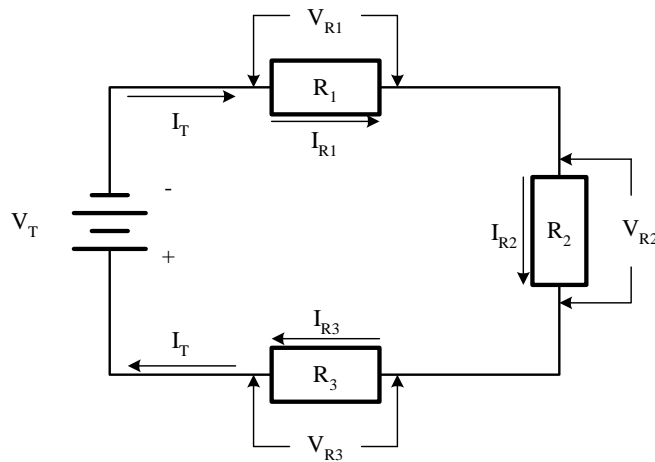
BASIC D.C. CIRCUITS

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SERIES CIRCUITS



The above circuit is classified as a **series circuit**. In this circuit there is only **one current path**. This distinguishes the series circuit from the parallel circuit. The battery is the voltage source and is usually referred to as the **applied or total voltage** of the circuit.

IMPORTANT PROPERTIES

- A. The amount of current flowing in one part of the circuit is equal to the amount flowing in any other part of the circuit. In other words, the same current flows through R_1 , R_2 , and R_3 .

$$I_T = I_{R1} = I_{R2} = I_{R3}$$

As seen from Ohm's Law, a current flowing through a resistor produces a potential difference across the terminals of the resistor. ($V = I \times R$) This potential difference is called a **Voltage drop**.

- B. **Kirchhoff's Voltage Law**

The sum of the voltage drops around a circuit loop must be equal to the applied voltage.

$$V_T = V_{R1} + V_{R2} + V_{R3}$$

OHM'S LAW

$$V_T = V_{R1} + V_{R2} + V_{R3} \text{ (Kirchhoff's Voltage Law for Series Circuits)}$$

$$I_T = I_{R1} = I_{R2} = I_{R3} \text{ (Current common in series circuits)}$$

$$V_{R1} = R_1 \cdot I_T$$

$$V_{R2} = R_2 \cdot I_T \quad \text{(Ohm's Law)}$$

$$V_{R3} = R_3 \cdot I_T$$

$$V_T = R_T \cdot I_T$$

$$R_T \cdot I_T = (R_1 \cdot I_T) + (R_2 \cdot I_T) + (R_3 \cdot I_T) \quad \text{(Substitute Ohm's Law into Kirchhoff's Law)}$$

Divide both sides of the equation by I_T

$$\frac{R_T \cdot I_T}{I_T} = \frac{R_1 \cdot I_T}{I_T} + \frac{R_2 \cdot I_T}{I_T} + \frac{R_3 \cdot I_T}{I_T}$$

I_T cancels and the following equation is the result:

RULE FOR SERIES CIRCUITS: Total resistance for any series resistive circuit is the sum of the individual resistances.

$$R_T = R_1 + R_2 + R_3$$

UNIT OF POWER

Power is the rate of doing work, and the unit of electrical power is the watt.

$$Power = \frac{Work}{Time}$$

Power is expressed as VOLTS X AMPS or as an equation. **P = V X I**

Note that: $I = V \div R$ and $V = I \times R$ (Ohm's Law).

By substituting Ohm's Law into the expression **P = V x I** we get:

$$P = \frac{V^2}{R}$$

or $P = I^2 R$

Example:

A device is connected across a supply of 230V. There is a current flow of 5 AMPS. What is the power dissipated by the circuit?

$$P = V \times I$$

$$P = 230V \times 5A = 1150W \text{ or } 1.15KW$$

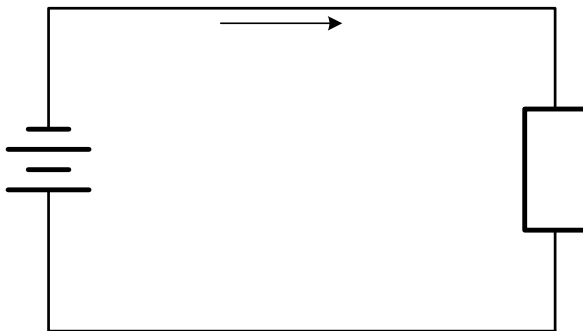
Power for electric motors is sometimes rated in watts or kilowatts, but more usually in Horsepower (hp).

$$1 \text{ hp} = 746 \text{ watts}$$

Energy and work are essentially the same and are expressed in identical units. Power is different, however, because it is the time rate of doing work. The Kilowatt-hour (KWh) is the practical commercial unit of electrical energy or work performed. If a device, as in the above example, were connected to the supply for a period of ten (10) hours, then 11.5 KWh would be used (1.15 KW x 10 Hrs.).

$$Work = Power \times time$$

Find the Power P_T :



1. $V_T = 48\text{v}$

$$I_T = 2\text{A}$$

$$P_T =$$

2. $R_1 = 10\Omega$

$$I_T = 8\text{A}$$

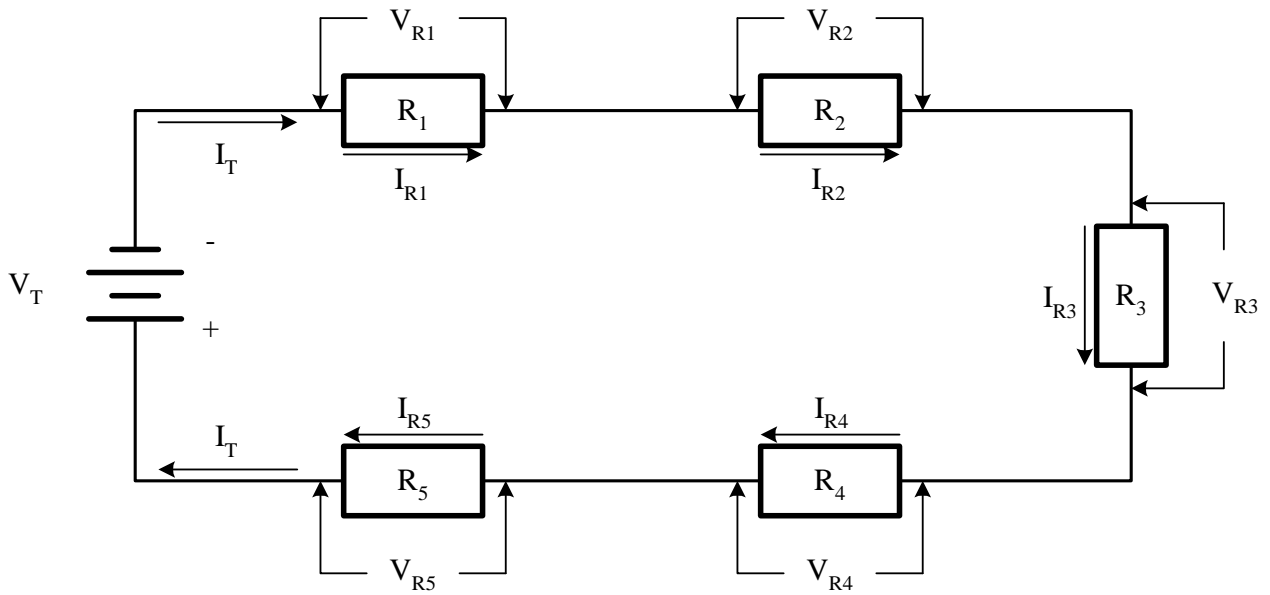
$$P_T =$$

3. $V_T = 40\text{v}$

$$R_1 = 100\Omega$$

$$P_T =$$

$$V_T$$



Given:

$$I_T = 60 \text{ A}$$

$$R_1 = 5 \ \Omega$$

$$R_2 = 3 \ \Omega$$

$$R_3 = 9 \ \Omega$$

$$R_4 = 5 \ \Omega$$

$$R_5 = 8 \ \Omega$$

Find:

$$V_T =$$

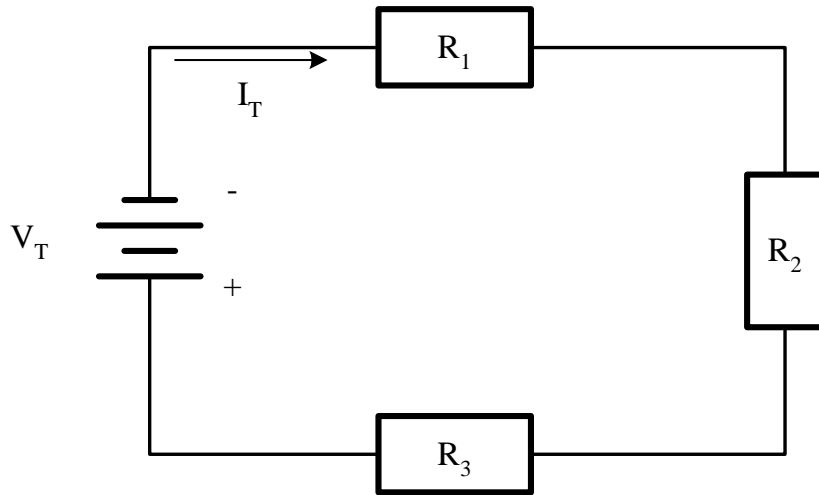
$$V_{R1} =$$

$$V_{R2} =$$

$$V_{R3} =$$

$$V_{R4} =$$

$$P_T =$$



Given:

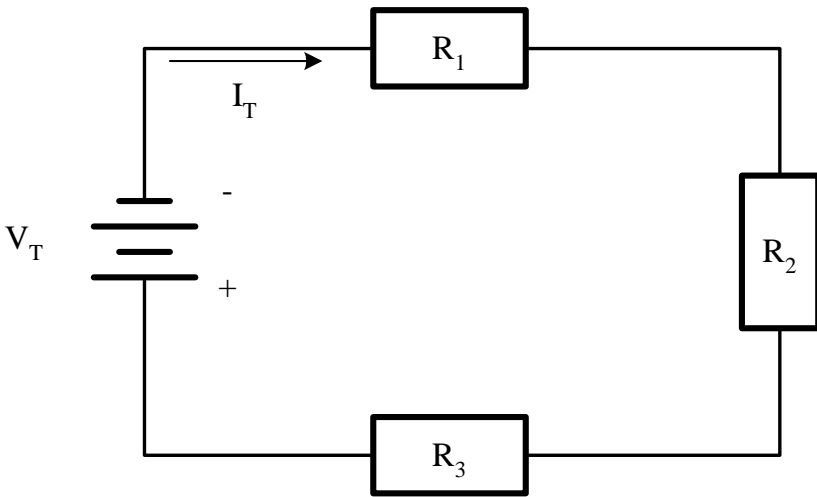
$$V_T = 210 \text{ V}$$

$$R_1 = 6 \ \Omega$$

$$R_2 = 19 \ \Omega$$

$$R_3 = 5 \ \Omega$$

Find: $I_T =$



Given:

$$V_T = 250 \text{ V}$$

$$I_T = 25 \text{ A}$$

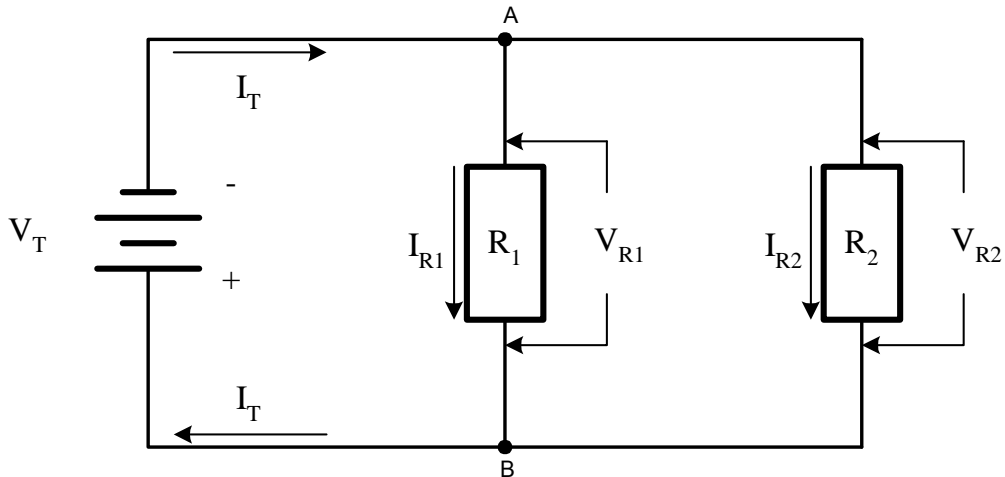
$$R_1 = 5 \ \Omega$$

$$R_2 = 2.5 \ \Omega$$

Find: $R_T =$

$$R_3 =$$

PARALLEL CIRCUITS



The above circuit is classified as a **parallel circuit**. In this circuit a total current (I_T) leaves the negative terminal of the battery. When the current reaches the junction labeled (**A**), it splits into two branch currents (I_{R1}) and (I_{R2}).

When (I_{R1}) and (I_{R2}) reach the junction labeled **B**, they join back together as I_T and continue on to the positive side of the battery. Since no current can be lost, the sum of I_{R1} and I_{R2} must be equal to I_T .

IMPORTANT PROPERTIES

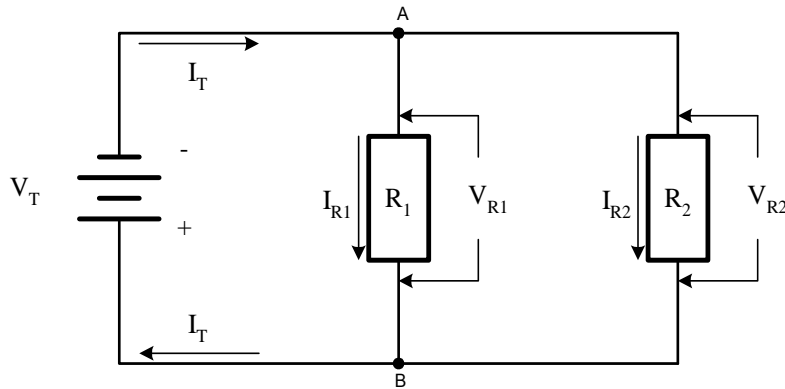
- A. The voltage across one branch of a parallel circuit is equal to the voltage across any other parallel branch of the circuit.

$$V_T = V_{R1} = V_{R2}$$

- B. **Kirchhoff's Current Law**

The sum of the currents entering a junction must equal the sum of currents leaving the junction.

$$I_T = I_{R1} + I_{R2}$$



When two resistors are connected in parallel, the electrons can move more easily. In a parallel circuit the electrons can move through one branch of the circuit without having to go through the other branch. The total current flowing through a parallel circuit splits up, some going one way and some going the other. The branch currents will add up.

$I_T = I_{R1} + I_{R2}$	(Kirchhoff's Current Law for Parallel Circuits)
$V_T = V_{R1} = V_{R2}$	(Voltage common in parallel circuits)

$I_{R1} = V_T \div R_1$	(Ohm's Law)
$I_{R2} = V_T \div R_2$	
$I_T = V_T \div R_T$	

(Substitute Ohm's Law into Kirchhoff's Current Law)

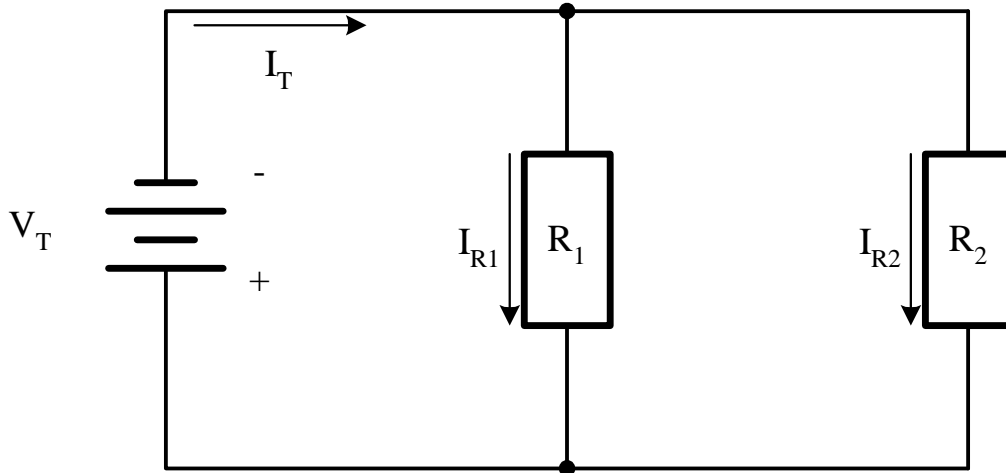
$$\frac{V_T}{R_T} = \frac{V_T}{R_1} + \frac{V_T}{R_2}$$

(Divide both sides of the equation by V_T)

$$\frac{V_T}{R_T} \cdot \left(\frac{1}{V_T}\right) = \left(\frac{V_T}{R_1} + \frac{V_T}{R_2}\right) \cdot \frac{1}{V_T} \qquad \text{And then,} \qquad \frac{V_T}{V_T R_T} = \frac{V_T}{V_T R_1} + \frac{V_T}{V_T R_2}$$

V_T now cancels out and the following equation is the result:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} \qquad \text{Use the reciprocal to get} \qquad R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$



Given:

$$V_T = 120 \text{ V}$$

$$R_1 = 15 \Omega$$

$$R_2 = 10 \Omega$$

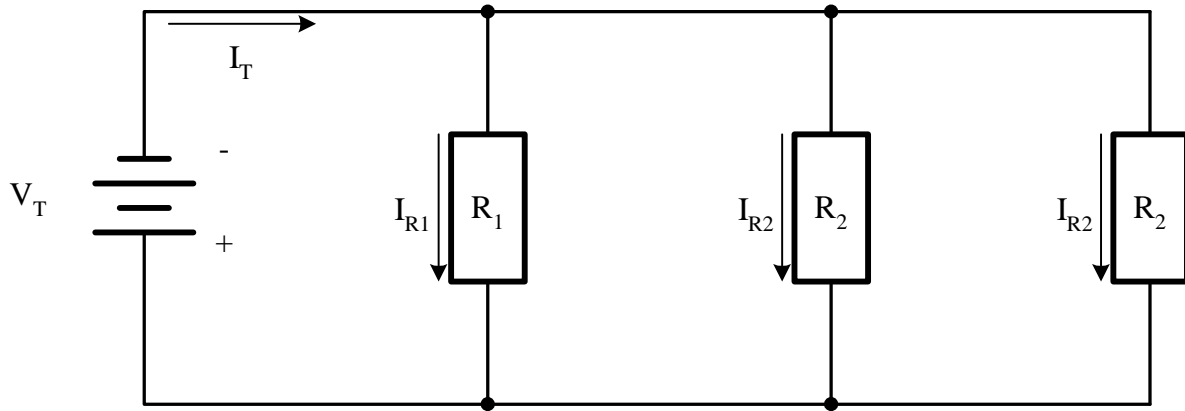
Find:

$$R_T =$$

$$I_T =$$

$$I_{R1} =$$

$$I_{R2} =$$



Given:

$$I_T = 3 \text{ A}$$

$$R_1 = 12 \ \Omega$$

$$R_2 = 15 \ \Omega$$

$$R_3 = 10 \ \Omega$$

Find:

$$R_T =$$

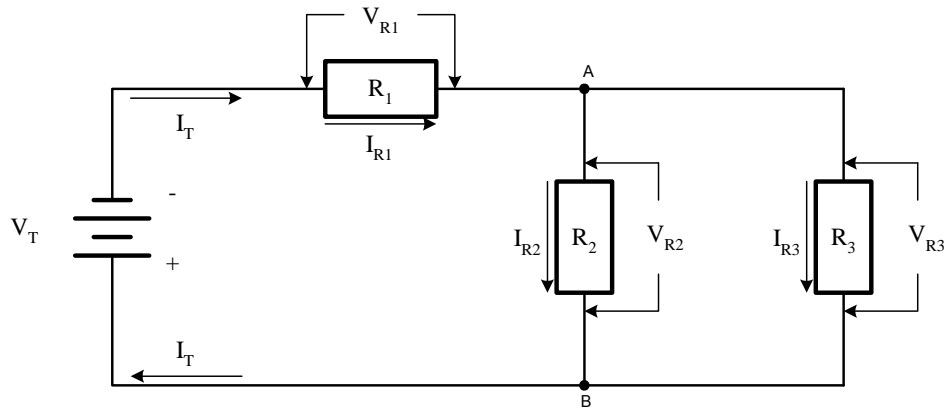
$$V_T =$$

$$I_{R1} =$$

$$I_{R2} =$$

$$I_{R3} =$$

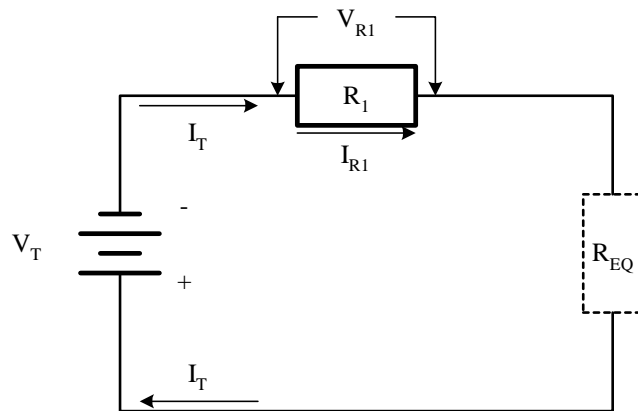
SERIES AND PARALLEL CIRCUITS



If resistors are arranged in both series and parallel in the same circuit, then solving the parallel section first and then the entire circuit is the simplest solution. In the circuit shown, R_2 and R_3 are in parallel and this combination is in series with R_1 . We may call the resistance of the parallel section R_{EQ} and find it by the reciprocal method:

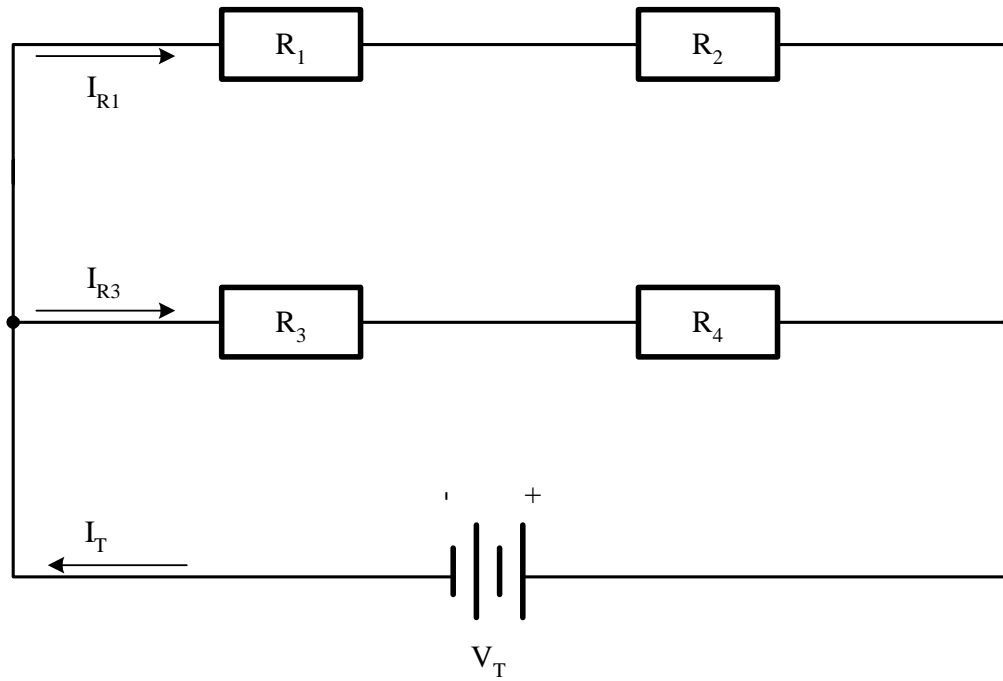
$$R_{EQ} = \frac{1}{\frac{1}{R_2} + \frac{1}{R_3}}$$

We may then redraw the circuit as shown below, where the branch with resistance R_{EQ} has replaced the parallel section R_2 and R_3 .



Now the resistance of the entire circuit is simply: $R_T = R_1 + R_{EQ}$.

Note: R_{EQ} = Equivalent resistance for R_2 in parallel with R_3 and is shown as a broken line.



Given:

$$V_T = 150 \text{ V}$$

$$R_1 = 6 \Omega$$

$$R_2 = 4 \Omega$$

$$R_3 = 14 \Omega$$

$$R_4 = 16 \Omega$$

Find:

$$I_T =$$

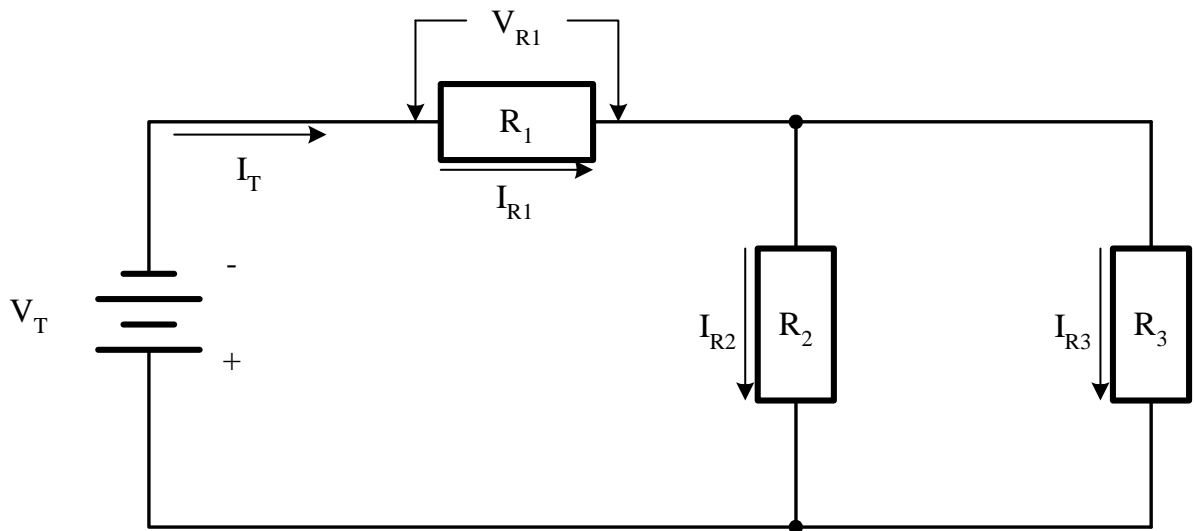
$$I_{R1} =$$

$$I_{R3} =$$

$$V_{R4} =$$

$$P_{R1} =$$

$$P_{R2} =$$



Given:

$$V_T = 30 \text{ V}$$

$$R_1 = 10 \ \Omega$$

$$R_2 = 15 \ \Omega$$

$$R_3 = 20 \ \Omega$$

Find:

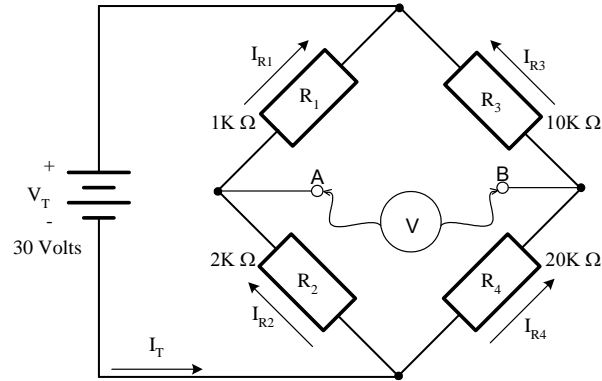
$$R_T =$$

$$I_T =$$

$$V_{R1} =$$

$$I_{R3} =$$

WHEATSTONE BRIDGE CIRCUIT



A type of circuit that is widely used for precision measurements of resistance is the Wheatstone bridge. The circuit diagram, as shown above, is the standard drawing configuration. This type circuit can be drawn and evaluated as a basic D.C. combination circuit. Before we redraw and look at some applications of Wheatstone bridges, let's look at the characteristics of this circuit.

A bridge circuit may be either **balanced** or **unbalanced**. A balanced bridge is one where the voltage across terminals A and B will equal zero ($V_{A \text{ to } B} = 0$). There would be a difference in potential across terminals A and B if the circuit were unbalanced. First, let's evaluate a balanced circuit.

If $V_{A \text{ to } B} = 0$ then:

$$I_{R1} = I_{R2} = \frac{V_T}{R_1 + R_2} = \frac{30\text{v}}{3\text{K}\Omega} = 10\text{mA}$$

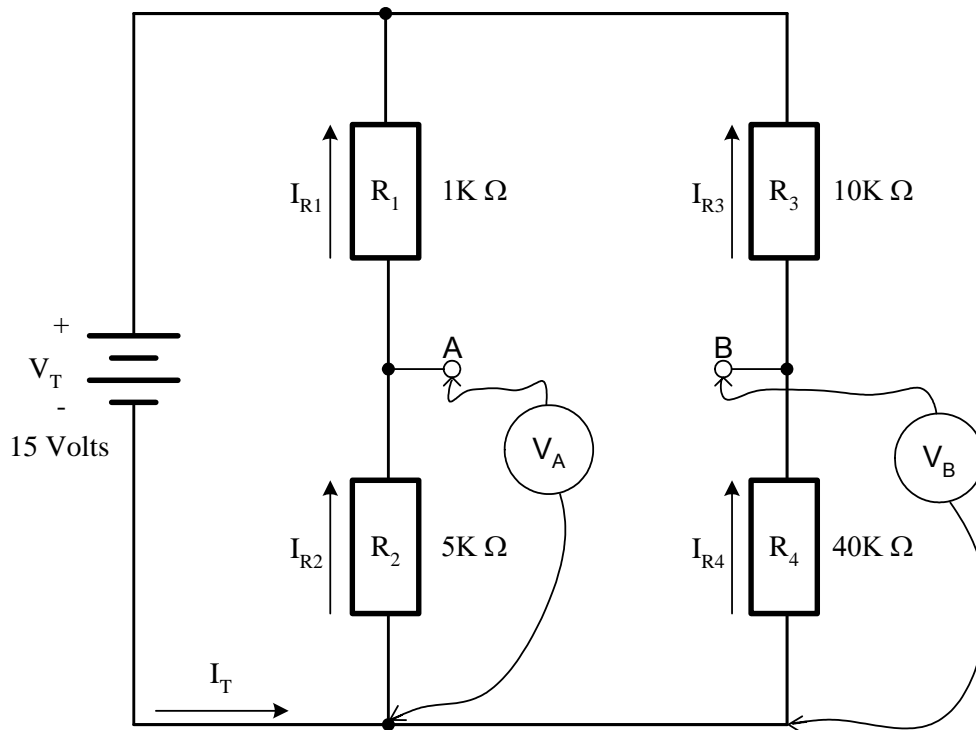
$$V_{R1} = I_{R1} \times R_1 = 10\text{mA} \times 1\text{K}\Omega = 10\text{volts}$$

$$V_{R2} = I_{R2} \times R_2 = 10\text{mA} \times 2\text{K}\Omega = 20\text{volts}$$

$$I_{R3} = I_{R4} = \frac{V_T}{R_3 + R_4} = \frac{30\text{v}}{30\text{K}\Omega} = 1\text{mA}$$

$$V_{R3} = I_{R3} \times R_3 = 1\text{mA} \times 10\text{K}\Omega = 10\text{volts}$$

$$V_{R4} = I_{R4} \times R_4 = 1\text{mA} \times 20\text{K}\Omega = 20\text{volts}$$

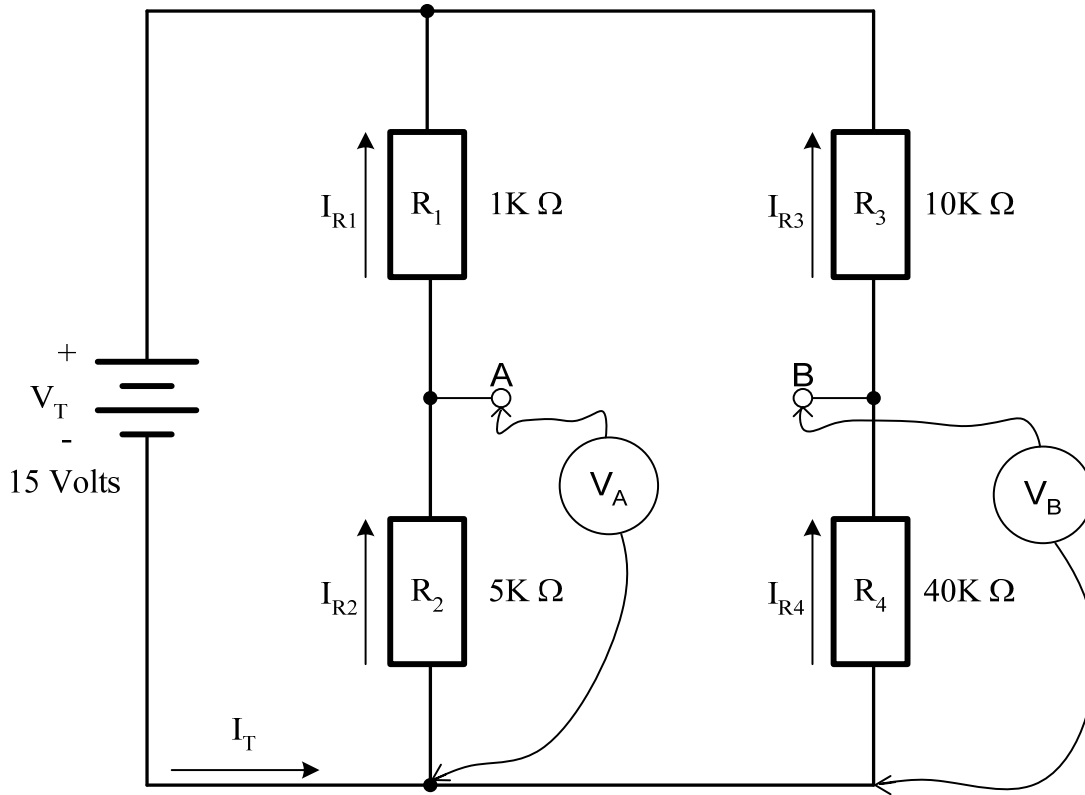


The calculations from the previous page determined that $V_{R2} = 20 \text{ volts}$ and $V_{R4} = 20 \text{ volts}$.

Let's measure the voltage at terminal **A** and **B** using the negative side of the battery as a reference (- lead of meter) and reading the voltage with the (+) positive lead of the meter. Since $V_{R2} = V_A$ and $V_{R4} = V_B$, we can state that $V_A = +20 \text{ volts}$ and $V_B = +20 \text{ volts}$. There is no potential difference across terminals A and B and therefore $V_{A \text{ to } B} = 0 \text{ volts}$. This bridge circuit is **balanced** and a relationship between the resistances can be written as follows.

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Note: For this relationship to be true the branch circuits must remain the same.



Now, let's evaluate another circuit to see if it is balanced or unbalanced. For the circuit to be balanced, $V_{AB} = 0v$ as we saw from the previous example. For the circuit to be unbalanced, $V_{AB} \neq 0v$. Let's use the resistance relationship from the previous example.

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}, \quad \frac{1K\Omega}{5K\Omega} = \frac{10K\Omega}{40K\Omega}, \quad \frac{1}{5} \neq \frac{1}{4}$$

The bridge is unbalanced. Now let's find $V_{A \text{ to } B}$.

$$I_{R1} = I_{R2} = \frac{V_T}{R_1 + R_2} = \frac{15v}{6K\Omega} = 2.5mA$$

$$V_{R1} = I_{R1} \times R_1 = 2.5mA \times 1K\Omega = 2.5volts$$

$$V_{R2} = I_{R2} \times R_2 = 2.5mA \times 5K\Omega = 12.5volts$$

$$I_{R3} = I_{R4} = \frac{V_T}{R_3 + R_4} = \frac{15v}{50K\Omega} = 0.3mA$$

$$V_{R3} = I_{R3} \times R_3 = 0.3mA \times 10K\Omega = 3volts$$

$$V_{R4} = I_{R4} \times R_4 = 0.3mA \times 40K\Omega = 12volts$$

Using the negative side of the battery as reference again, measure the voltage:

$V_A = 12.5$ volts,

$V_B = 12$ volts,

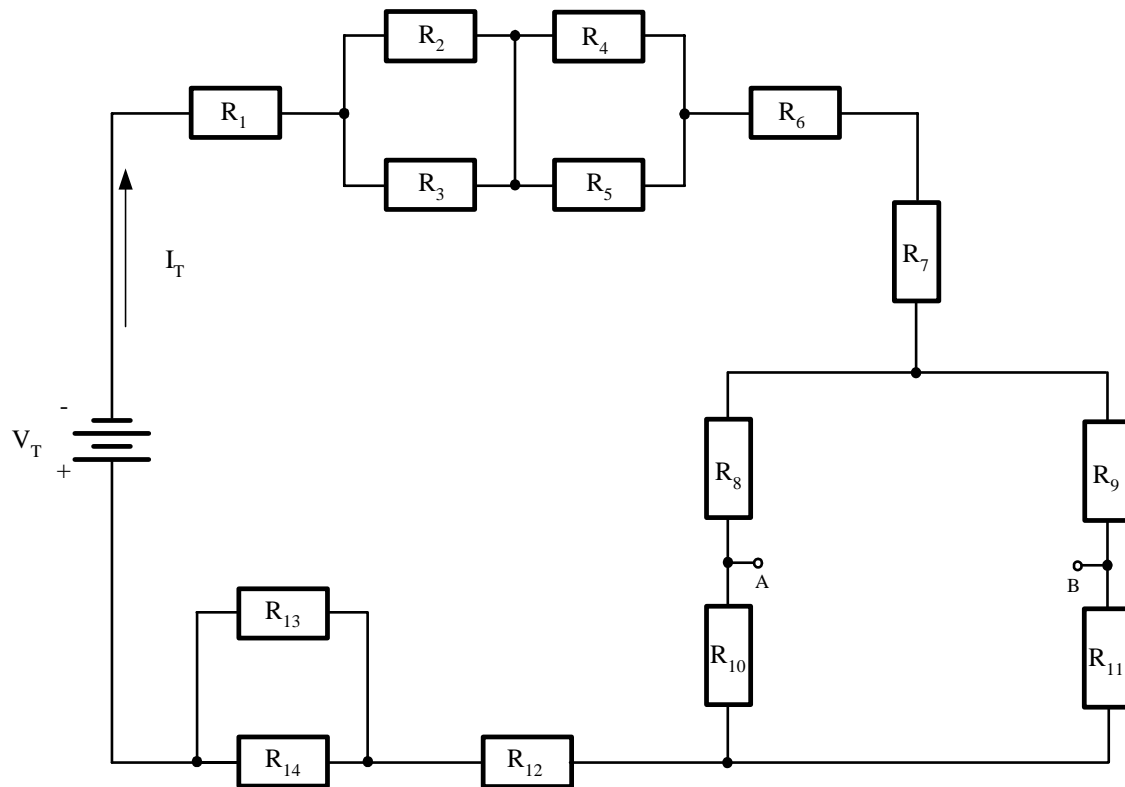
$V_{A \text{ to } B} = 0.5$ volts

If a voltmeter were connected across terminal **A** and **B**, there would be a potential difference of **0.5 volts** and the bridge is **unbalanced**.

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Given:

- $V_T = 150 \text{ V}$
- $R_1, R_2, R_3 = 10\Omega$
- $R_4 = 7\Omega$
- $R_5 = 13\Omega$
- $R_6 = 15\Omega$
- $R_7 = 3\Omega$
- $R_8 = 12\Omega$
- $R_9 = 5\Omega$
- $R_{10} = 8\Omega$
- $R_{11} = 15\Omega$
- $R_{12} = 3\Omega$
- $R_{13} = 20\Omega$
- $R_{14} = 10\Omega$

Find:

- $R_T =$
- $I_T =$
- $I_{R9} =$
- $V_{R6} =$
- $P_{R12} =$
- $V_{A-B} =$



INDUCTANCE IN A.C.

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INDUCTANCE

The study of inductance presents a very challenging but rewarding segment of electricity. It is challenging in the sense that, at first, it will seem that new concepts are being introduced. The reader will realize as this unit progresses that these "new concepts" are merely extensions and enlargements of fundamental principles that have been acquired previously in the study of magnetism. The study of inductance is rewarding in the sense that a thorough understanding of it will enable the reader to acquire a working knowledge of electrical circuits more rapidly and with more surety of purpose than would otherwise be possible.

Inductance is the characteristic of an electrical circuit that makes itself evident by opposing the starting, stopping, or changing of current flow. The above statement is of such importance to the study of inductance that it bears repeating in a simplified form.

Inductance is the characteristic of an electrical conductor, which opposes a CHANGE in current flow.

One does not have to look far to find a physical analogy of inductance. Anyone who has ever had to push a heavy load (wheelbarrow, car, etc.) is aware that it takes more work to start the load moving than it does to keep it moving. This is because the load possesses the property of inertia. Inertia is the characteristic of mass that opposes a CHANGE in velocity. Therefore, inertia can hinder us in some ways and help us in others. Inductance exhibits the same effect on current in an electric circuit as inertia does on velocity of a mechanical object. The effects of inductance are sometimes desirable and sometimes undesirable.

Michael Faraday started to experiment with electricity around 1805 while working as an apprentice bookbinder. It was in 1831 that Faraday performed experiments on magnetically coupled coils. A voltage was induced in one of the coils due to a magnetic field created by current flow in the other coil. From this experiment came the induction coil, the theory of which eventually made possible many of our modern conveniences such as the automobile, doorbell, auto radio, etc. In performing this experiment Faraday also invented the first transformer, but since alternating current had not yet been discovered the transformer had few practical applications. Two months later, based on these experiments, Faraday constructed the first direct current generator. At the same time Faraday was doing his work in England, Joseph Henry was working independently along the same lines in New York. The discovery of the property of self-induction of a coil was actually made by Henry a little in advance of Faraday and it is in honor of Joseph Henry that the unit of inductance is called the **HENRY**.

Unit of Inductance

The unit for measuring inductance (**L**) is the **HENRY (h)**. An inductor has an inductance of 1 henry if an emf of 1 volt is induced in the inductor when the current through the inductor is **changing** at the rate of 1 ampere per second. The relation between the induced voltage, inductance, and the rate of change of current with respect to time is stated mathematically as:

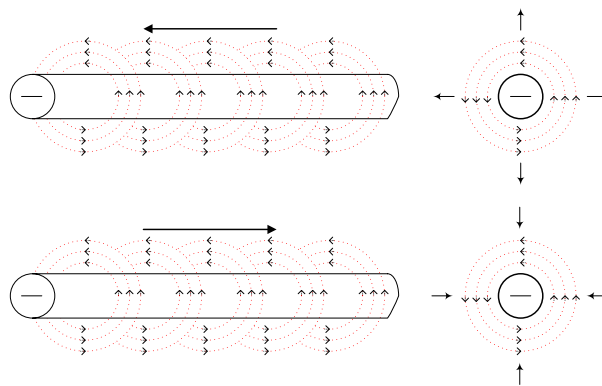
$$V_{\text{induced}} = L \frac{\Delta I}{\Delta t}$$

Where I_{induced} is the induced emf in volts, L is the inductance in henrys, and ΔI is the change in current in amperes occurring in Δt seconds. (Delta, symbol Δ , means "a change in.....")

The henry is a large unit of inductance and is used with relatively large inductors. The unit employed with small inductors is the millihenry, mh. For still smaller inductors the unit of inductance is the microhenry, μh .

Self-Inductance

Even a perfectly straight length of conductor has some inductance. As previously explained, current in a conductor always produces a magnetic field surrounding, or linking with, the conductor. When the current changes, the magnetic field changes, and an emf is induced in the conductor. This emf is called a **SELF-INDUCED EMF** because it is induced in the conductor carrying the current. The direction of the induced emf has a definite relation to the direction in which the field that induces the emf varies. When the current in a circuit is increasing, the flux linking with the circuit is increasing. This flux cuts across the conductor and induces an emf in the conductor in such a direction as to oppose the increase in current and flux. This emf is sometimes referred to as counter-electro-motive-force (**Cemf**) or back emf. Likewise, when the current is decreasing, an emf is induced in the opposite direction and opposes the decrease in current. These effects are summarized by Lenz's Law, which states that **the induced emf in any circuit is always in a direction to oppose the effect that produced it.**



Shaping a conductor so that the electromagnetic field around each portion of the conductor cuts across some other portion of the same conductor increases the inductance (*as illustrated on the next page*). A length of conductor is looped so those two portions of the conductor lie adjacent and parallel to each other. This conductor is in the form of a **coil or inductor**.

When an alternating voltage is applied to the loops of the conductor and a current starts to flow through the conductor loops, a concentric magnetic field starts to expand around all portions of the looped conductor. With increasing current, the field expands outward, cutting across a portion of the adjacent conductor. The resultant induced emf in that conductor opposes the main current. The direction of this induced voltage and current may be determined by applying the Left-Hand-Rule for Generators. To do this we will reference the middle conductor and evaluate what effects the expanding magnetic field around the left conductor has on **relative motion, flux, and direction of the induced current** in the middle conductor.

In applying this rule we will need to use the thumb, the index finger and the middle finger. The thumb of the left hand points in the direction that a conductor is moved through a field (**F - relative motion**). With the conductor stationary, the magnetic field is expanding or moving. This would be the same as if the conductor were moving in the opposite direction). The index finger points in the direction of the magnetic field from North to South (**B**). The middle finger will now indicate the direction of the induced or generated current (**I**).

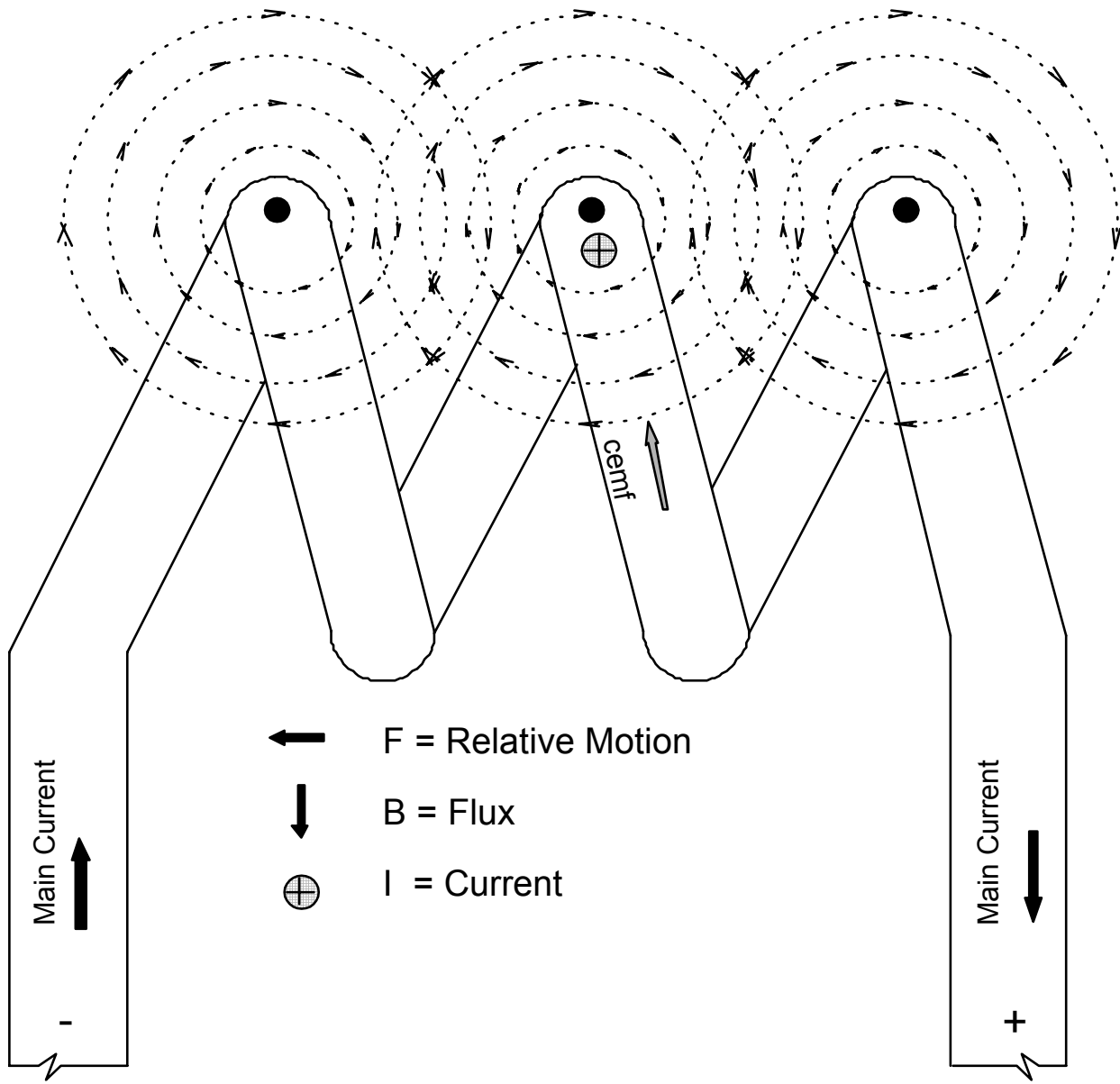
CHARACTERISTICS OF COILS

Physical Characteristics

A coil's inductance depends on how it is wound, the core material on which it is wound, and the number of turns of wire with which it is wound.

$$L = \mu_r \frac{N^2 A}{l}$$

1. Inductance (**L**) increases as the relative permeability μ_r of the core material increases.
2. Inductance increases as the square of the number of turns **N** of wire around the core increases.
3. Inductance increases as the area **A** enclosed by each turn increases. Since the area is a function of the square of the diameter of the coil, inductance increases as the square of the diameter.
4. Inductance decreases as the length **l** of the coil increases (assuming the number of turns remains the constant).



Reactance of a Coil

When an AC voltage is applied across a coil:

1. The AC voltage will produce an alternating current.
2. When a current flows in a conductor, magnetic flux lines are produced around the conductor.
3. Large currents produce many lines of flux and small currents produce only a few lines of flux.
4. As the current changes, the number of lines of flux will change. The magnetic field will expand and contract as the current increases and decreases.
5. As the magnetic field expands and contracts around one conductor, these lines of flux cut across the conductors which form the turns of the coil.
6. When a conductor cuts lines of magnetic flux, a voltage and current is induced in the conductor.
7. This induced voltage is in a direction so as to oppose the supply voltage and is called counter-emf (Cemf) or back-emf.
8. The overall effect of this Cemf is to reduce the voltage across the inductive component of the coil. The net effect of this Cemf is to oppose the change of current due to the alternating voltage. **This opposition to current flow causes the voltage to lead the current by 90°.**
9. In this sense, the Cemf is acting like a resistance in reducing the current.
10. Actually, it is extremely convenient to consider the current-reducing effect of this Cemf as a number of ohms of effective resistance. However, since a Cemf is not actually a resistance but merely **acts** as a resistance, we use the term **inductive reactance** to describe this effect. The inductive reactance of a coil is the number of ohms of resistance that the coil **seems** to offer as a result of a Cemf induced in it. Its symbol is X_L to differentiate it from the DC resistance r .

INDUCTIVE REACTANCE

Inductive reactance, X_L is the opposition to AC current due to the inductance in the circuit. The unit of inductive reactance is the ohm. The formula for inductive reactance is

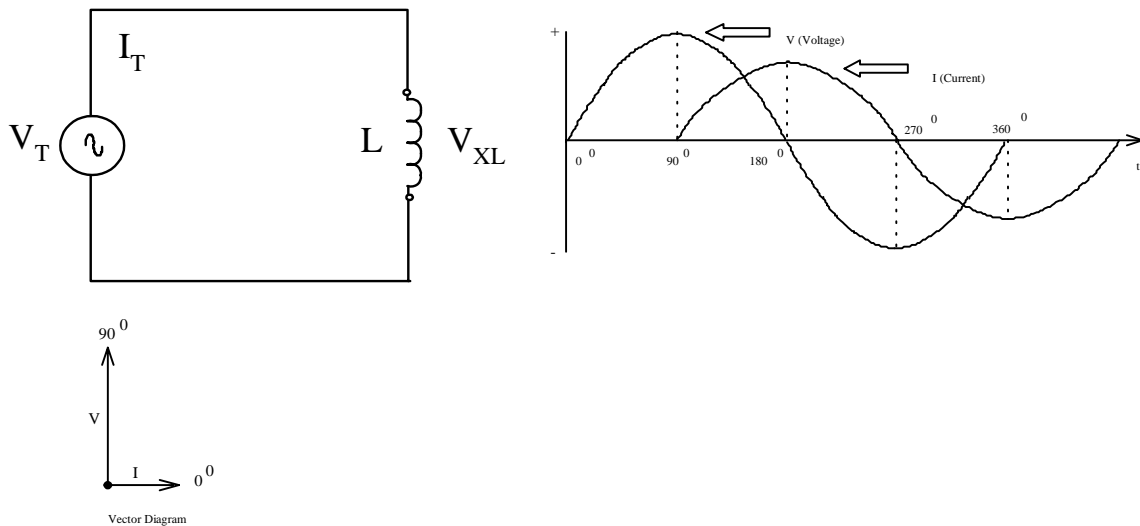
$$X_L = 2\pi fL$$

where $X_L =$ inductive reactance, measured in Ω

$f =$ frequency, measured in Hz

$L =$ inductance, measured in henrys(h)

In a circuit containing only inductance, Ohm's Law can be used to find current and voltage by substituting X_L for R . The circuit below would be considered a **purely inductive circuit in theory only**. This purely inductive circuit is used only to help us understand more about the out of phase relationship. In the circuit below the supply voltage leads the current by 90° due to the counter-emf caused by the pure inductor. This 90° phase angle (θ) is only theoretical since there is no actual **pure inductor**.



$$I_{X_L} = \frac{V_{X_L}}{X_L}$$

Since $V_{X_L} = V_T$ and $I_{X_L} = I_T$

$$\text{then } I_T = \frac{V_T}{X_L}$$

The equation above will only be true for a purely inductive circuit.

Inductive Reactance and Series *Internal* Resistance

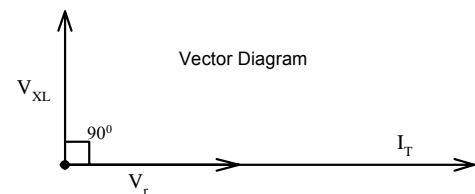
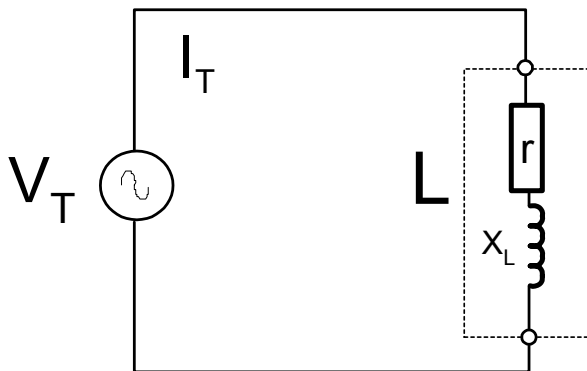
Because any practical inductor must be wound with wire that has **resistance**, it is **impossible** to obtain a coil without some internal DC resistance. The internal DC resistance associated with a coil, **L**, may be considered as a separate resistor, **r**, in series with the inductive reactance, **X_L**. This internal DC resistance would be the actual resistance of the coil if you connected an ohmmeter across its terminals.

For clarity and consistency, we will show the inductor (L) with an internal resistance (r) and an inductive reactance (X_L) inside a dotted line. This will show that the inductor is one device with two internal components in series as shown below.

Since the circuit below is a series circuit, the total current (**I_T**) is equal to the current through the internal resistance (**I_r**) and is equal to the current through the inductive reactance (**I_{XL}**). With this series internal resistance added, the *rms* current (**I_T**) is limited by both the inductive reactance (**X_L**) and the internal resistance (**r**). The current, **I_T** is the reference since it is common through **X_L** and **r** for a series circuit.

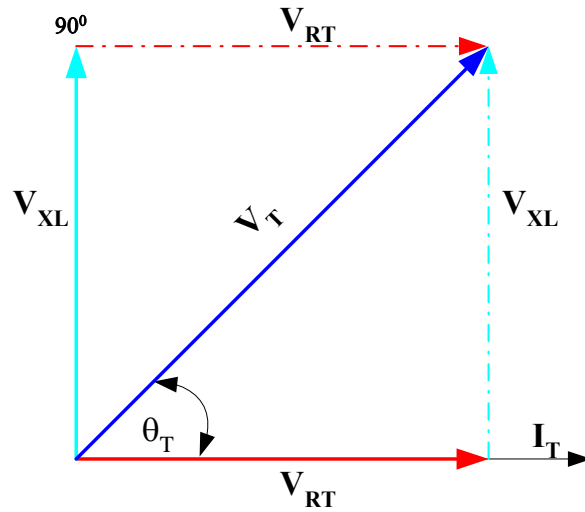
The voltage drop across **r** is **V_r = I_r × r**. The current **I_r** through **r** and its voltage drop happen at the same time and are in phase so the phase angle (**θ**) is 0°.

The voltage drop across **X_L** is **V_{XL} = I_{XL} × X_L**. The voltage across **X_L** leads the current through **X_L** by 90° and they do not happen at the same time. This is the phase angle (**θ**) between the current through the inductive reactance and the self-induced voltage caused by the inductive reactance.



Since Ohm's Law applies to V_r and V_{XL} , then V_T should be the sum of the two. However, the voltage drops don't happen at the same time and are not **in phase** with each other. Therefore they can not be added directly. Their sums must be added **vectorially**. This can be done graphically by using a vector diagram and projecting the vectors to an intersection point or coordinate. Then the resultant vector can be drawn from the origin to this coordinate. The resultant vector V_T is the vector sum of V_r and V_{XL} .

This **voltage relationship or triangle** can also be expressed from the geometry of a right triangle using the **Pythagorean Theorem** which states, *the hypotenuse is equal to the square root of the sum of the squares of*



Voltage Vector Diagram

the other two sides.

$$V_T = \sqrt{V_r^2 + V_{XL}^2}$$

The phase angle (θ) can also be calculated by trigonometric functions.

$$\sin \angle \phi = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{V_{XL}}{V_T}$$

$$\cos \angle \phi = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{V_r}{V_T}$$

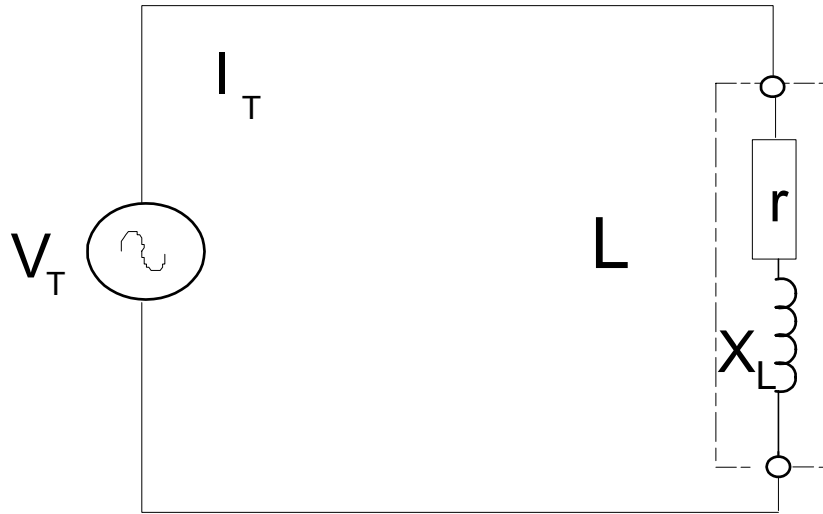
$$\tan \angle \phi = \frac{\text{opposite}}{\text{adjacent}} = \frac{V_{XL}}{V_r}$$

Example:

Given: $V_T = 120$ Volts
 $I_T = 595.367$ mAmps
 $X_L = 200 \Omega$
 $r = 25 \Omega$

Solve for: $V_r =$
 $V_{XL} =$
 $\theta_T =$

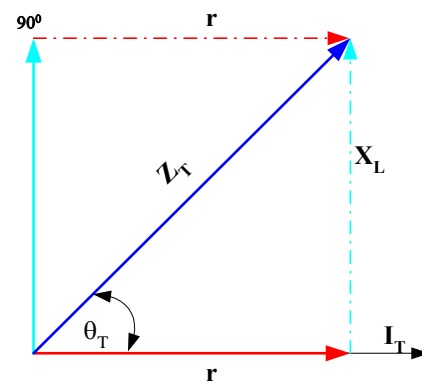
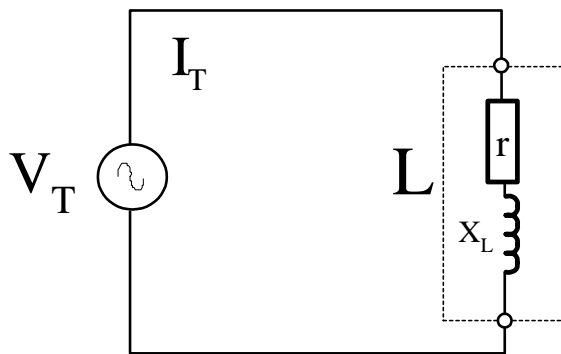
Draw the voltage vector diagram.



IMPEDANCE

The total opposition to current flow in a purely resistive AC series circuit is the resistance (**R**). In a purely inductive AC series circuit the total opposition to current flow is the inductive reactance (**X_L**). In an AC series circuit containing both resistance and inductive reactance, the total opposition to current flow is called **impedance (Z)**.

Just as with the voltage relationship, the current (**I**) is the reference since it is a series circuit and is common to both components. The internal resistance will be drawn at 0° with reference to the series current. This is due to the current through it and the voltage across it being in phase with each other. The inductive reactance, however, is drawn at 90° with reference to the series current because the voltage across it is out of phase with the current through it. The total impedance (**Z_T**) for this circuit is the vector sum of the internal resistance (**r**) and the inductive reactance (**X_L**) of the coil. . The internal resistance (**r**) is the total resistance in the circuit above. Later we will see how the addition of external resistance (**R**) affects the circuit.



Impedance Vector Diagram

This **impedance relationship or triangle** can also be expressed from the geometry of a right triangle using the **Pythagorean Theorem** which states, *the hypotenuse is equal to the square root of the sum of the squares of the other two sides*

$$Z_T = \sqrt{r^2 + X_L^2}$$

The phase angle (θ) can also be calculated by trigonometric functions. It also should be noted that this phase angle (θ) is the same as the phase angle (θ) for the voltage relationship.

$$\sin \angle \phi = \frac{\textit{opposite}}{\textit{hypotenuse}} = \frac{X_L}{Z_T}$$

$$\cos \angle \phi = \frac{\textit{adjacent}}{\textit{hypotenuse}} = \frac{R_T}{Z_T}$$

$$\tan \angle \phi = \frac{\textit{opposite}}{\textit{adjacent}} = \frac{X_L}{R_T}$$

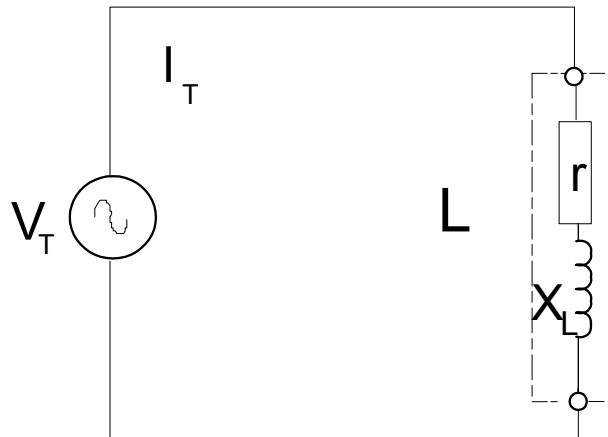
Example:

Given: $V_T = 110$ Volts
 $L = 40$ mh
 $r = 30 \Omega$
 $f = 60$ Hz

Solve for: $I_T =$
 $Z_T =$
 $\theta_T =$

Draw the impedance vector diagram.

Solve the circuit parameters now if $f = 120$ Hz.



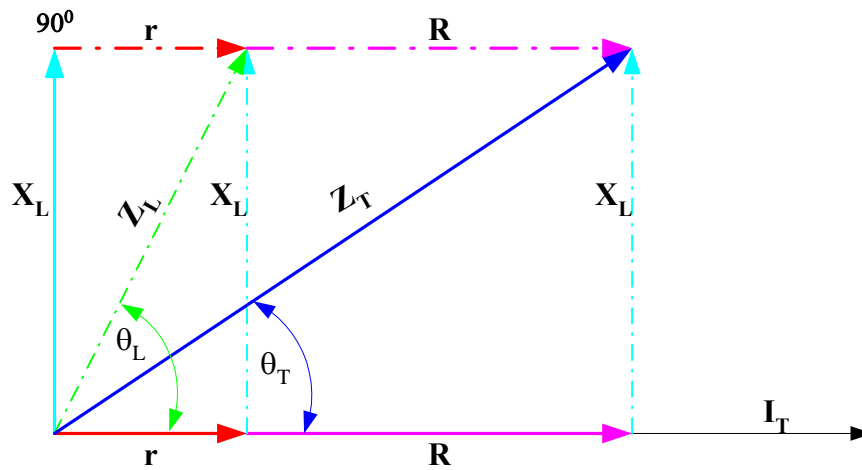
RL - RESISTIVE INDUCTIVE CIRCUITS

In most AC circuit applications, there would be more resistance in the circuit than just the internal DC resistance (r) of the coil. This external resistance is sometimes shown as only one resistor that includes the internal resistance. For our applications, we will show these two resistances as two separate resistors. The total resistance in the circuit is equal to the sum of all resistances in the circuit.

$$R_T = r + R_1 + R_2 + R_3 \dots$$

For the circuit below, there is a series resistance (R) added to the circuit. The inductor (L) still has internal resistance (r) and inductive reactance (X_L). The impedance (Z_L not Z_{Total}) and phase angle (θ_L not θ_{Total}) of the inductor or coil would be the same as discussed before and is illustrated with the dotted vector and angle. The external resistance (R) is added to the x-axis along with the internal resistance (r). These two resistances would equal R_T and could be represented as one vector. Once the external resistance has been added to the x-axis, the phase angle (θ_{Total}) and the impedance vector for the total impedance in the circuit (Z_{Total}) will change. The inductive reactance (X_L) has not changed in the circuit.

Vector Diagram

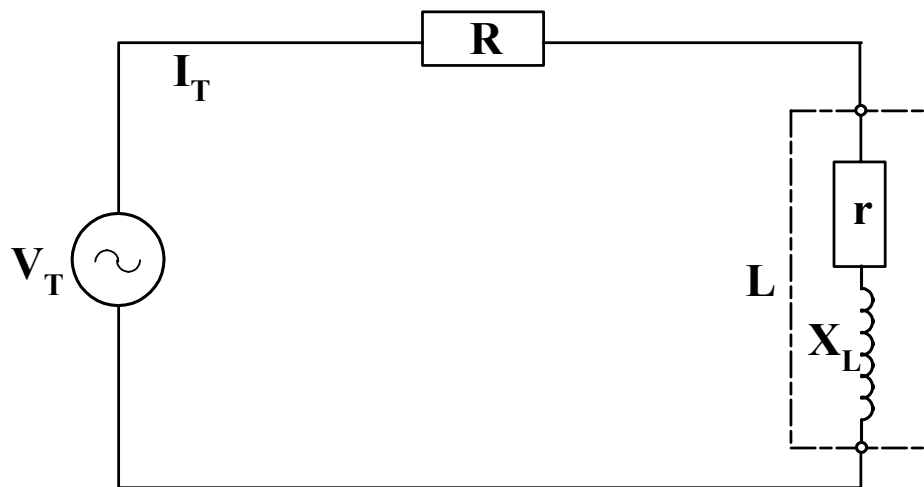


Example:

Given: $V_T = 110$ Volts
 $L = 100$ mh
 $r = 10 \Omega$
 $R = 30 \Omega$
 $f = 60$ Hz

Solve for: $I_T =$
 $Z_L =$
 $Z_T =$
 $\theta_T =$

Draw the voltage and impedance vector diagrams.



POWER IN RL CIRCUITS

Real Power

In an AC circuit with inductive reactance, the applied voltage leads the line current. The real power, **P**, is equal to the voltage multiplied by only that portion of the line current that is in phase with the voltage. The current and voltage are only in phase for the resistive components. The inductive or reactive components are always out of phase. Real Power is measured in **Watts** and is equal to:

$$P_{Real} = V_T \bullet I_T \bullet \cos \theta$$

The **cos θ** is equal to the **power factor** of the circuit and is sometimes represented by **PF**.

$$PF = \cos \theta$$

The real power can also be expressed using current and resistance. However, **all resistances in the circuit must be taken into account**.

$$P_{Real} = I_T^2 \bullet R_T$$

Reactive Power

Reactive power in an AC circuit is the product of voltage and the out-of-phase current. It represents the stored energy due to the expansion of the magnetic field. The reactive power, **Q**, is measured in volt-amperes reactive (**VARs**) and is equal to:

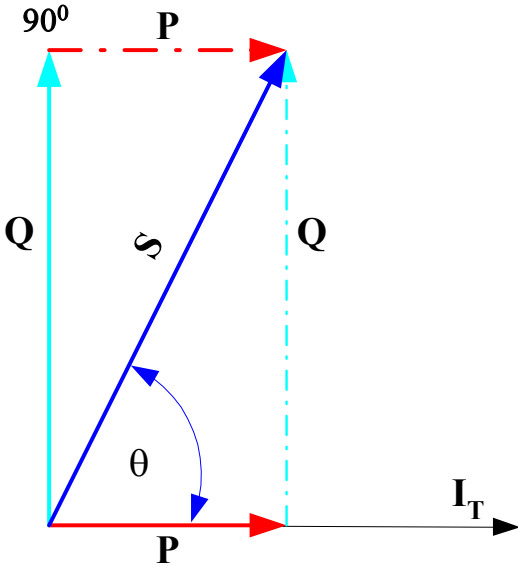
$$Q_{Reactive} = V_T \bullet I_T \bullet \sin \theta$$

Apparent Power

Apparent power in an AC circuit is the product of the rms voltage and rms current. It is the vector sum of real and reactive power. The apparent power, **S**, is measured in volt amperes (**VA**) and is equal to:

$$S_{Apparent} = V_T \bullet I_T$$

In all power formulas, the V and I are rms values. The power vector diagram can illustrate the relationships of real, reactive, and apparent power.

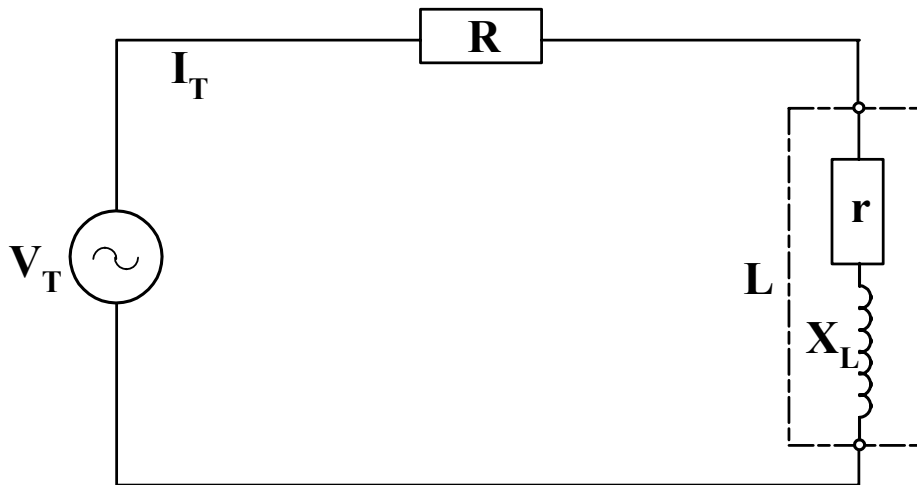


Example:

Given: $V_L = 230$ Volts
 $L = 600$ mh
 $r = 30 \Omega$
 $R = 60 \Omega$
 $f = 60$ Hz

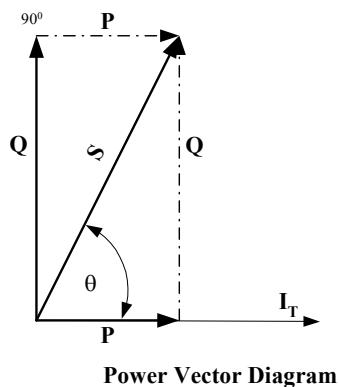
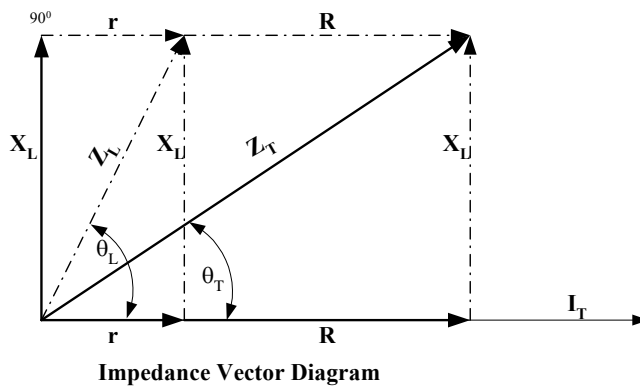
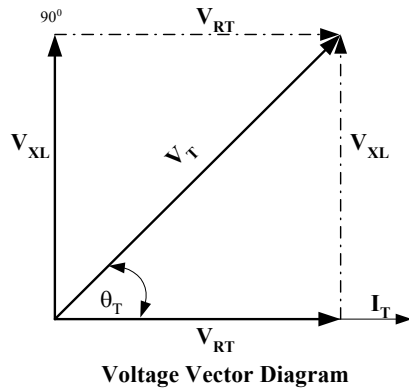
Solve for: $P =$
 $Q =$
 $S =$

Draw the power vector diagram.



Summary of Voltage, Impedance, and Power in AC

In the three vector relationships discussed in this section, the circuit current was always the common factor. The triangles formed by these relationships are similar. The phase angles (θ) of the three triangles are equal even though the magnitudes of the sides are different.



DEFINITIONS

INDUCTOR (L)	-	A device that opposes the change in current
INDUCTANCE (L)	-	The characteristic of an electrical conductor which opposes a CHANGE in current flow The measure of a coils ability to oppose a change in current, measured in henrys
INDUCTIVE REACTANCE (X_L)	-	The opposition to the flow of alternating current caused by the inductance of a circuit, measured in ohms.
IMPEDANCE (Z)	-	The total opposition to current flow in an AC circuit. It is the vector sum of resistance and reactance, measured in ohms.
HENRY (h)	-	The unit of measure for inductance
REAL POWER (P)	-	Equal to the voltage multiplied by only that portion of the line current which is in phase with the voltage, measured in watts .
REACTIVE POWER (Q)	-	The product of voltage and the out-of-phase current. It represents the stored energy due to the expansion of the magnetic field, measured in VARs .
APPARENT POWER (S)	-	The product of the rms voltage and rms current. It is the vector sum of real and reactive power, measured in VA .
POWER FACTOR (PF)	-	The ratio of total watts to the total rms volt-amperes. PF = $\cos \theta$



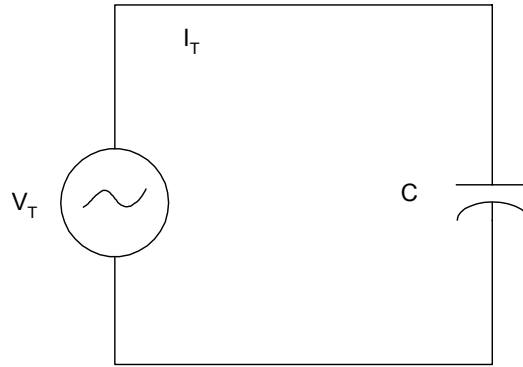
CAPACITANCE IN A.C.

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CAPACITANCE

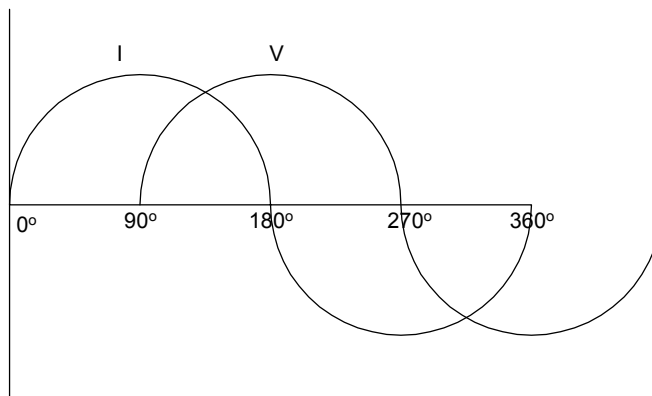


Electrically, *capacitance* is the ability to store an electric charge. In the DC section, we learned that capacitance is equal to the amount of charge that can be stored in a capacitor divided by the voltage applied across the plates.

$$C = \frac{Q}{V}$$

Where C = capacitance in Farads
 Q = amount of charge in Coulombs
 V = voltage in Volts

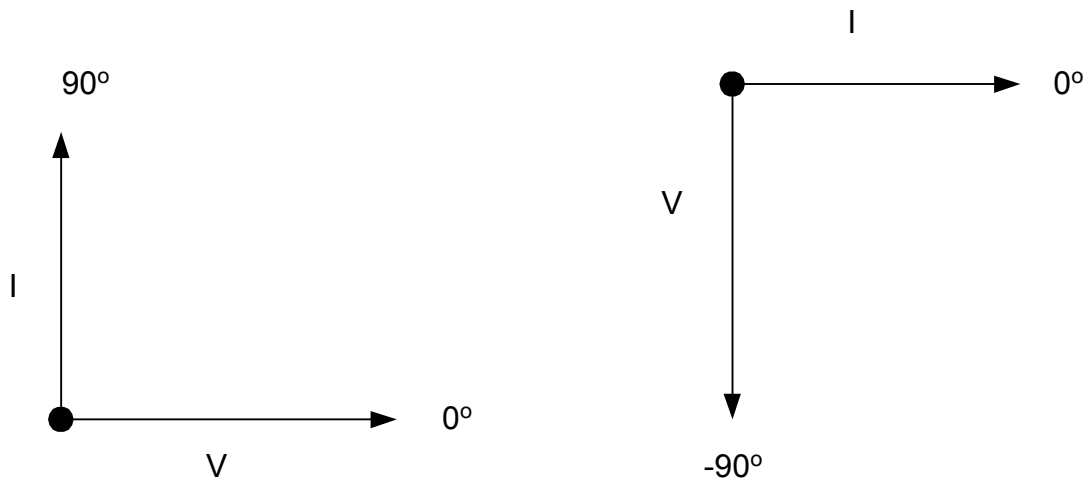
A capacitor that is initially uncharged tends to draw a large current when a DC voltage is first applied. During the charging period, the capacitor voltage rises. After the capacitor has received sufficient charge the capacitor voltage equals the applied voltage and the current flow ceases. After the capacitor has charged, it looks like an open circuit in a DC circuit. This is not the case in AC. If an AC voltage is applied to a pure capacitor, the current is at maximum when the voltage begins to rise from zero, and the current is zero when the voltage across the capacitor is at maximum. **The current leads the applied voltage by 90°**, as indicated with the waveform below.



The voltage and current relationships are shown below in vector diagram form. Vector diagram A shows the current leading the voltage by 90° in the 1st quadrant with the voltage vector at 0°. Vector diagram B shows the current leading the voltage by 90° in the 4th quadrant with the current at 0°. Since we will be dealing with series circuits only, vector diagram B will be most useful. Note that the voltage vector is downward, exactly opposite from an inductive circuit, because of the opposite phase angle.

Factors That Control Charging Current

Because a capacitor of large capacitance can store more energy than one of small capacitance, a larger current must flow to charge a large capacitor than to charge a small one, assuming the same time interval in both cases. Also, because the current flow depends on the rate of charge and discharge, the higher the frequency, the greater is the current flow per unit time.



The charging current in **purely** capacitive circuits varies directly with the capacitance, voltage, and frequency.

$$I = 2\pi fCV$$

Where I is effective current in amperes, f is frequency in hertz, C is the capacitance in farads, and V is the effective voltage in volts.

CAPACITIVE REACTANCE

The ratio of the effective voltage across the capacitor to the effective current is called the **Capacitive Reactance, X_C** .

$$X_C = \frac{V_{RMS}}{I_{RMS}}$$

Capacitive Reactance, X_C represents the opposition to current flow in a purely capacitive circuit, measured in ohms. Using the formula on the previous page, let's substitute X_C .

$$I = 2\pi fCV$$

$$\frac{I}{V} = 2\pi fC$$

$$\frac{V}{I} = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{2\pi fC}$$

When f is in hertz, and C is in farads, then X_C is in ohms.

Example: What is the capacitive reactance of a capacitor operating at a frequency of 60 Hz and having a capacitance of 133 μF .

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{2 \bullet \pi \bullet 60\text{Hz} \bullet 133 \times 10^{-6} F}$$

$$X_C = 19.944\Omega$$

Voltage and current in a circuit containing only capacitive reactance can be found using Ohm's Law. However, in the case of a capacitive circuit, R is replaced by X_C .

$$V_{X_C} = I_{X_C} X_C$$

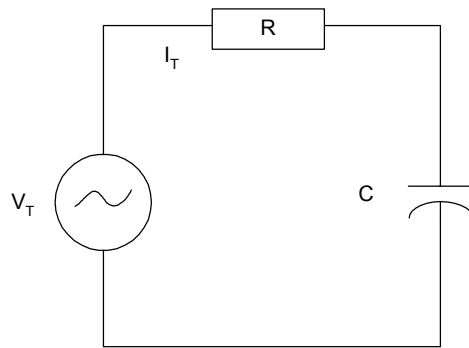
$$I_{X_C} = \frac{V_{X_C}}{X_C}$$

$$X_C = \frac{V_{X_C}}{I_{X_C}}$$

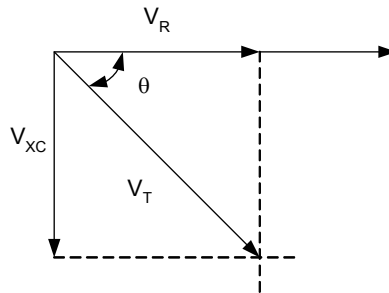
Where:

- I_{X_C} = the current through the capacitor, Amps
- V_{X_C} = the voltage across the capacitor, Volts
- X_C = capacitive reactance, Ohms

RC – RESISTIVE CAPACITIVE CIRCUITS IN SERIES



As with inductive circuits, the combination of resistance and capacitive reactance is called **impedance**. In a series circuit containing R and X_C , the same current I_T flows in X_C and R . The voltage drop across R is $V_R = I_T R_T$, and the voltage drop across X_C is $V_{X_C} = I_T X_C$. The current through X_C leads the voltage across X_C by 90° . The current through R_T is in phase with the voltage across R_T since resistance does not produce a phase shift. To find the total voltage V_T , we add the vectors V_R and V_{X_C} since they form a right triangle.



This voltage relationship or triangle can be expressed from the geometry of a right triangle using the Pythagorean Theorem which states, *the hypotenuse is equal to the square root of the sum of the squares of the other two sides.*

$$V_T = \sqrt{V_R^2 + V_{X_C}^2}$$

The phase angle (θ) can also be calculated by trigonometric functions.

$$\sin \angle \theta = \frac{\textit{opposite}}{\textit{hypotenuse}} = \frac{V_{X_C}}{V_T}$$

$$\cos \angle \theta = \frac{\textit{adjacent}}{\textit{hypotenuse}} = \frac{V_R}{V_T}$$

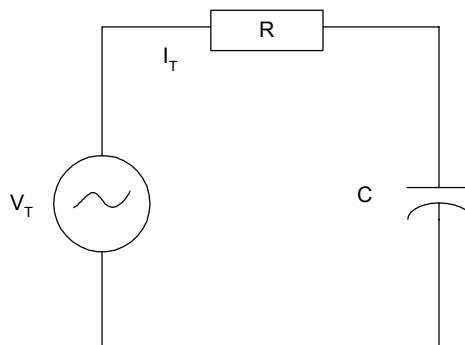
$$\tan \angle \theta = \frac{\textit{opposite}}{\textit{adjacent}} = \frac{V_{X_C}}{V_R}$$

EXAMPLE:

Given: $I_T = 1 \text{ Amp}$
 $X_C = 120\Omega$
 $R = 50\Omega$

Solve for: $V_R =$
 $V_{XC} =$
 $V_T =$
 $\theta =$

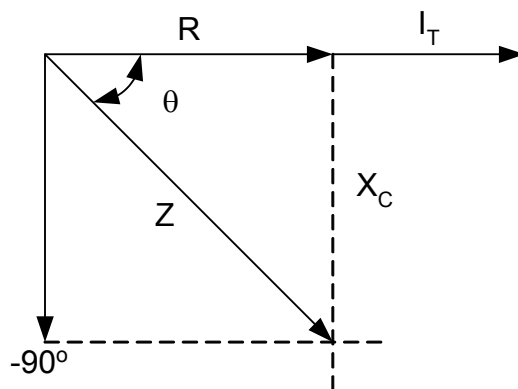
Draw the voltage vector diagram



IMPEDANCE IN SERIES RC CIRCUITS

The total opposition to current flow in a purely resistive AC series circuit is the resistance (**R**). In a purely capacitive AC series circuit the total opposition to current flow is the capacitive reactance (**X_C**). In an AC series circuit containing both resistance and capacitive reactance, the total opposition to current flow is called **impedance (Z)**.

Just as with the voltage relationship, the current (**I**) is the reference since it is a series circuit and is common to both components. The resistance will be drawn at 0° with reference to the series current. This is due to the current through it and the voltage across it being in phase with each other. The capacitive reactance, however, is drawn at -90° with reference to the series current because the current through it is out of phase with the voltage across it.



This **impedance relationship or triangle** can also be expressed from the geometry of a right triangle using the **Pythagorean Theorem** which states, *the hypotenuse is equal to the square root of the sum of the squares of the other two sides*. R_T is the total combination of the resistance (**R**) in the circuit.

$$Z_T = \sqrt{R_T^2 + X_C^2}$$

The phase angle (**θ**) can also be calculated by trigonometric functions. It also should be noted that this phase angle (**θ**) is the same as the phase angle (**θ**) for the voltage relationship.

$$\sin \angle \theta = \frac{\textit{opposite}}{\textit{hypotenuse}} = \frac{X_C}{Z_T}$$

$$\cos \angle \theta = \frac{\textit{adjacent}}{\textit{hypotenuse}} = \frac{R_T}{Z_T}$$

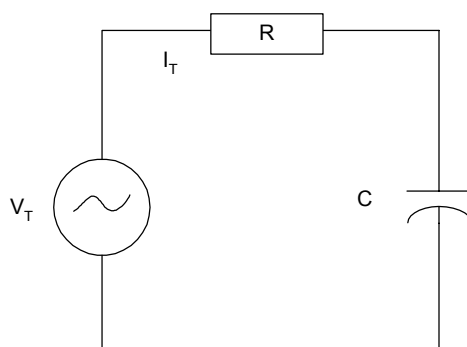
$$\tan \angle \theta = \frac{\textit{opposite}}{\textit{adjacent}} = \frac{X_C}{R_T}$$

EXAMPLE:

Given: $V_T = 120$ Volts
 $C = 50 \mu\text{F}$
 $R = 100 \Omega$
 $f = 60$ Hz

Solve for: $I_T =$
 $Z_T =$
 $X_C =$
 $\theta =$

Draw the voltage and impedance vector diagram



POWER IN AC CIRCUITS

Real Power

In an AC circuit with capacitive reactance, the line current leads the applied voltage. The real power, **P**, is equal to the voltage multiplied by only that portion of the line current that is in phase with the voltage. The current and voltage are only in phase for the resistive components. The capacitive or reactive components are always out of phase. **Real Power** is measured in **Watts** and is equal to:

$$P_{REAL} = V_T \cdot I_T \cdot \cos \theta$$

The $\cos \theta$ is equal to the **power factor** of the circuit and is sometimes represented by **PF**.

$$PF = \cos \theta$$

The real power can also be expressed using current and resistance. However, all resistances (R_T) in the circuit must be taken into account.

$$P_{REAL} = I_T^2 \cdot R_T$$

Reactive Power

Reactive power in an AC circuit is the product of voltage and the out-of-phase current. It represents the stored energy due to the charging and discharging of the capacitor. The Reactive Power, Q, is measured in volt-amperes reactive (VARs) and is equal to:

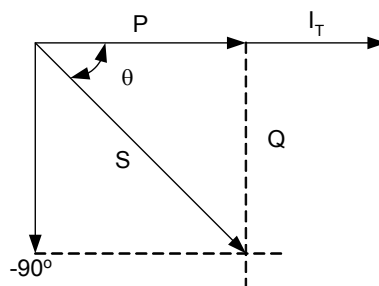
$$Q_{Reactive} = V_T \cdot I_T \cdot \sin \theta$$

Apparent Power

Apparent power in an AC circuit is the product of the rms voltage and rms current. It is the vector sum of real and reactive power. The apparent power, S, is measured in volt amperes (VA) and is equal to:

$$S_{Apparent} = V_T \cdot I_T$$

In all power formulas, the V and I are rms values. The relationships of real, reactive, and apparent power can be illustrated by the power vector diagram.

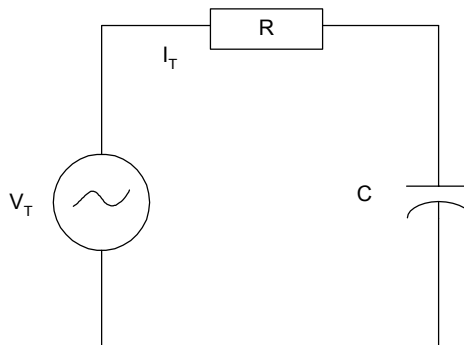


EXAMPLE:

Given: $V_T = 120$ Volts
 $X_C = 40 \Omega$
 $R = 30 \Omega$
 $f = 60$ Hz

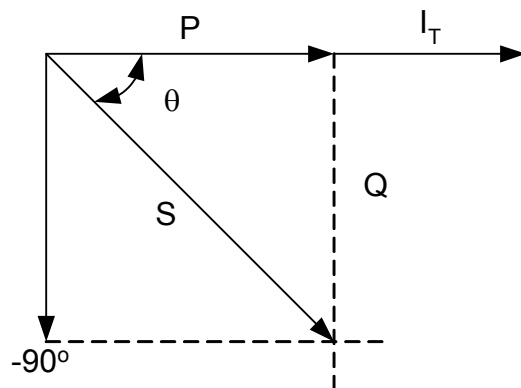
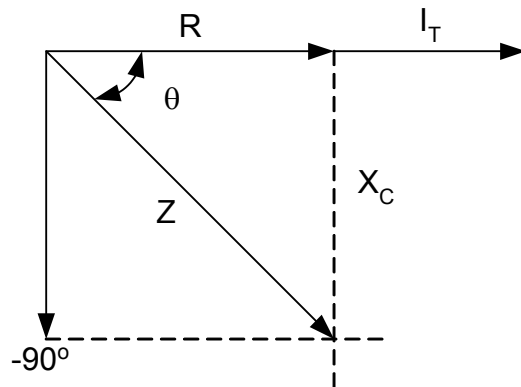
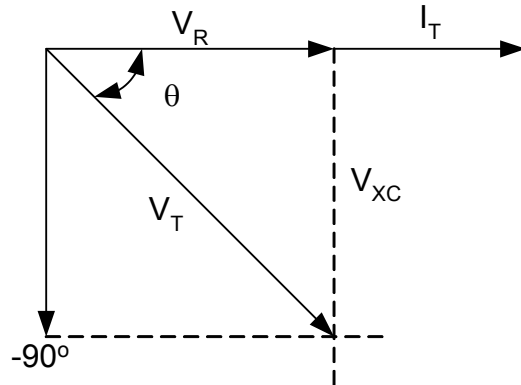
Solve for: $P =$
 $Q =$
 $S =$

Draw the Power vector diagram



Summary of Voltage, Impedance, and Power in AC

In the three vector relationships discussed in this section, the circuit current was always the common factor. The triangles formed by these relationships are similar. The phase angles (θ) of the three triangles are equal even though the magnitudes of the sides are different.



DEFINITIONS

- CAPACITOR (C)** - A device which stores an electric charge.
- CAPACITANCE (C)** - The ability of a device or circuit to store an electric charge.
- CAPACITIVE REACTANCE (X_C)** - The opposition to the flow of alternating current caused by the capacitance of a circuit, measured in ohms.
- IMPEDANCE (Z)** - The total opposition to current flow in an AC circuit. It is the **vector sum** of resistance and reactance, measured in ohms.
- FARAD (F)** - The unit of measure for capacitance.
- REAL POWER (P)** - Equal to the voltage multiplied by only that portion of the line current which is in phase with the voltage, measured in **watts**.
- REACTIVE POWER (Q)** - The product of voltage and the out-of-phase current. It represents the stored energy due to the charging and discharging of the capacitor, measured in **VARs**.
- APPARENT POWER (S)** - The product of the rms voltage and rms current. It is the vector sum of real and reactive power, measured in **VA**.
- POWER FACTOR (PF)** - The ratio of total watts to the total rms volt-amperes. **PF = $\cos \theta$**



SINGLE PHASE TRANSFORMERS

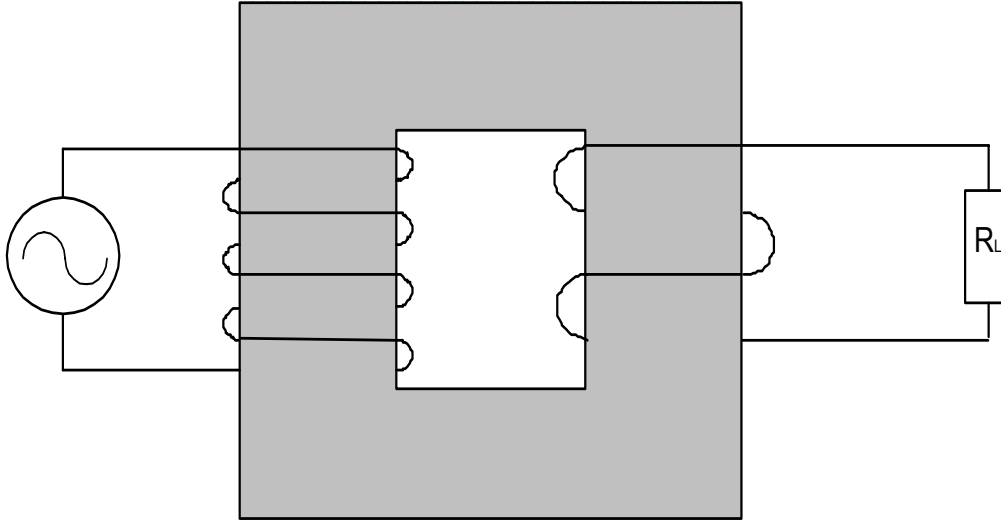
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IDEAL TRANSFORMER CHARACTERISTICS

The basic transformer consists of two coils electrically insulated from each other and wound upon a common core. Magnetic coupling is used to transfer electric energy from one coil to another. The coil, which receives energy from the AC source, is called the **primary**. The coil, which delivers energy to the AC load, is called the **secondary**. The core of transformers used at low frequencies is generally made of magnetic material, usually sheet steel. Cores of transformers used at higher frequencies are made of powdered iron and ceramics, or nonmagnetic materials. Some coils are simply wound on nonmagnetic hollow forms such as cardboard or plastic so that the core material is actually air.



If a transformer is assumed to be operating under an ideal or perfect condition, the transfer of energy from one voltage to another is accompanied by **no losses**.

VOLTAGE RELATIONSHIP

The voltage (**V**) on the coils of a transformer is directly proportional to the number (**N**) of turns on the coils. This voltage relationship is expressed by the formula:

$$\frac{V_{pri}}{V_{sec}} = \frac{N_{pri}}{N_{sec}}$$

where

- V_{pri} = voltage on primary coil, **V**
- V_{sec} = voltage on secondary coil, **V**
- N_{pri} = number of turns on primary coil
- N_{sec} = number of turns on secondary coil

Step-up and Step-down transformers

A voltage ratio of 1:4 (read as 1 to 4) means that for each volt on the transformer primary, there is 4 volts on the secondary. When the secondary voltage is greater than the primary voltage, the transformer is a **step-up** transformer. A voltage ratio of 4:1 means that for every 4 volts on the primary, there is only 1 volt on the secondary. When the secondary voltage is less than the primary voltage, the transformer is called a **step-down** transformer. The voltage relationship discussed previously will apply to both step-up and step-down transformers.

CURRENT RELATIONSHIP

The current (**I**) in the coils of a transformer is inversely proportional to the voltage (**V**) on the coils. This current relationship is expressed by the formula:

$$\frac{V_{pri}}{V_{sec}} = \frac{I_{sec}}{I_{pri}}$$

Where
V_{pri} = voltage on primary coil, **V**
V_{sec} = voltage on secondary coil, **V**
I_{pri} = current in the primary coil, **A**
I_{sec} = current in the secondary coil, **A**

EFFICIENCY

The efficiency of a transformer is equal to the ratio of the power output of the secondary winding to power input of the primary winding. An ideal transformer is 100% efficient because it delivers all the energy it receives. Because of core and copper losses, the efficiency of even the best practical transformer is less than 100%. Efficiency expressed as an equation is:

$$Eff = \frac{\text{output power}}{\text{input power}} = \frac{P_{sec}}{P_{pri}}$$

Where
Eff = efficiency
P_{sec} = power output from the secondary coil, **W**
P_{pri} = power input to the primary coil, **W**

TRANSFORMER RATINGS

Transformer capacity is rated in kilo-volt-amperes (**KVA**). This transformer rating is sometimes represented by the letter **S**. Since power in an AC circuit depends on the power factor of the load and the current in the load, an output rating in kilowatts must specify the power factor.

For an ideal transformer we would assume efficiency to be 100%. Since our calculations will deal with ideal transformers, we can state the following relationships:

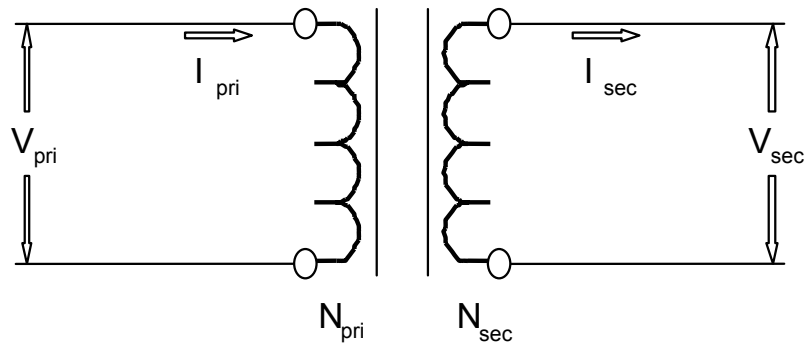
$$VA_{pri} = V_{pri} \bullet I_{pri}$$

$$VA_{sec} = V_{sec} \bullet I_{sec}$$

$$VA_{pri} = VA_{sec}$$

Where

- VA_{pri} = power input to the primary coil, **VA**
- VA_{sec} = power output from the secondary coil, **VA**
- V_{pri} = primary voltage
- I_{pri} = primary current
- V_{sec} = secondary voltage
- I_{sec} = secondary current



EXERCISES

1. Given: $N_{\text{pri}} = 1500$ turns
 $N_{\text{sec}} = 1000$ turns
 $V_{\text{pri}} = 100$ V

Find: $V_{\text{sec}} =$

2. Given: $N_{\text{pri}} = 4000$ turns
 $N_{\text{sec}} = 400$ turns
 $I_{\text{sec}} = 6$ A

Find: $I_{\text{pri}} =$
 What is the turn's ratio?

3. Given: $V_{\text{pri}} = 300$ V
 $V_{\text{sec}} = 24$ V
 $I_{\text{sec}} = 1$ A
 $N_{\text{pri}} = 1000$ turns

Find: $N_{\text{sec}} =$
 $I_{\text{pri}} =$

4. Given: $VA_{\text{pri}} = 100$
 $V_{\text{pri}} = 460$ V
 $V_{\text{sec}} = 110$ V

Find: $I_{\text{pri}} =$
 $I_{\text{sec}} =$



THREE PHASE SYSTEMS

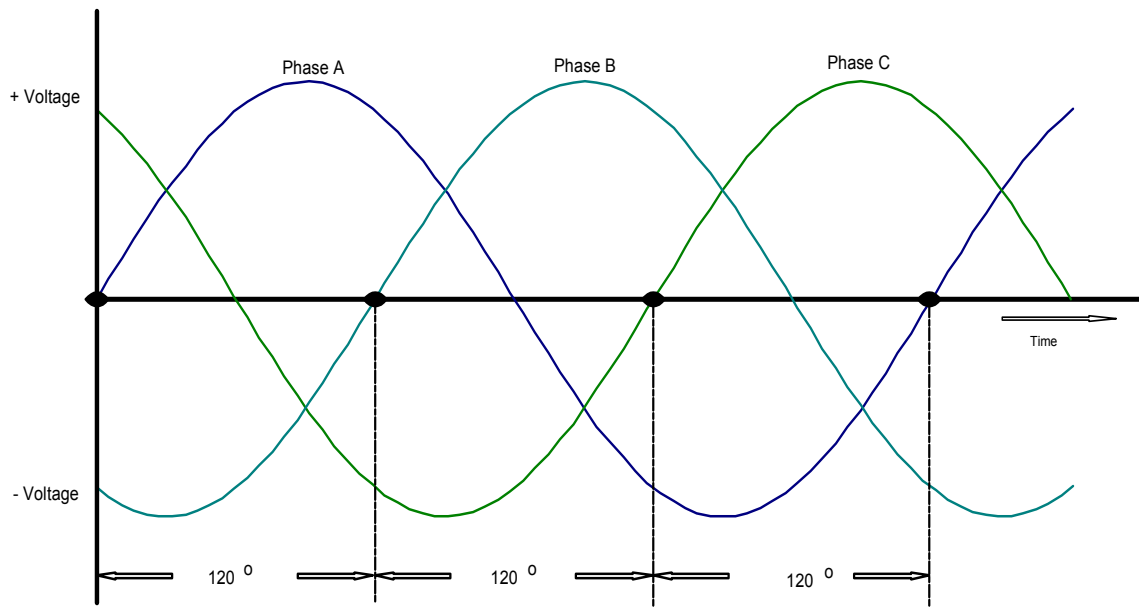
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CHARACTERISTICS OF THREE PHASE SYSTEMS

A three phase (3 ϕ) system is a combination of three single phase (1 ϕ) systems. In a 3 ϕ balanced system, the power comes from an AC generator that produces three separate but equal voltages, each of which is out of phase with the other voltages by 120°(illustrated below). When any of the three voltages is at its maximum value (negative or positive), each of the other two voltages will be at 50 percent of their maximum value in the opposite direction. Although 1 ϕ circuits are widely used in electrical systems, most generation and distribution of alternating current is 3 ϕ



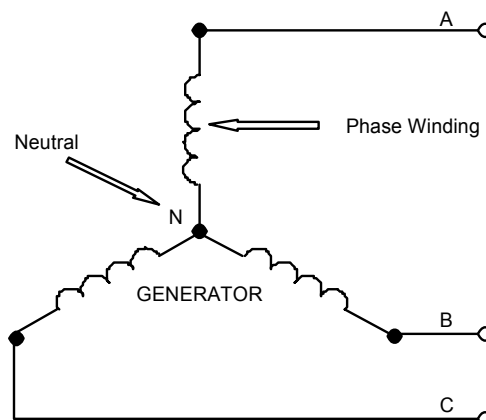
- | | | |
|--|---|--|
| Single Phase System | - | System energized by a single alternating voltage. |
| Poly Phase System | - | System energized by two, three or more alternating voltages. |
| Three Phase System | - | System energized by three equal alternating voltages 120° apart. |
| Line Voltage (V_L) | - | The voltage measured between terminals of an alternator, motor or branch circuit feeder wires. |
| Phase | - | Each winding of an alternator, of a motor, or of a branch circuit forming part of a load. |
| Phase Voltage (V_{ph}) | - | The voltage measured across a phase of an alternator, motor or load. |

Advantages of 3 ϕ versus 1 ϕ

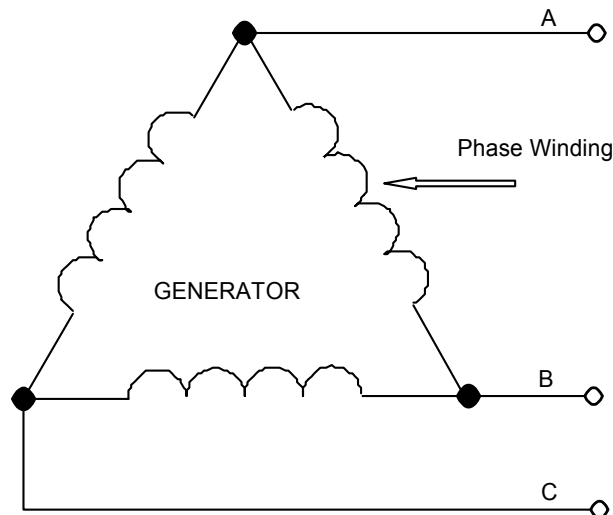
- 3 ϕ circuits require **less weight of conductors** than 1 ϕ circuits of the same power rating.
- 3 ϕ circuits permit flexibility in the **choice of voltages**.
- 3 ϕ circuits can be used for 1 ϕ loads.
- 3 ϕ equipment is **smaller in size, lighter in weight, and more efficient** than 1 ϕ machinery of the same rated capacity.

The three phases of a 3 ϕ system may be connected in two ways.

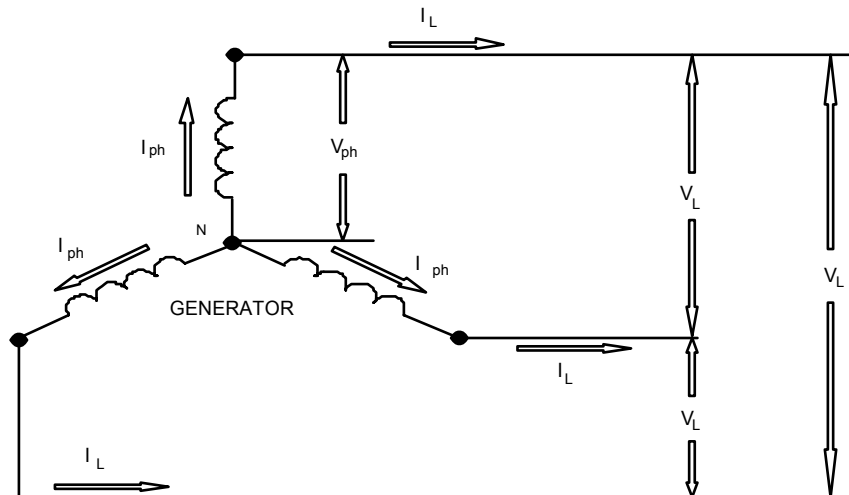
1. If the three common ends of each phase are connected together at a common terminal marked N for neutral, and the other three ends are connected to the 3 ϕ line, the system is *Wye* or *Y-connected*. This configuration can be related as being connected in series. Sometimes the neutral connection is brought out to form a 3 ϕ , 4-wire system.



2. If the three phase connected. This configuration can be related as being connected in parallel.



THREE PHASE RELATIONSHIPS



Voltage Relationship in a Wye Configuration - Since the line voltage is connected across two windings and the phase voltage is only connected across one winding, the line voltage (V_L) is much larger than the phase voltage (V_{ph}). At first, you would think that the line voltage is twice as large as the phase voltage, this is not the case. The actual relationship is as follows:

$$V_L = \sqrt{3} \cdot V_{ph}$$

$$\text{or } V_{ph} = \frac{V_L}{\sqrt{3}}$$

Current Relationship in a Wye Configuration - **Since the line current does not split as it enters the phase winding, the line current (I_L) is equal to the phase current (I_{ph}).** The relationship is as follows:

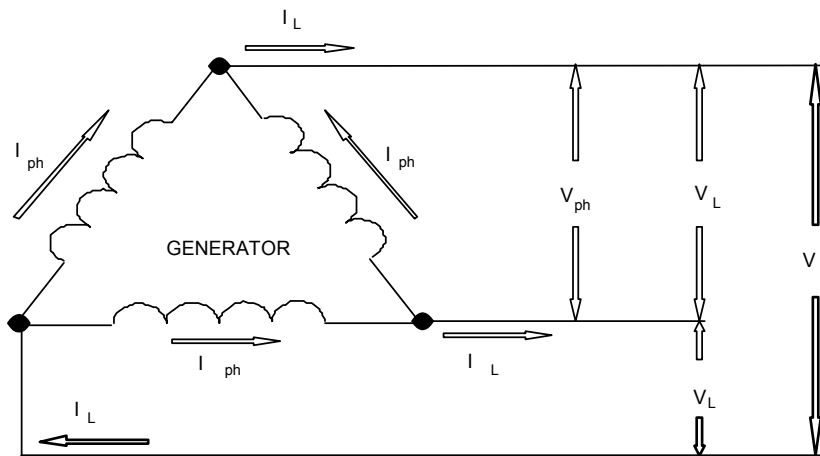
$$I_L = I_{ph}$$

Power Relationship in a Wye Configuration - As discussed in AC concepts, there are three different power relationships for AC circuits. **Real, reactive and apparent power** still applies for three phase circuits. There are some minor differences as shown with the relationships below:

$$P_{Real} = \sqrt{3} \cdot V_L \cdot I_L \cdot \cos \theta$$

$$Q_{Reactive} = \sqrt{3} \cdot V_L \cdot I_L \cdot \sin \theta$$

$$S_{Apparent} = \sqrt{3} \cdot V_L \cdot I_L$$



Voltage Relationship in a Delta Configuration - Since the line voltage is connected across one winding just as is the phase voltage, the line voltage (V_L) is equal to the phase voltage (V_{ph}). The actual relationship is as follows:

$$V_L = V_{ph}$$

Current Relationship in a Delta Configuration - Since the line current is a combination of current from two windings and the phase current only comes from one winding, the line current (I_L) is much larger than the phase current (I_{ph}). At first, you would think that the line current is twice as large as the phase current, this is not the case. The actual relationship is as follows:

$$I_L = \sqrt{3} \cdot I_{ph}$$

$$\text{or } I_{ph} = \frac{I_L}{\sqrt{3}}$$

Power Relationship in a Delta Configuration - As discussed in AC concepts, there are three different power relationships for AC circuits. Real, reactive and apparent power still applies for three phase circuits. There are some minor differences as shown with the relationships below:

$$P_{Real} = \sqrt{3} \cdot V_L \cdot I_L \cdot \cos \theta$$

$$Q_{Reactive} = \sqrt{3} \cdot V_L \cdot I_L \cdot \sin \theta$$

$$S_{Apparent} = \sqrt{3} \cdot V_L \cdot I_L$$

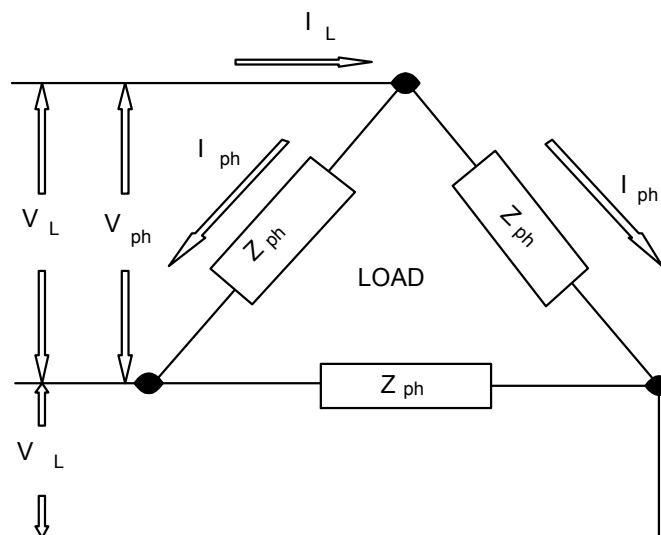
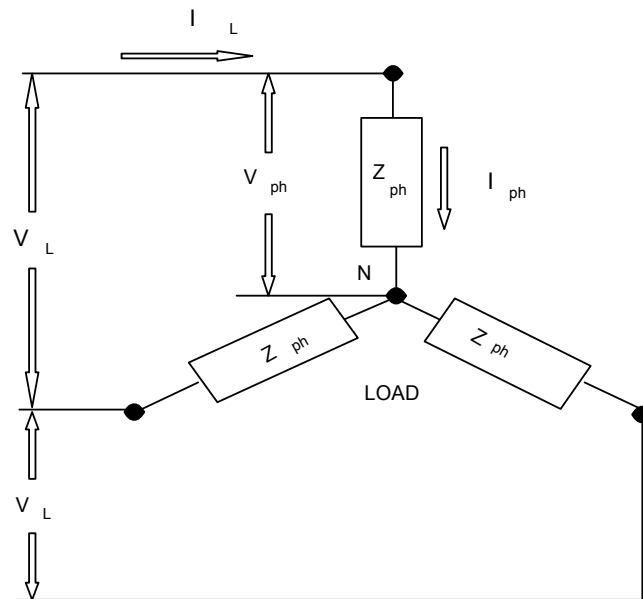
THREE PHASE LOADS

The generation of 3 ϕ AC and the associated relationships has been discussed.

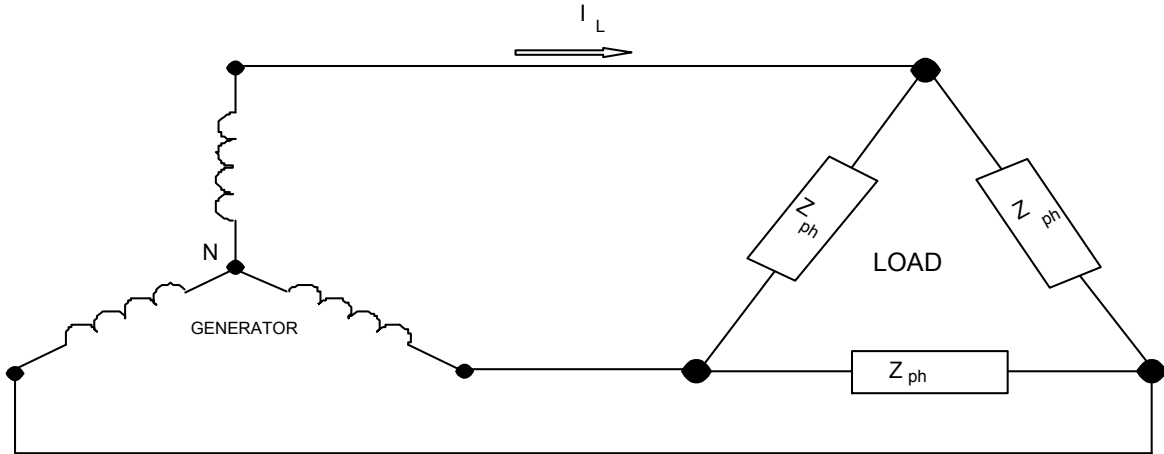
We now need to talk about the 3 ϕ loads and their associated relationships.

The voltage, current and power relationships that apply to the generation of 3 ϕ AC also applies to 3 ϕ loads. There are two different types of loads: balanced and unbalanced. We will only be discussing the balanced loads.

Balanced 3 ϕ loads have identical impedances in each winding. The phase voltage V_{ph} and the phase current I_{ph} are the same for each winding. Once the phase voltage V_{ph} and phase current I_{ph} are established, the circuit can be evaluated just as a single phase AC circuit.



Practice Exercise



Given: $V_{ph} = 120\text{v}$ (Generator)

$F = 60\text{Hz}$

$R = 12\Omega$

$L = 0.5\text{h}$

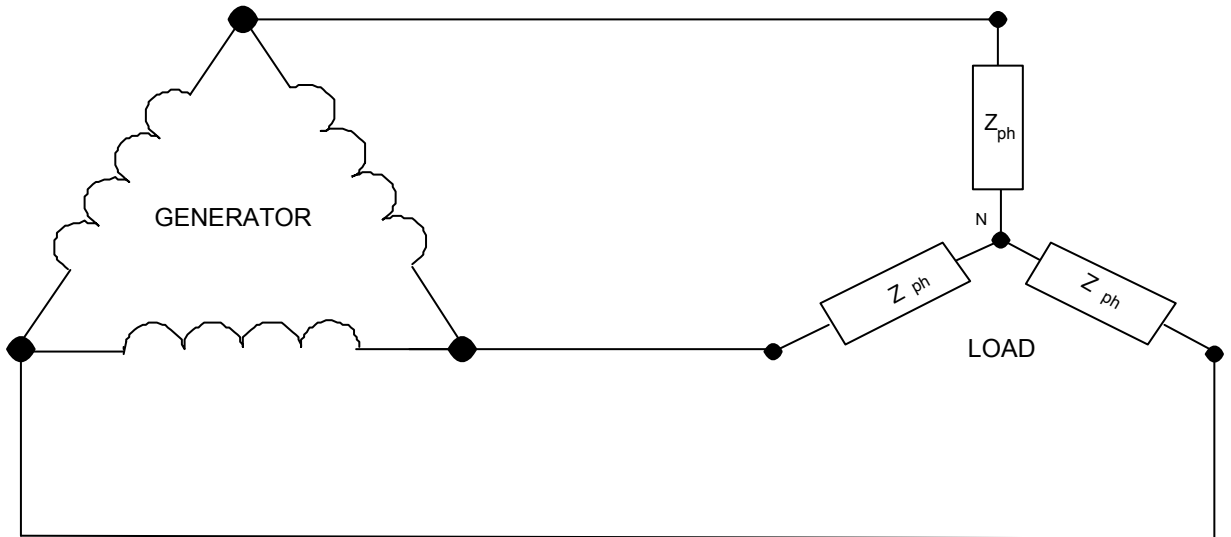
Find: $P_{\text{Real}} =$

$I_L =$

P.F. =

VA =

Practice Exercise



Given:

$$f = 60\text{Hz}$$

$$R = 100\Omega$$

$$L = 0.2\text{h}$$

Find: $P_{\text{Real}} =$

$$I_L =$$

$$\text{P.F.} =$$

$$\text{VA} =$$



AC MOTORS

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INTRODUCTION

Since alternating voltage can be easily transformed from high voltages to low voltages or vice versa, it can be transmitted over a much greater distance without too much loss in efficiency. Therefore, power generating systems today produce alternating current usually. Thus, it follows that a great majority of the electrical motors utilized today are designed to operate on alternating current. However, there are other advantages in the use of AC motors besides the wide availability of AC power.

Advantages of AC Motors versus DC Motors

- **A readily available power supply**
- **Cheaper**
- **Maintenance cost**
- **Less weight**

DC motors are best suited for applications that require variable-speed motors. However, AC motors along with variable speed AC drives are becoming more widely used.

AC motors are manufactured in **many** different sizes, shapes, and ratings, for use on an even greater number of applications. They are designed for use with either **single-phase** or **polyphase** power systems. This unit cannot possibly discuss all aspects of the subject of AC motors. Consequently, it will deal with the most common type, which is the **three phase induction motor**.

Three Phase AC Motors

There are two classes of Three Phase AC Motors: Synchronous and **Asynchronous**.

The main difference between these two classes of AC motors is their physical construction. While both have the **same stator construction**, their **rotors vary greatly**.

The purpose of the stator in both class motors is to create a rotating magnetic field.

A synchronous motor is one whose **rotor speed (N_r)** is equal to the speed of the **stator rotating magnetic field (N_s)**. In other words the speed of the shaft is rotating at the same speed as the rotating magnetic field.

$$N_s = N_r$$

An asynchronous motor is one whose rotor speed (N_r) is not equal to the speed of the rotating magnetic field (N_s). The asynchronous motor is more commonly called an **induction motor**.

$$N_s > N_r$$

Three Phase AC Induction Motors

There are two main types of induction motors:

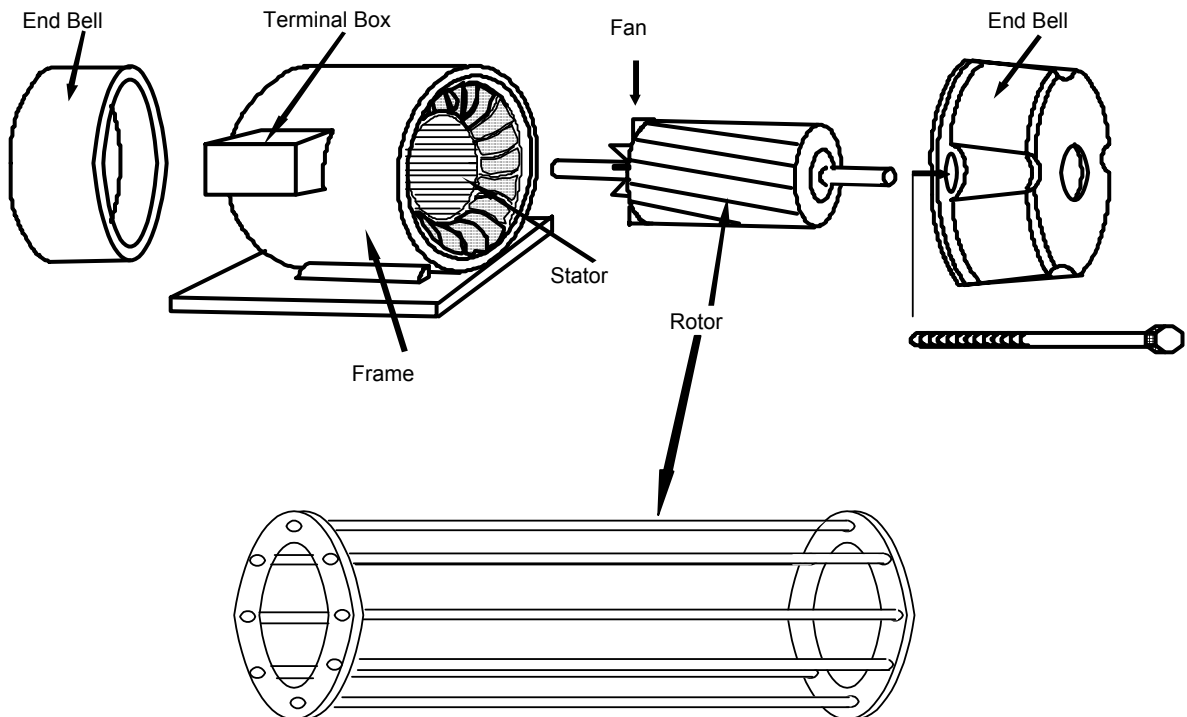
Squirrel-Cage
Wound Rotor

Both motors operate on induction and the principles are very similar. Let's first discuss the squirrel-cage motor and its construction since it is the simplest form. We will then look at the differences and applications of the wound rotor induction motor.

SQUIRREL-CAGE INDUCTION MOTOR

Construction

- Stator** - The stationary winding of the motor and it provides the rotating magnetic field. The stator windings are wound around the laminated pole pieces, which are mounted to the outside housing of the motor. It is also connected to the AC supply.
- Rotor** - The rotating member of the motor and it provides the torque or power to do the mechanical work. The rotor is made of circular laminations with copper or aluminum bars imbedded around the outside edge. It is connected to the shaft of the motor.
- End Bells** - Support the shaft of the motor and house the bearings.



Rotating Magnetic Field

The speed of the rotating magnetic field is called the *synchronous* speed of the motor. The following formula can be used to determine the speed of the rotating magnetic field created by the stator:

$$N_s = \frac{60 \cdot f}{P}$$

Where N_s is the speed of the stator rotating magnetic field in RPMs
 f is the frequency of the applied voltage in hertz (Hz)
 P is the number of pair of poles per phase in the stator winding

When motor manufacturers describe a 2-pole motor, they are talking about the numbers of poles that are **created in the rotor** due to the rotating magnetic field.

For a 2-pole motor which has only 1 pair of poles per phase:
 $N_s = 3600$ rpm (assuming 60 Hz)

For a 4-pole motor which has 2 pair of poles per phase:
 $N_s = 1800$ rpm (assuming 60 Hz)

For a 6-pole motor which has 3 pair of poles per phase:
 $N_s = 1200$ rpm (assuming 60 Hz)

For a 8-pole motor which has 4 pair of poles per phase:
 $N_s = 900$ rpm (assuming 60 Hz)

In AC theory we learned the left-hand rule for conductors, the left-hand rule for coils, and the left-hand rule for generators. We now can use those rules to show how the rotating magnetic field is created in the stator. The following diagrams can be used to illustrate the creation of the stator rotating magnetic field and explain why the rotor rotates:

Induction Motor Slip

An induction motor cannot run at synchronous speed since the rotor would be standing still with respect to the rotating field and no current would be induced in the rotor. The rotor speed must be slightly less than synchronous speed in order that current be induced in the rotor to permit rotor rotation. The difference between rotor speed and synchronous speed is called *slip*:

$$slip = N_s - N_r$$

Where N_s = synchronous speed, in rpm
 N_r = rotor speed, in rpm

Slip can also be expressed as a percent of synchronous speed:

$$\% slip = \frac{N_s - N_r}{N_s} \times 100$$

Where N_s = synchronous speed, in rpm
 N_r = rotor speed, in rpm

To calculate the actual shaft speed of an induction motor this relationship will be used:

$$N_r = \frac{60 \cdot f}{P} - slip$$

Where N_r = is the actual shaft speed in RPMs
 f = is the frequency of the applied voltage in hertz (Hz)
 P = is the number of pair of poles per phase in the stator winding

Induction Motor Efficiency

The three-phase, squirrel-cage induction motor operates at a relatively constant speed from no-load to full-load. Because of the extremely low impedance of the rotor, only a slight decrease in speed is necessary to cause a large increase in rotor current to develop the necessary torque to turn the increased load. The percent slip at no-load is less than 1% while at full-load it is usually between 3-5%. This small change in percent slip from no-load to full-load likewise indicates why a squirrel-cage induction motor is considered a fairly constant speed motor. As the slip increases in a straight line characteristic, the rotor current will likewise increase in practically a direct proportion and cause the torque to increase as a straight line characteristic.

The losses in an induction motor consist of the stray power losses and the copper losses. The stray power losses include mechanical friction losses, windage losses, and iron losses. These remain relatively constant at all load points and are often called fixed losses. The second group of losses, called copper losses, is the I^2R losses in the windings of the motor. As the current increases in the motor windings with an increase in load, the I^2R losses increase. At light loads the percent efficiency (η) is low because the fixed losses become a smaller part of the input and the efficiency increases to its maximum value. However, when the rated capacity of the motor is exceeded, the copper losses become excessive and the efficiency decreases.

The efficiency of an AC induction motor can be determined by:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Where η = Greek letter **eta**, percent efficiency
 P_{out} = the output power produced by the shaft in watts
 P_{in} = the input power required in watts

Example:

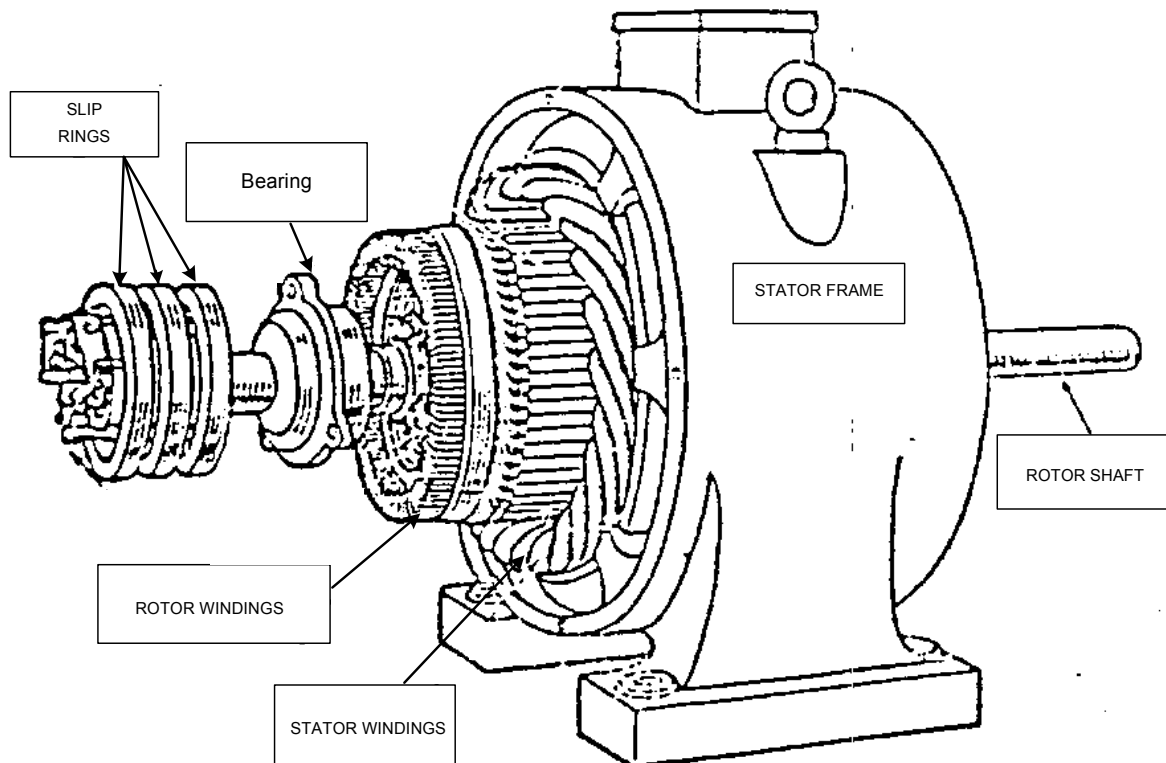
Given: $P_{in} = 8500$ watts
 $P_{out} = 10$ hp

Find: $\eta =$

THE WOUND ROTOR INDUCTION MOTOR

The motor consists of three electrical parts:

1. A set of insulated windings mounted on the body of the motor. These windings are similar to those of the squirrel-cage induction motor and are also called the stator windings.
2. A set of insulated windings recessed into the laminated plates of the rotor. These windings are always connected in the wye configuration with the three free ends brought out and each one connected to each of three brass rings mounted on the motor shaft. These rings are the **slip rings**.
3. A means of making electrical connection with the slip rings is needed so that current may flow through the rotor windings when they are in rotation. These connections are by means of **brushes**, which are held in position in contact with the slip rings by the brush-holder.

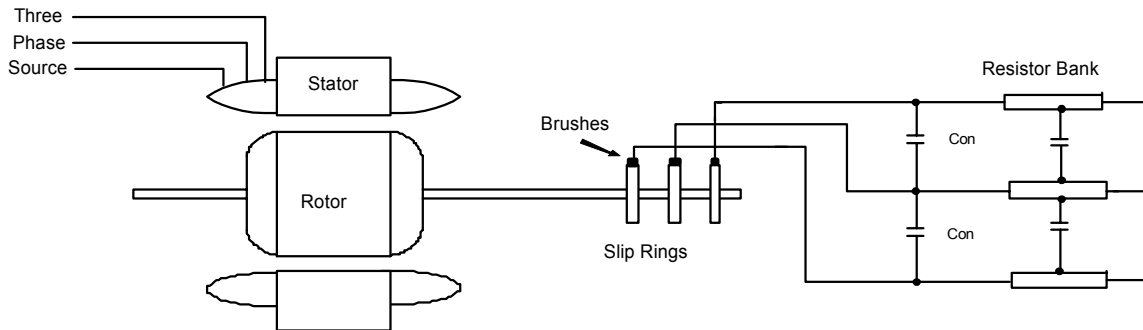


Construction

As stated the wound rotor is constructed of windings instead of shorting bars, as in the squirrel-cage induction motor. Like the squirrel-cage induction motor, it receives its power through induction. Its windings are connected in a star configuration, and are accessible through the use of slip rings and brush assembly.

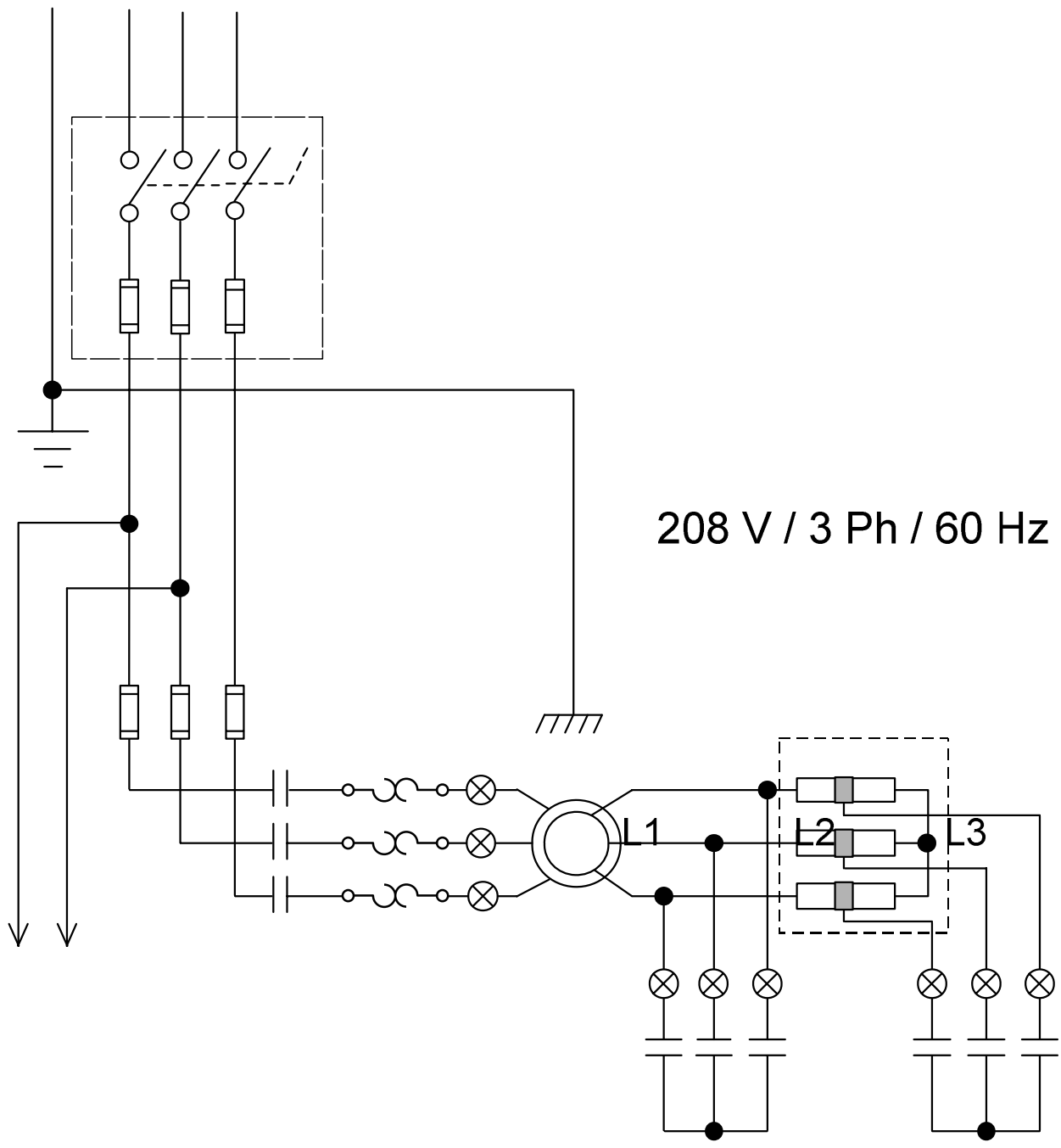
This access to the rotor circuit is the major advantage of the wound rotor induction motor. It allows changes in rotor impedance, through external resistance changes. This allows the **torque** of the motor to be controlled. The wound rotor induction motor can be used where the maximum torque is desired throughout the entire speed range. As the speed changes, rotor circuit resistance is varied to maintain the resistance of the rotor equal to the inductive reactance of the rotor ($R = X_L$). When R and X_L are equal, the phase angle of the impedance of the rotor is 45° .

The following basic block diagram illustrates the connection of external resistors to the rotor:



The ϵ

rotor reactance at standstill. The wound-rotor motor is usually started with all the resistance in the rotor circuit. Starting torque with all the resistance is at maximum. As the motor comes up to speed, the rotor resistance is shorted out by a contactor. With all external rotor resistance cut out, the motor has good speed regulation, but somewhat less than that of the standard squirrel-cage motor. This can also be done in stages with numerous contactors as is illustrated on the following page.



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Operating Characteristics

The insertion of resistance in the rotor circuit limits the starting surge of current and also permits high starting torque and adjustable speed. If all the resistance of the resistor banks is connected into the rotor circuit when the motor is running, the rotor current becomes less, and the motor slows down. As the rotor speed decreases, more voltage is induced in the rotor windings due to the stator rotating magnetic field speed being constant. As a result, more current flows in the rotor windings, which creates the necessary torque at the reduced speed.

Speed Regulation

To increase the speed, for full speed operation, the rotor winding resistance is shorted out through the contactor.

Although the insertion of resistance in the rotor circuit improves the starting torque at low speeds, it has the opposite effect at normal speeds. Thus the speed regulation of the motor is poorer with resistance in the rotor circuit. The resistance is shorted out as the motor comes up to speed in order to maintain running torque and better speed regulation.

Although inserting the external resistance into the rotor circuit will vary the speed of the motor by changing the torque, this method is only seen in older installations.

Applications



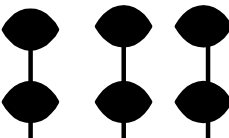
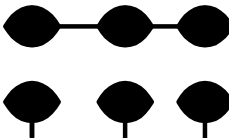
Because the wound rotor induction motor is similar to the squirrel-cage induction motor, it is used in similar applications. However, the wound rotor induction motor is seen more often in applications where some speed or torque control is needed. As discussed earlier, we can manipulate the torque of the wound rotor induction motor by changing the value of the externally connected resistances. Because torque has a direct affect on speed, we will also be varying the speed of the motor.

Wound rotor motors can be used as variable-speed motors. Their initial cost is much greater, so they are usually used only where frequent large starting currents exist and for loads that require slow acceleration with controlled torque. Wound rotor motors are most frequently used in applications where high values of starting torque and low starting currents are required; also, where the inertia of the driven machine is extremely high.

MOTOR NAMEPLATES

MODEL 5K143AL234E		NO CRF	
HP 1		SERVICE FACTOR 115	
VOLTS 230/460		PHASE 3	HERTZ 60
AMP 3.7/1.85		EFFICIENCY	
RPM 1745		TIME RATING CONT	
40 DEG. C MAX. AMB		INS	NEMA
FRAME 143T		CLASS	DESIGN
		A	B
TYPE K CODE M			
STOCK NO. K-137			
GENERAL ELECTRIC			
INDUCTION MOTOR			

TYPICAL AMERICAN

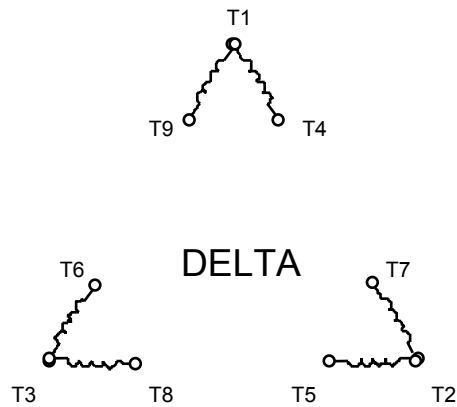
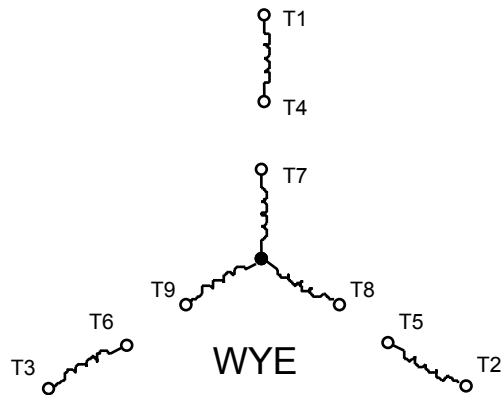
MOTEURS PATAY LYON			
Type BCVL38B2 No. 592320			
ch 1.7		tr/mn 1000	
kw 1.25	Hz 50	Sce SI	
V 220 		V 380 	
			
A 4.1		A 2.4	
FREIN-Type FM138-2 Couple 1 m kg			

TYPICAL EUROPEAN

DUAL VOLTAGE MOTOR CONNECTIONS

It is common for electric motor manufacturers to build motors for connection to many different voltage sources. Manufacturing motors for dual voltages, such as 480/240 volt, enables the same motor to be used in applications where the line voltages are different. These motors have the same characteristics on either voltage. The speed and horsepower remain the same if the motor is operated on either the higher or lower voltage.

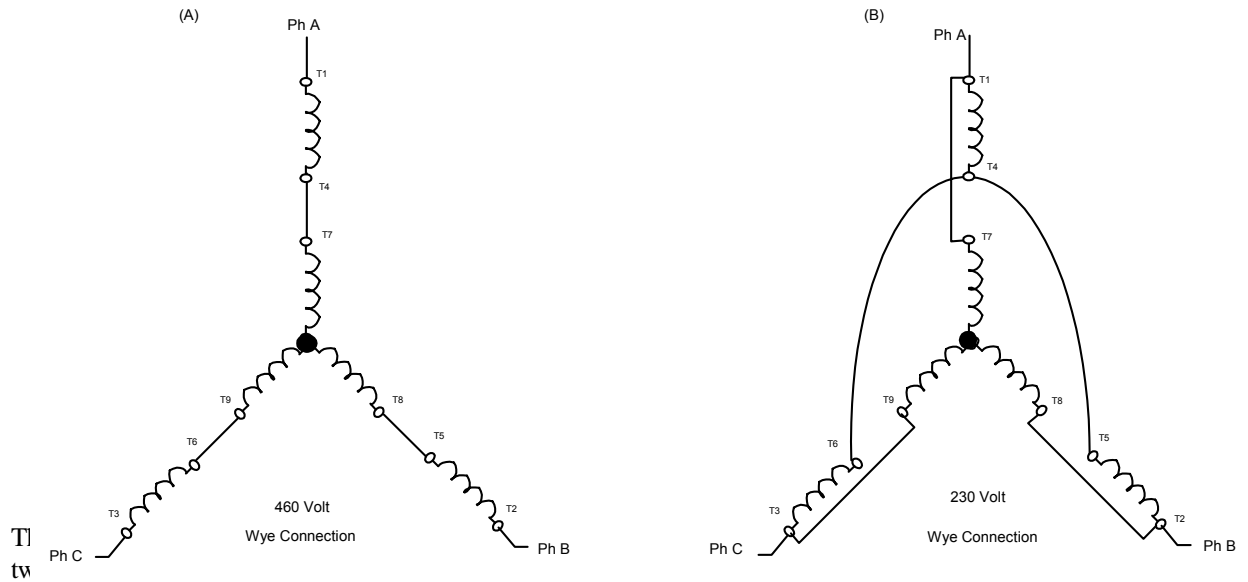
Dual-voltage connections are either wye-connected or delta-connected. Each phase is divided into two sections with the same number of pole-phase groups in each section and nine external connections are brought out from these sections when the motor is wound. Each external lead or connection is stamped at the terminal block with a number from one to nine.



Wye-Connected Motors

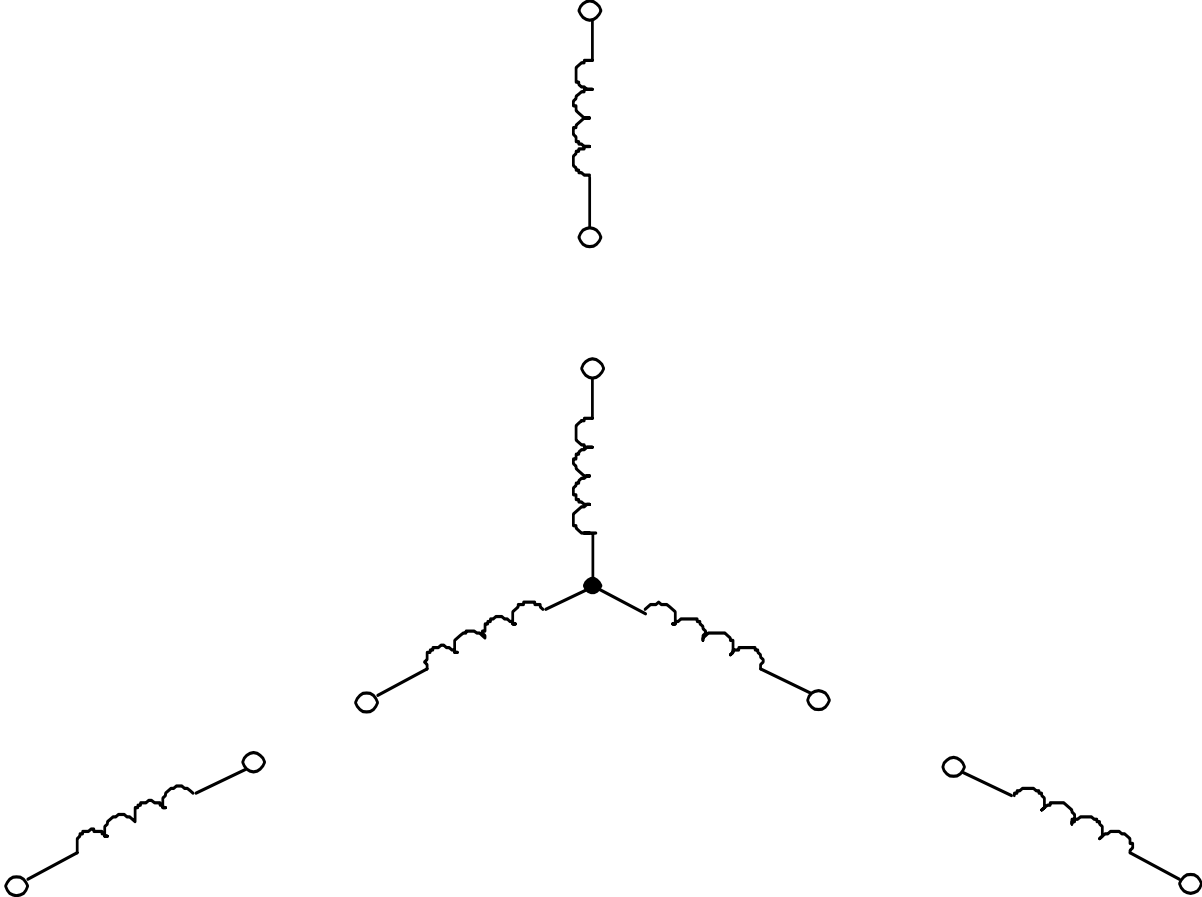
Below illustrates the connections and terminal markings for a wye-connected, dual-voltage induction motor. In the series-wye connection illustrated on the left, the ascending numbers go in succession in a clockwise direction to the three points of the wye. Then starting at the end of the T1 winding, go around clockwise again, completing the three outside groups. The third start is on the inside wye just below T4, and go around clockwise again. This makes the nine external terminals of the six windings. The other three terminals of the internal wye are connected inside the motor for a nine lead motor.

Note on the diagram on the left that this connection has two windings for each phase connected in **series**. This is known as a series-wye connection and is always the **higher voltage connection** in a dual-voltage, wye-connected motor.

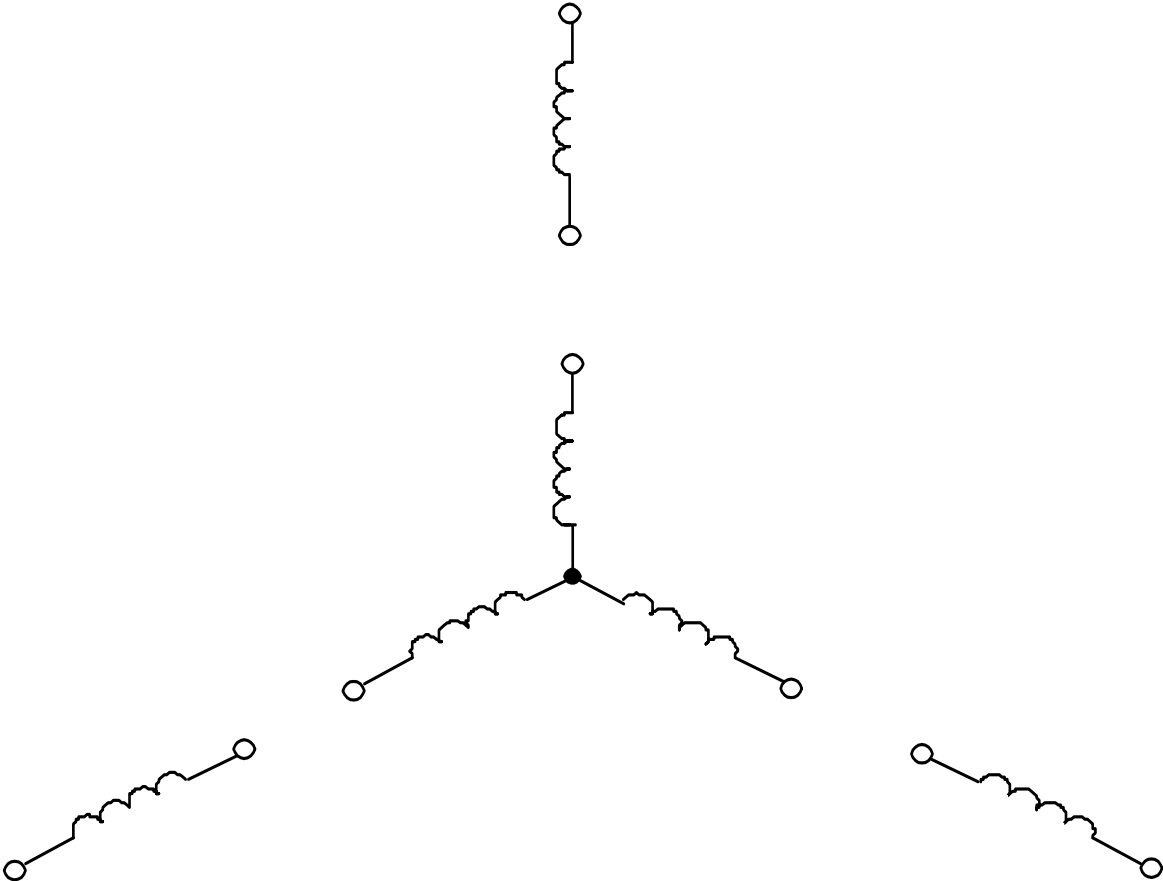


known as a parallel-wye connection, and is always the **lower voltage connection** for any dual-voltage, wye-connected motor. In this connection there are two wye center points. The original internal wye and an external wye formed by connecting leads T4, T5, and T6 together as illustrated.

Use the diagram below to practice the connections for a high voltage wye-connected, 9-lead American motor.



Use the diagram below to practice the connections for a low voltage wye-connected, 9-lead American motor.

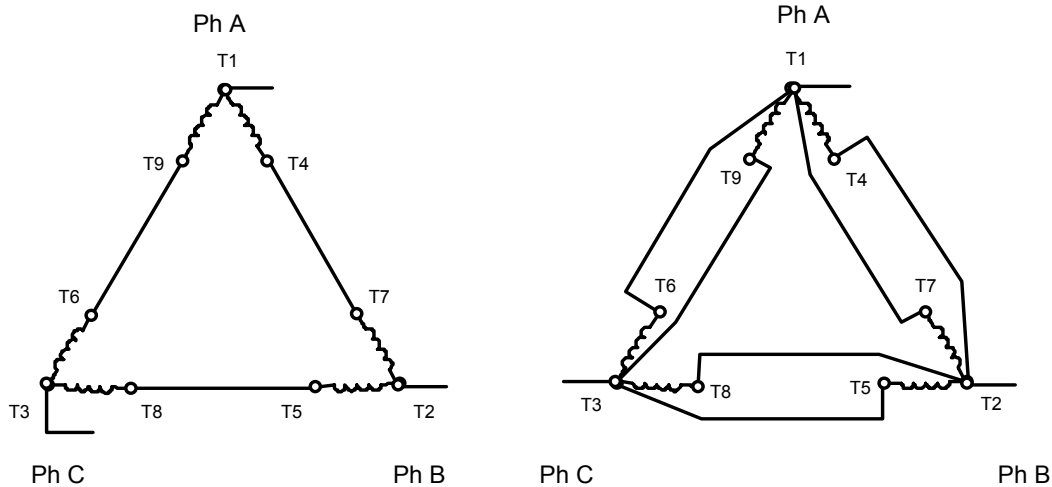


Delta-Connected Motors

The diagrams below illustrate the connections and terminal markings for a delta-connected, dual-voltage induction motor.

The diagram on the left shows the method of numbering and connecting the nine external leads for high voltage operation. The method of numbering for the delta is much the same as the wye. Starting at the top corner of the delta, number the three corners T1, T2, T3. Then start at the end of the T1 winding and go clockwise to number for T4, T2 to T5, and T3 to T6. For the next terminal, start at the T4 winding and go clockwise to the next terminal for T7, then go to clockwise of T5 and label T8, and finally label T9.

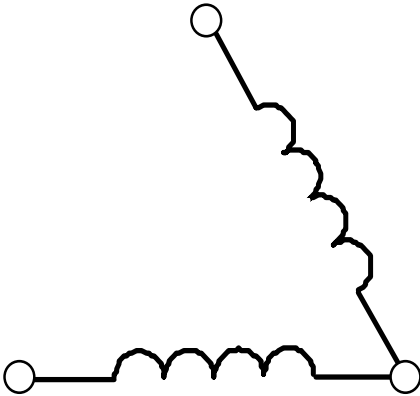
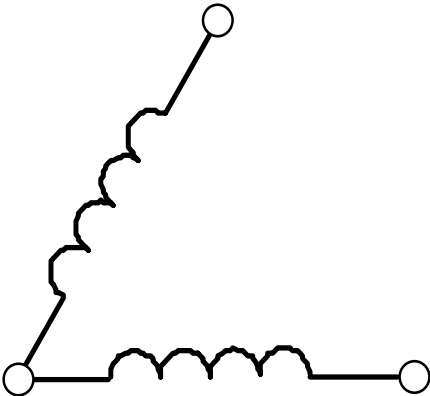
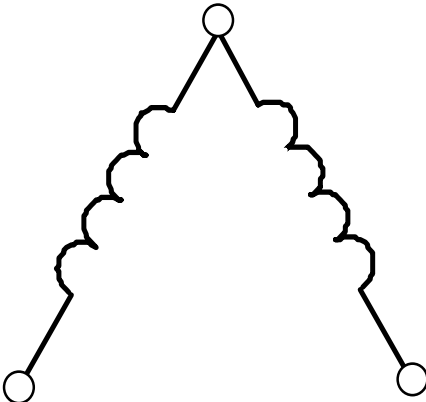
Note the diagram on the left, that the two sections of each phase are connected in series for the **high voltage connection**.



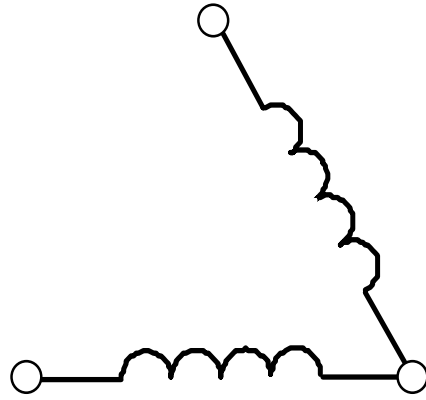
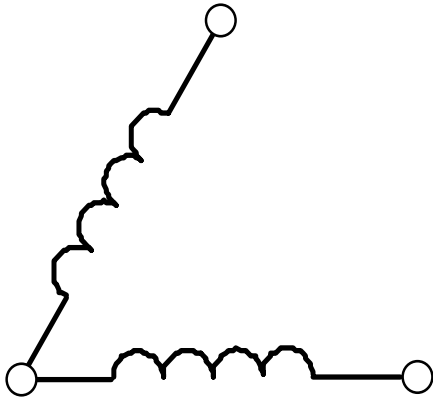
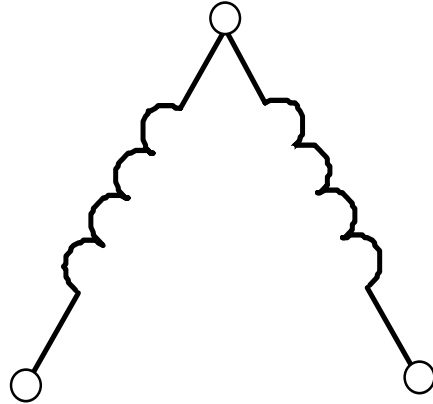
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dual-voltage, delta-connected motor.

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Use the diagram below to practice the connections for a high voltage delta-connected, 9-lead American motor.

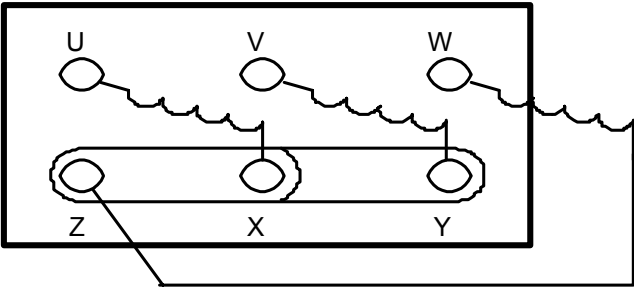
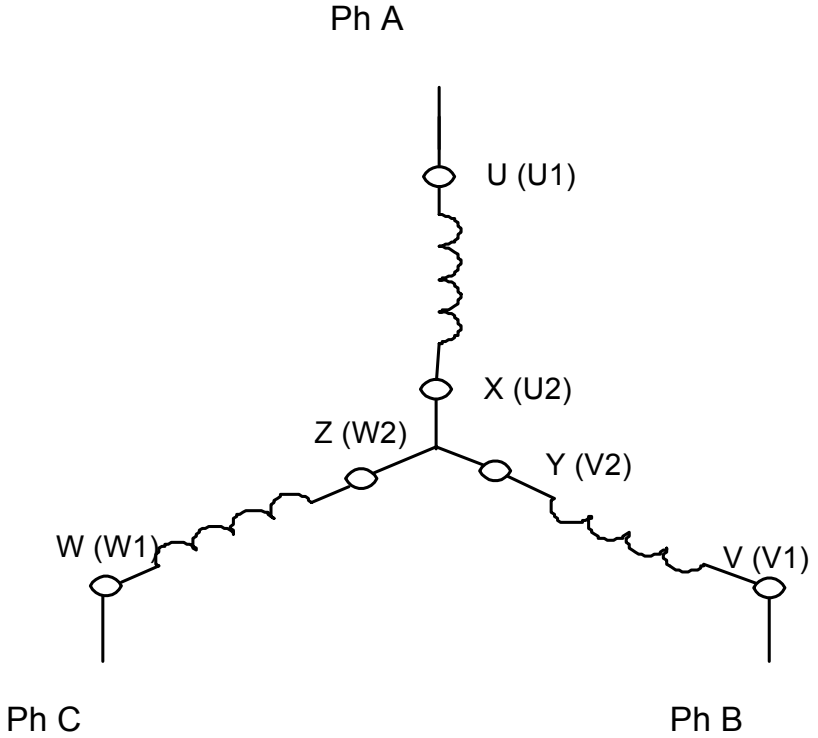


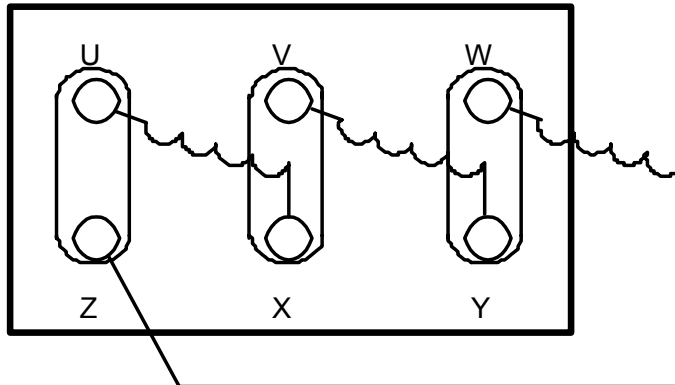
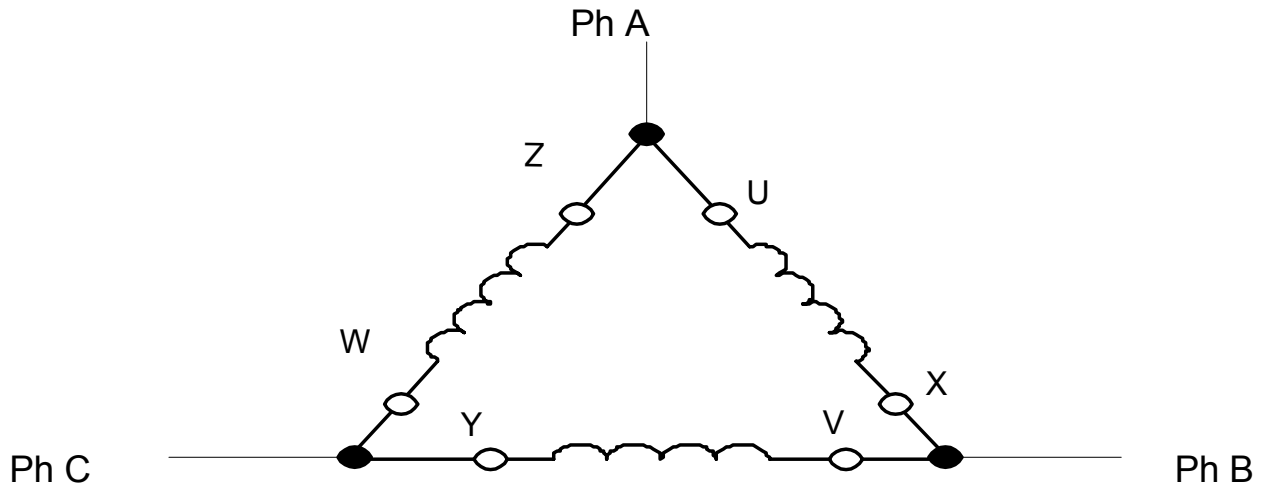
Use the diagram below to practice the connections for a low voltage delta-connected, 9-lead American motor.



EUROPEAN MOTORS

These motors have six leads, three coils, and have the capability of being connected either wye or delta. The wye connection is used for high voltage, and the delta connection is used for low voltage. Another point to consider is that these motors were designed for 380V or 220V. Normally in the plant, 480 volts will be used; and as you might expect, the motor does not last as long. When they are burned out, they are rewound for 480 volts (wye connected) and will have only three terminal wires. They then are no longer dual voltage motors. One additional factor is the European motor is designed to operate on 50 Hertz. In the U.S., we have 60 Hertz and therefore, the nameplate rpms will not be correct.







OPEN CIRCUIT FAULTS IN THE CONTROL CIRCUIT

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GENERAL TROUBLESHOOTING PROCEDURE

Symptom - The machine does not start when the start button is pressed.

At this point the problem could be mechanical or electrical. We will focus on just the electrical faults for now. This fault could be located in either the power circuit or the control circuit. The fault could also be many different types, such as, open circuit fault, short circuit fault or a ground fault. This **general troubleshooting procedure** is designed to start in the middle of the problem area and give us the best idea which direction to go. The control transformer is a good place to start since it is in the middle of the circuit and is part of the power and control circuits.

The first three steps of this procedure will be the same for all faults and the rest will be completed throughout this chapter in more than one procedure. There is no one procedure that can guide you through any given problem.

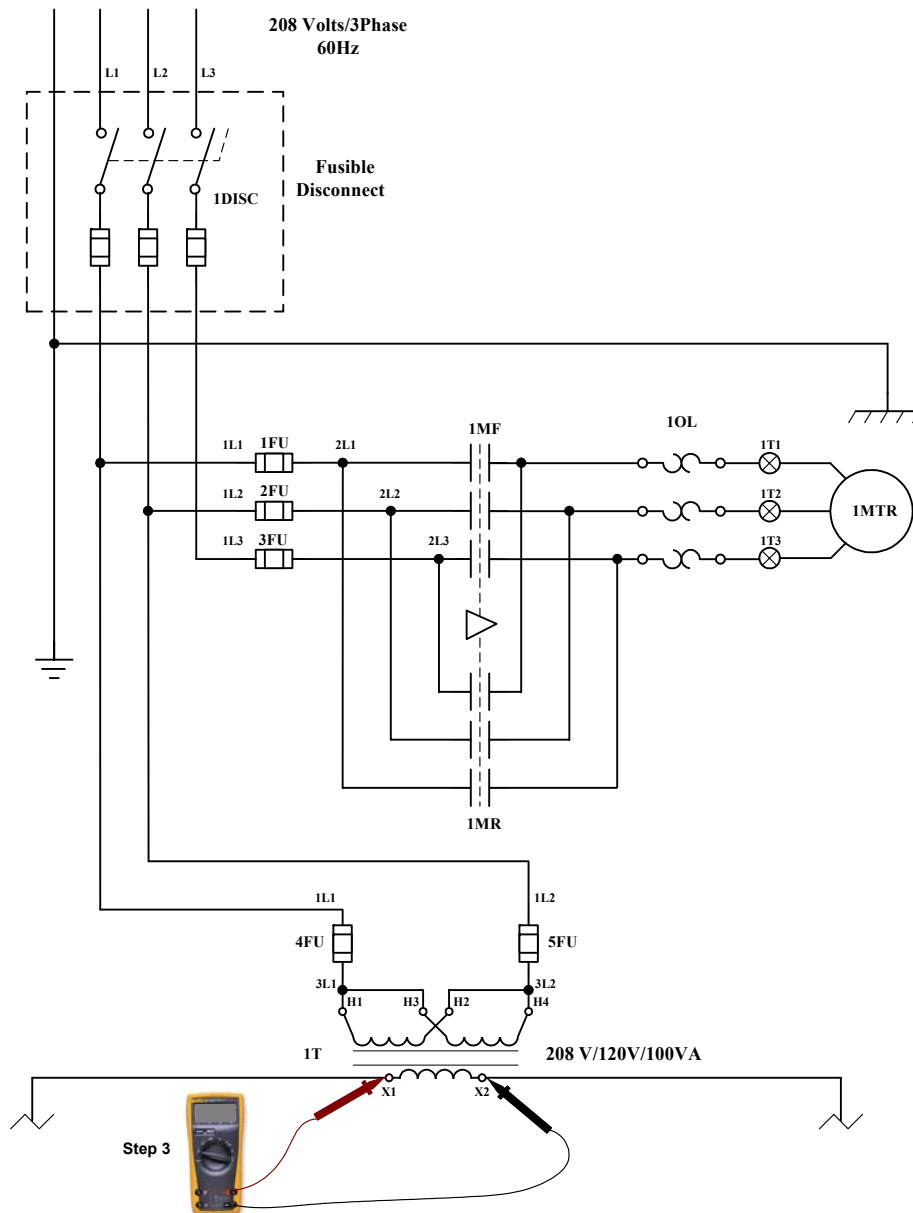
For simplicity's sake we will now take one area and one type of fault at a time. The first fault we will investigate is the **open circuit fault**. We will now investigate open circuit faults in the control circuit.

Open Circuit Faults in the Control Circuit

Open circuit faults - An open circuit fault is any fault that stops the operation of a machine due to an open wire or component.

Let's develop our procedure for troubleshooting an open circuit in the control circuit. Remember that the first three steps will be the same for all faults.

- Step 1.** You must analyze the schematic diagram for a general circuit overview.
- Step 2.** You must carefully open the control panel with power energized since voltage checks will need to be made. (The operation of the voltmeter should have been verified before continuing)
- Step 3.** You should check the voltage at the X1 and X2 terminals at the secondary of the control transformer.
- If correct voltage is not present, then the problem is in the power circuit.
 - If correct voltage is present and the contactor is energized, then the problem is in the power circuit.
 - If correct voltage is present, the contactor is not energized and the OL is not tripped, then the problem is in the control circuit.



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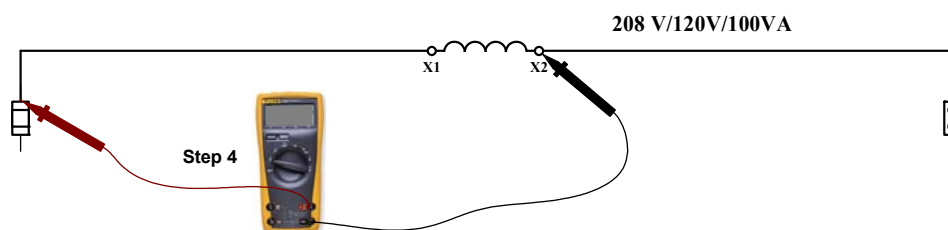
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Scenario A is the motor does not start when the start button is pressed. The **correct voltage is present at X1 and X2**, the contactor is not energized and the OL is not tripped, then the problem is in the control circuit. For Scenario A, the fault is an **open circuit fault and inside the panel**. From the schematic on the previous page you should have read 120volts at terminals X1 and X2.

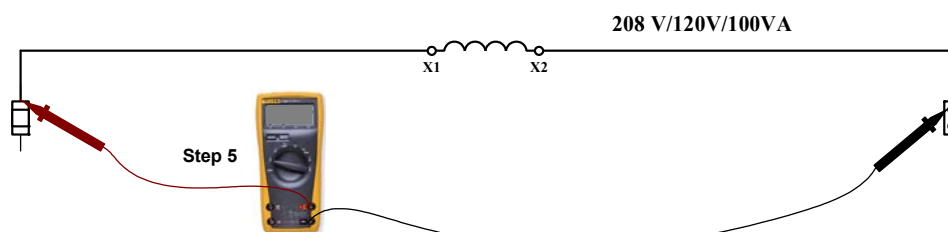
Since the correct voltage is present we must troubleshoot the system in a logical order until we lose the correct voltage.

If the voltage changes from a good reading on one device to a different reading on the next device in logical order, then the device or wire in between those readings is open.

- Step 4.** You should check the voltage on X1 at the top of the control circuit fuse and X2 terminal at the secondary of the control transformer.
- If the correct voltage is present, continue to Step 5.
 - If the correct voltage is not present, then X1 wire is open from the top of the fuse to the terminal on the secondary of the transformer.

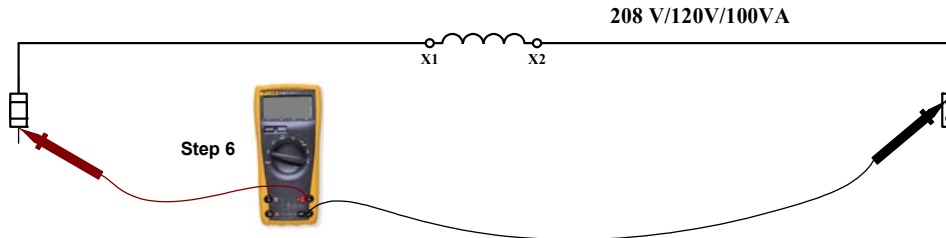


- Step 5.** You should check the voltage on X1 at the top of the control circuit fuse and X2 at the top of the neutral link.
- If the correct voltage is present, continue to Step 6.
 - If the correct voltage is not present, then X2 wire is open from the top of the neutral link to the terminal on the secondary of the transformer.



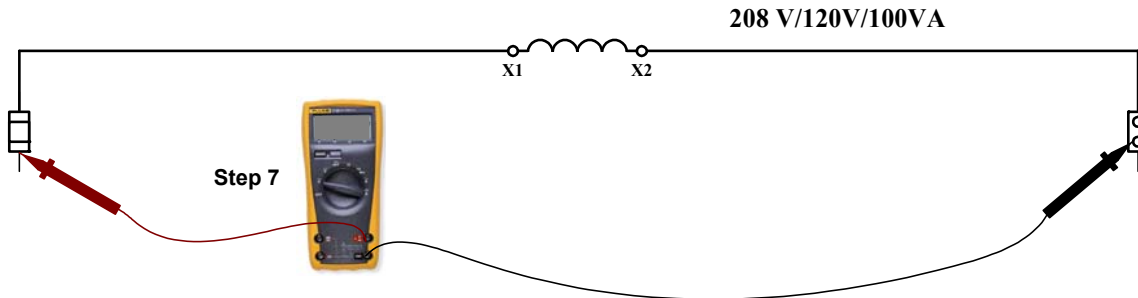
Step 6. You should check the voltage on wire #1 at the bottom of the control fuse and X2 at the top of the neutral link.

- If the correct voltage is present, continue to Step 7.
- If the correct voltage is not present, then the control fuse is open. **If the fuse is open, then there is either a short circuit or ground fault. If the fuse is not open, then there is an open circuit fault. This is our first indication that the fault is an open circuit fault.**

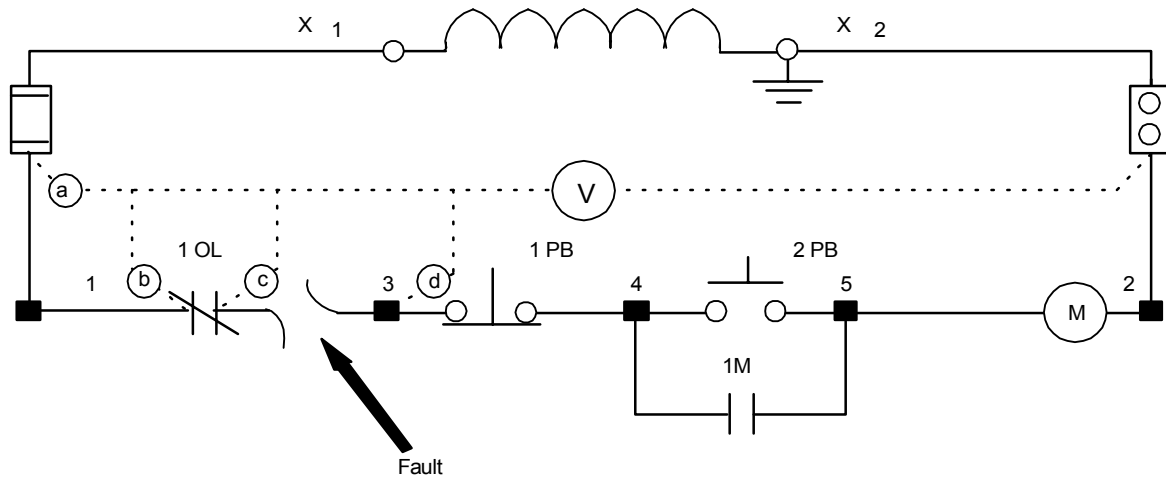


Step 7. You should check the voltage on wire #1 at the bottom of the control fuse and wire #2 on the bottom of the neutral link.

- If the correct voltage is present, continue to Step 8.
- If the correct voltage is not present, then the neutral link is open.



Use the schematic diagram below as an illustration for Scenario A, assuming that we don't know the location of the fault:



- Step 8.** Since the voltage at point **a** (bottom of the fuse) is the correct voltage, we will use wire #2 as our reference. We will make our measurements from **left to right** and then **top to bottom** until we find the voltage not present.
- If the correct voltage is present, continue to Step 9.
- Step 9.** Check the voltage at point **b** (left side of 1OL) with wire #2 as a reference.
- If the correct voltage is present, continue to Step 10.
 - If the correct voltage is not present, then wire #1 is open from the bottom of the fuse to the left of the normally closed contacts for 1OL.
- Step 10.** Check the voltage at point **c** (right side of 1OL) with wire #2 as a reference.
- If the correct voltage is present, continue to Step 11.
 - If the correct voltage is not present, then 1OL normally closed contacts are open.
- Step 11.** Check the voltage at point **d** (top of terminal #3) with wire #2 as a reference.
- If the correct voltage is present, continue to Step 12.
 - If the correct voltage is not present, then wire #3 is open between the right side of 1OL and the top of #3 terminal.

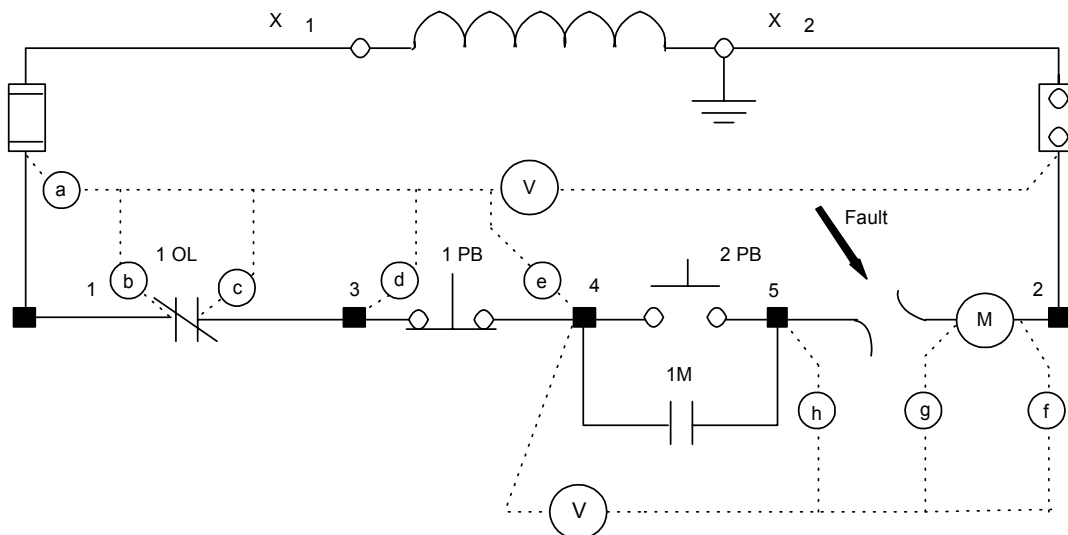
The fault is between the point where the voltage is present and the point at which it is not present anymore.

Scenario B is the motor does not start when the start button is pressed. The **correct voltage is present at X1 and X2**, the contactor is not energized and the OL is not tripped, then the problem is in the control circuit. For Scenario B, the fault is an **open circuit fault and inside the panel**.

Since the correct voltage is present we must troubleshoot the system in a logical order until we lose the correct voltage. Follow **Steps 1 through 7** just as we did in Scenario A.

If the voltage changes from a good reading on one device to a different reading on the next device in logical order, then the device or wire in between those readings is open.

Use the schematic diagram below as an illustration for Scenario B, assuming that we don't know the location of the fault:



- Step 8.** Since the voltage at point **a** (bottom of the fuse) is the correct voltage, we will use wire #2 as our reference. We will make our measurements from **left to right** and then **top to bottom** until we find the voltage not present.
- If the correct voltage is present, continue to Step 9.
- Step 9.** Check the voltage at point **b** (left of 1OL) with wire #2 as a reference.
- If the correct voltage is present, continue to Step 10.
 - If the correct voltage is not present, then wire #1 is open from the bottom of the fuse to the left of the normally closed contacts for 1OL.

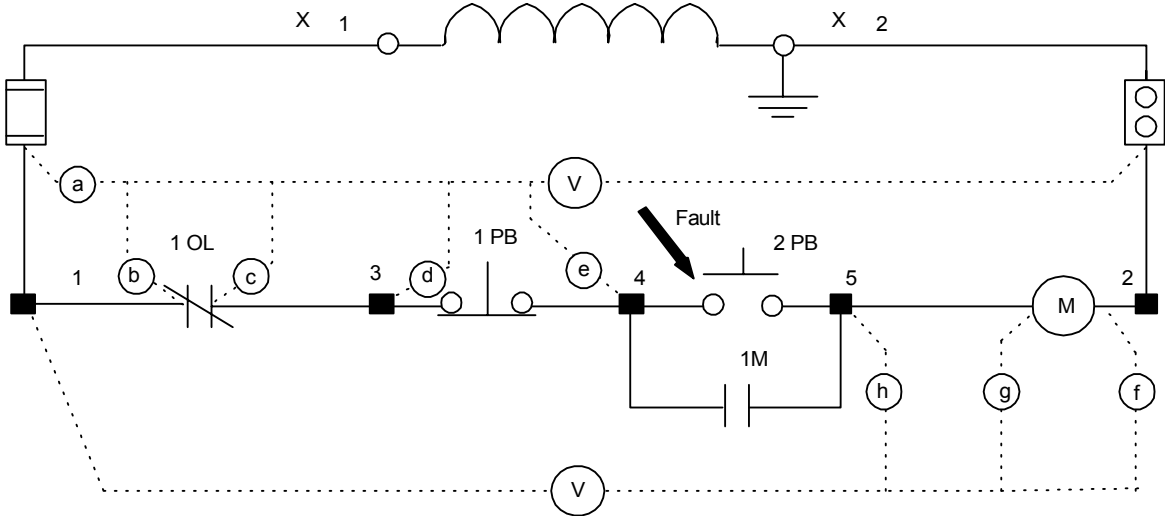
- Step 10.** Check the voltage at point **c** (right of 1OL) with wire #2 as a reference.
- If the correct voltage is present, continue to Step 11.
 - If the correct voltage is not present, then 1OL normally closed contacts are open.
- Step 11.** Check the voltage at point **d** (top of terminal #3) with wire #2 as a reference.
- If the correct voltage is present, continue to Step 12.
 - If the correct voltage is not present, then wire #3 is open between the right side of 1OL and the top of #3 terminal.
- Step 12.** Since switch 1PB is located outside the panel, we must go to the next terminal inside the panel. Check the voltage at point **e** (top of terminal #4) with wire #2 as a reference.
- If the correct voltage is present, continue to Step 13.
 - If the correct voltage is not present, then wire #3 or wire #4 is open somewhere between the bottom side of #3 terminal and the bottom side of #4 terminal.
- Step 13.** The next logical measurement would be to check the voltage at terminal #5 with wire #2 as a reference. Since switch 2PB and contacts 1M are open, there is no path for current flow. The voltage would be 0volts normally. So we must use the wire #4 now as our reference and check the voltage at point **f** (A2 terminal on the contactor coil). We will make our measurements from **right to left** and then **top to bottom** until we find the voltage not present. **Be very careful because the meter lead will be electrical hot.**
- If the correct voltage is present, continue to Step 14.
 - If the correct voltage is not present, then wire #2 is open between the neutral link (NL) and the A2 terminal on the contactor coil.
- Step 14.** Check the voltage at point **g** (A1 terminal on the contactor coil) with wire #4 as a reference.
- If the correct voltage is present, continue to Step 15.
 - If the correct voltage is not present, then the contactor coil is open.
- Step 15.** Check the voltage at point **h** (top of terminal #5) with wire #4 as a reference.
- If the correct voltage is present, continue to Step 16.
 - If the correct voltage is not present, then wire #5 is open between the top of the #5 terminal and the A1 terminal on the contactor coil.
- The fault is between the point where the voltage is present and the point at which it is not present anymore.**

Scenario C is the motor does not start when the start button is pressed. The **correct voltage is present at X1 and X2**, the contactor is not energized and the OL is not tripped, then the problem is in the control circuit. For Scenario C, the fault is an **open circuit fault and outside the panel**. The normally open contacts for the start pushbutton (2PB) are bad and won't close.

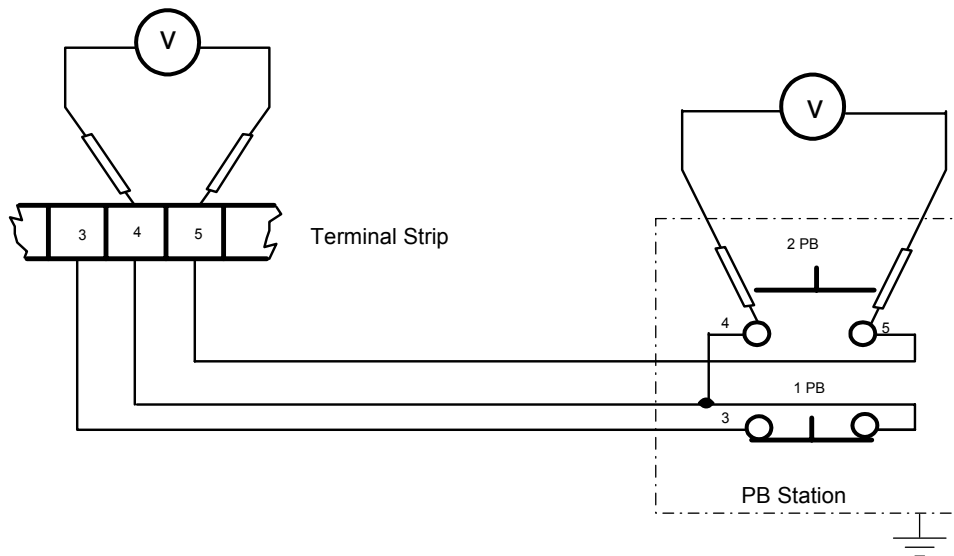
Since the correct voltage is present we must troubleshoot the system in a logical order until we lose the correct voltage. Follow **Steps 1 through 15** just as we did in Scenario B. The correct voltage is present from the top of terminal #4 to the top of terminal #5.

If the voltage changes from a good reading on one device to a different reading on the next device in logical order, then the device or wire in between those readings is open.

Use the schematic diagram on the following page as an illustration for Scenario C, assuming that we don't know the location of the fault:



- Step 16.** Check the voltage at the bottom of terminal #4 and the top of terminal #5.
- If the correct voltage is present, continue to Step 17.
 - If the correct voltage is not present, then terminal #4 is open.
- Step 17.** Check the voltage at the bottom of terminal #4 and the bottom of terminal #5.
- If the correct voltage is present, continue to Step 18.
 - If the correct voltage is not present, then terminal #5 is open.
- Step 18.** Since you have made all the measurements possible inside the panel, the fault must be **outside the panel** and you must go to the pushbutton station for 2PB. Carefully remove the cover. Check the voltage across the terminals where wire #4 and wire #5 are connected.
- If the correct voltage is present, then push 2PB pushbutton. The motor does not start. The normally open contacts for pushbutton 2PB are bad and will not close. **This is the fault.**
 - If the correct voltage had not been present, then there is an open circuit between the bottom of the #4 terminal and the bottom of terminal #5 outside the panel.

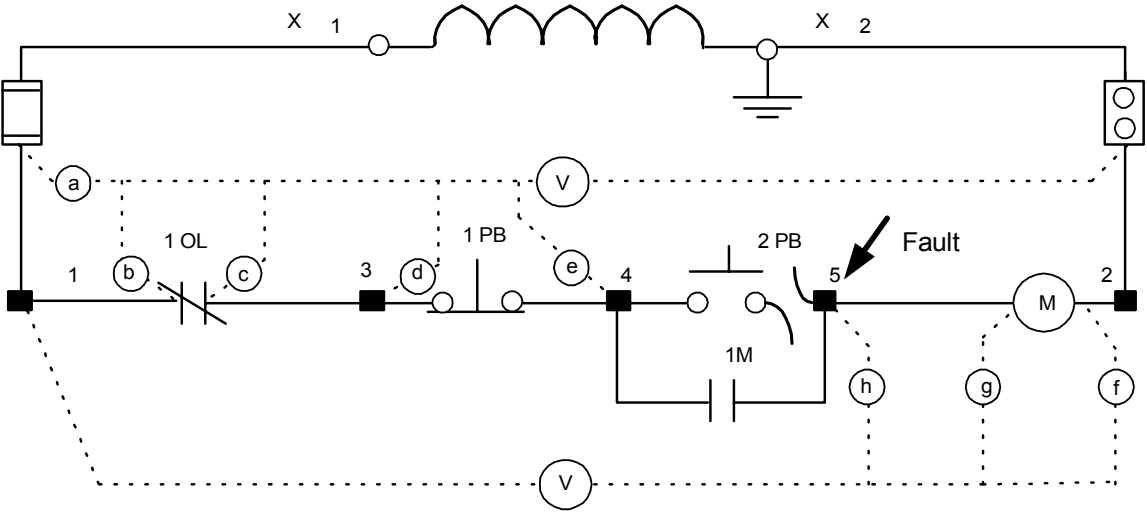


Scenario D is the motor does not start when the start button is pressed. The **correct voltage is present at X1 and X2**, the contactor is not energized and the OL is not tripped, then the problem is in the control circuit. For Scenario D, the fault is an **open circuit fault and outside the panel**. Wire #5 is open between the bottom of the #5 terminal and terminal on 2PB.

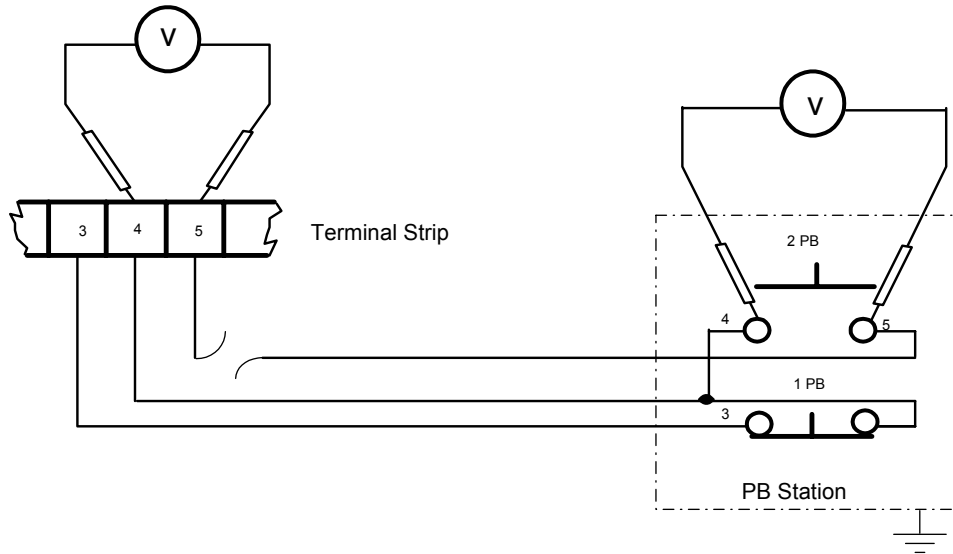
Since the correct voltage is present we must troubleshoot the system in a logical order until we lose the correct voltage. Follow **Steps 1 through 17** just as we did in Scenario C. The correct voltage is present from the bottom of terminal #4 to the bottom of terminal #5.

If the voltage changes from a good reading on one device to a different reading on the next device in logical order, then the device or wire in between those readings is open.

Use the schematic diagram on the following page as an illustration for Scenario D, assuming that we don't know the location of the fault:

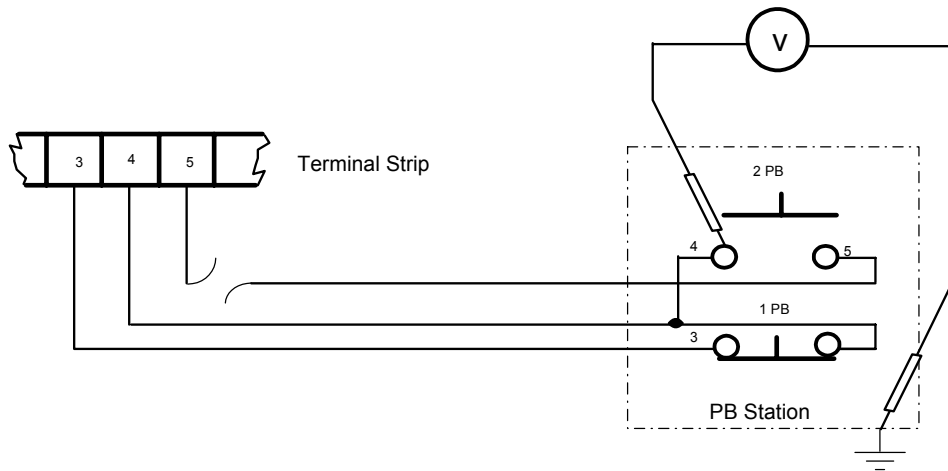


- Step 18.** Since you have made all the measurements possible inside the panel, the fault is must be **outside the panel** and you must go to the pushbutton station for 2PB. Carefully remove the cover. Check the voltage across the terminals where wire #4 and wire #5 are connected.
- If the correct voltage is present, then push 2PB pushbutton. The motor does not start. The normally open contacts for pushbutton 2PB are bad and will not close.
 - If the correct voltage is not present, then there is an open circuit between the bottom of the terminal #4 and the bottom of terminal #5 outside the panel; so continue to Step 19.



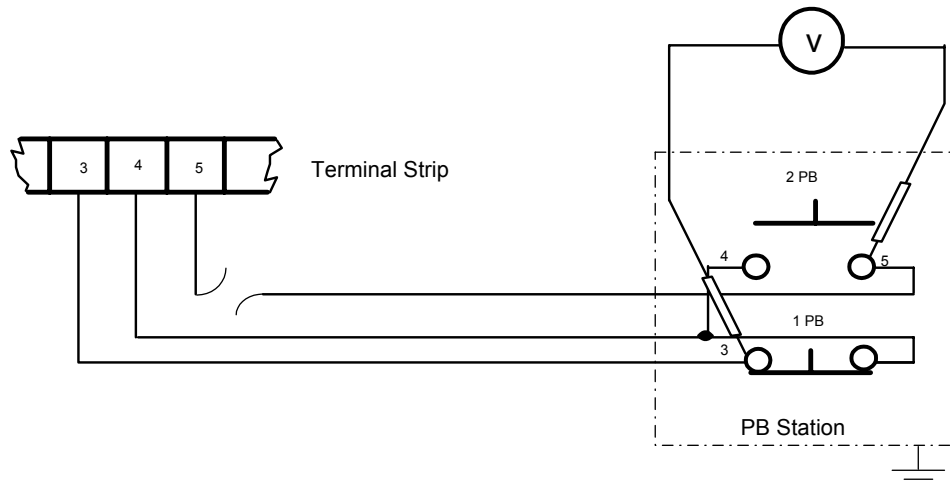
Step 19. You know that wire #4 or wire #5 is open between the bottom of the terminal strip and the pushbutton. There are two different methods to eliminate the possibilities. First method, check the voltage across the terminal with wire #4 to the ground terminal as a reference.

- If the voltage is present, then wire #4 is good and wire #5 must be open between the bottom of the terminal strip and the 2PB.
- If the voltage is not present, then wire #4 must be open between the bottom of the terminal strip and 2PB.



Second method, check the voltage across the terminal with wire #5 to wire #3 as a reference.

- If the voltage is present, then wire #5 is good and wire #4 must be open.
- If the voltage is not present, then wire #5 must be open.





SHORT CIRCUIT AND GROUND FAULTS IN THE CONTROL CIRCUIT

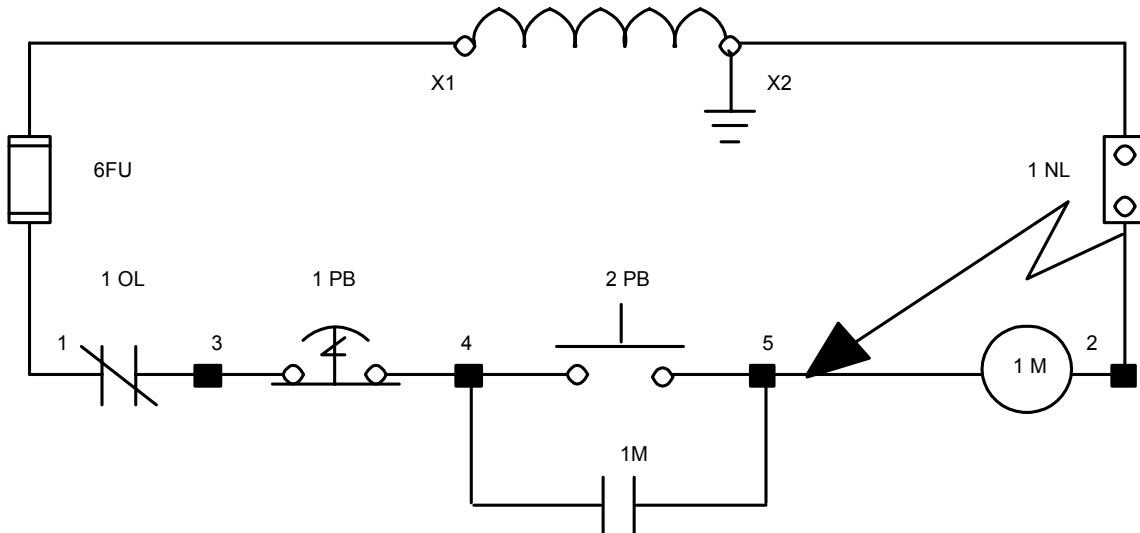
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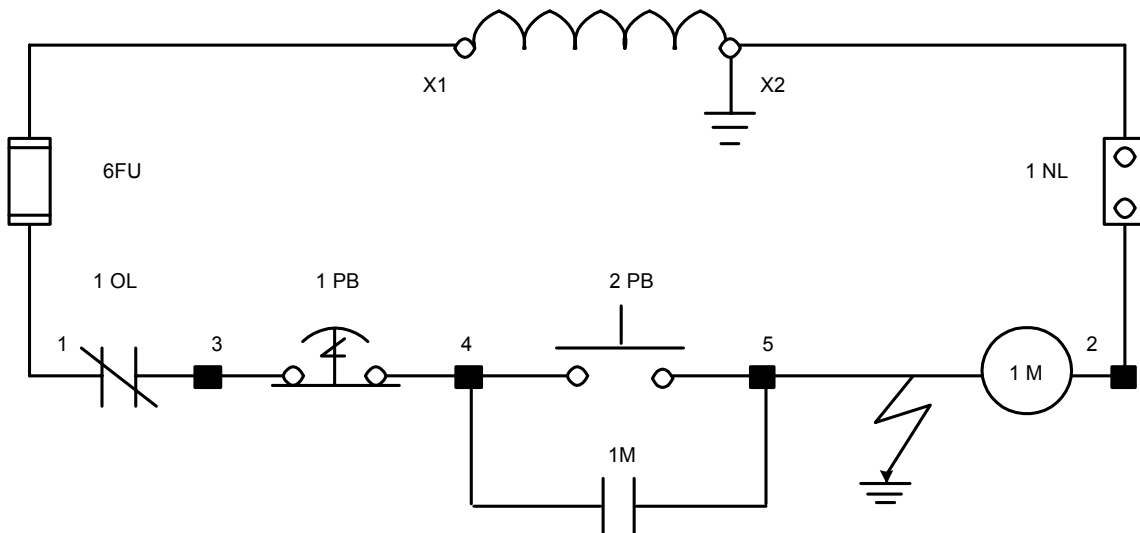
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Short Circuit and Ground Faults in the Control Circuit

Short Circuit in the Control Circuit - An abnormal connection (including an arc) of relatively low impedance, whether made accidentally or intentionally, between two points of different potential. **These abnormal connections will always causes one or more fuses to open.**

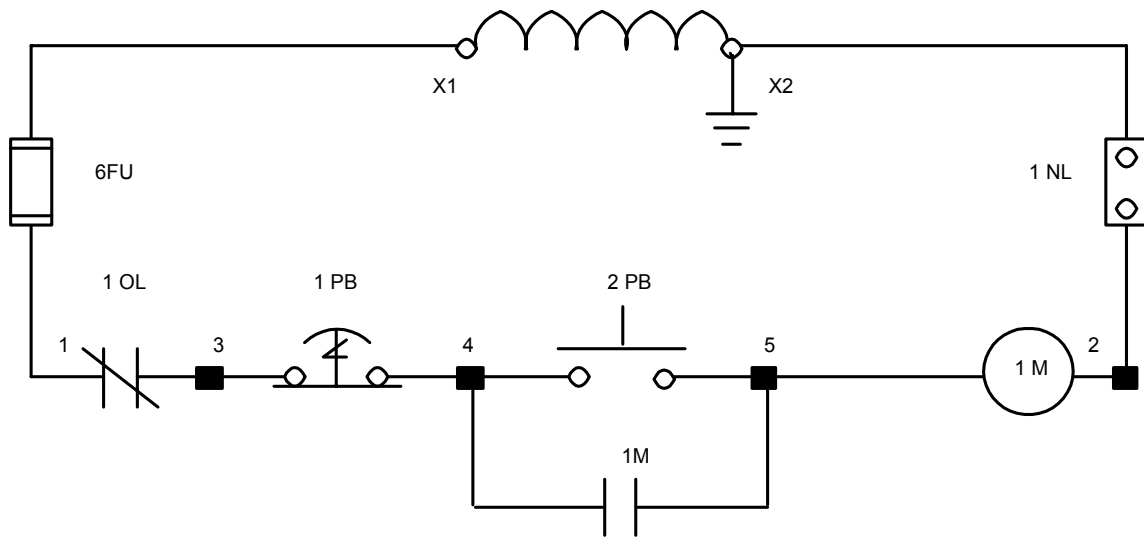


Ground Fault in the Control Circuit - The ground fault is any unwanted current between a line and earth ground or to the chassis of a machine. **This unwanted current will always cause one or more fuses to open.**



For both, short circuit faults or ground faults, one or more fuses will blow. The symptoms for these faults are sometimes similar (0Ω) but a troubleshooter must know the difference in order to evaluate the fault. The short circuit and ground faults analysis has already been evaluated for the power circuit. Let's now look at ways to troubleshoot the control circuit and evaluate whether it's a short circuit or ground fault.

Let's use the schematic below as an example. It is easy to see that if a short circuit occurs, it must be inside the cabinet because wire #2 does not leave the cabinet. The ground fault, however, can occur either inside or outside the cabinet because the pushbuttons (1PB and 2PB) are located outside the cabinet.

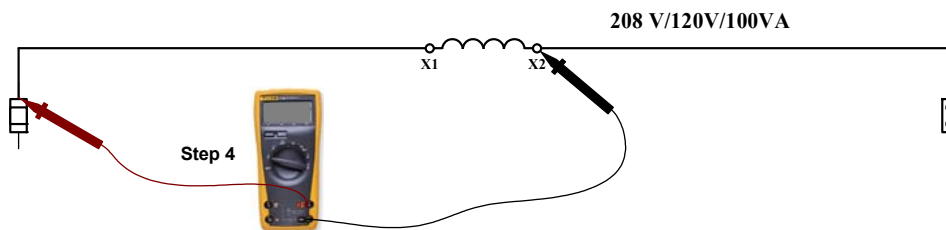


Scenario A is the motor does not start when the start button is pressed. The **correct voltage is present at X1 and X2**, the contactor is not energized and the problem is in the control circuit. For Scenario A, the fault is a **short circuit fault** from wire #9 to wire #2 and **inside the panel**.

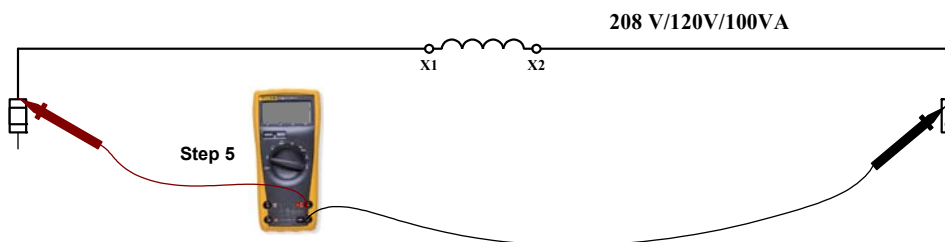
Remember the first three steps will always be the same. You should have read the voltage at terminals X1 and X2 and the correct voltage is present (120 volts).

Since the correct voltage is present we must troubleshoot the system in a logical order until we lose the correct voltage. The following measurements are just like open circuit troubleshooting in the control circuit until we find that a **fuse is open**.

- Step 8.** You should check the voltage on X1 at the top of the control circuit fuse and X2 terminal at the secondary of the control transformer.
- If the correct voltage is present, continue to Step 5.
 - If the correct voltage is not present, then X1 wire is open from the top of the fuse to the terminal on the secondary of the transformer.

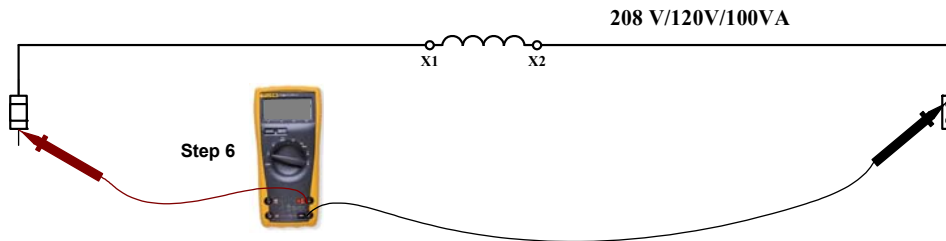


- Step 9.** You should check the voltage on X1 at the top of the control circuit fuse and X2 at the top of the neutral link.
- If the correct voltage is present, continue to Step 6.
 - If the correct voltage is not present, then X2 wire is open from the top of the neutral link to the terminal on the secondary of the transformer.



Step 10. You should check the voltage on wire #1 at the bottom of the control fuse and X2 at the top of the neutral link.

- If the correct voltage is present, continue to Step 7.
- If the correct voltage is not present, then the control fuse is open. **If the fuse is open, then there is either a short circuit or ground fault. This is our first indication that the fault is a short circuit or ground fault.**



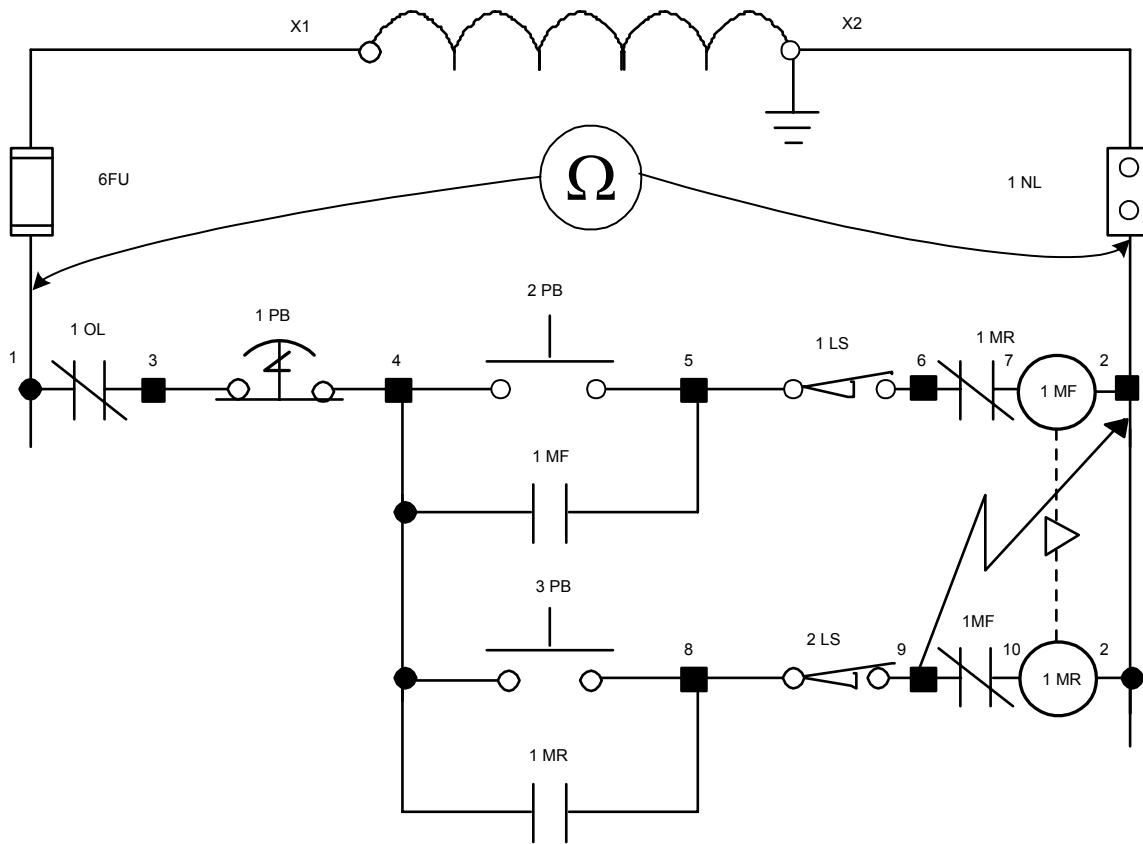
Since we have determined that a fuse has opened, voltage readings can not be used. We must find out the cause. It could be a **short circuit or a ground fault**. We don't know which yet but both give the same indication (**0Ω**).

We will use the ohmmeter and use logical troubleshooting from left to right, top to bottom

We will be using wire #2 as a reference for the following measurements.

We will, first, find the 0 Ω reading and then determine if it is a short circuit or a ground fault.

You should follow the appropriate lockout procedure.



Step 11. Measure the ohmic value from wire #1 to #2.

- If the meter reads 0 Ω, then wire #1 and everything connected to it are either shorted or grounded.
- If the meter reads the expected ohmic value (open loop), then wire #1 is OK. Go to Step 8.

Step 12. Measure the ohmic value from wire #3 to #2.

- If the meter reads 0 Ω, then wire #3 and everything connected to it are either shorted or grounded.
- If the meter reads the expected ohmic value (open loop), then wire #3 is OK. Go to Step 9.

- Step 13.** Measure the ohmic value from wire #4 to #2.
- If the meter reads 0 Ω , then wire #4 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (open loop), then wire #4 is OK. Go to Step 10.
- Step 14.** Measure the ohmic value from wire #5 to #2.
- If the meter reads 0 Ω , then wire #5 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (**100 Ω**), then wire #5 is OK. Go to Step 11.
- Step 15.** Measure the ohmic value from wire #6 to #2.
- If the meter reads 0 Ω , then wire #6 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (**100 Ω**), then wire #6 is OK. Go to Step 12.
- Step 16.** Measure the ohmic value from wire #7 to #2.
- If the meter reads 0 Ω , then wire #7 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (**100 Ω**), then wire #7 is OK. Go to Step 13.
- Step 17.** Measure the ohmic value from wire #8 to #2.
- If the meter reads 0 Ω , then wire #8 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (**100 Ω**), then wire #8 is OK.

Wire #8 read 0 Ω and should have read 100 Ω . We have located the problem area, but there are still many different possibilities, wire #8, 9, 10 are either shorted or grounded.

- Step 18.** Measure the ohmic value from wire #8 to #2 again. It should still be 0 Ω . Now open the neutral link.
- If the meter still reads 0 Ω , then wire #8 and everything connected to it are **shorted**.
 - If the meter reads the expected ohmic value (100 Ω), then wire #8 is **grounded**. To verify, measure the ohmic value from wire #8 to earth ground. The reading should be 0 Ω .

The 0 Ω reading to wire #2 proves to us that the fault is a short circuit to wire #2 and is not a ground fault. This neutral link is provided for that specific reason. Since we know that our fault is a short circuit to wire #2 and it doesn't leave the panel, we know that wire #8, 9 or 10 is touching wire #2 in the panel. We must now eliminate the possibilities.

- Step 19.** Push 1MF in to open the normally closed contacts with wire #9 and #10 connected. Measure the ohmic value from wire #10 to #2.
- If the meter still reads 0 Ω , then wire #10 is shorted.
 - If the meter reads the expected ohmic value (100 Ω), then wire #10 is eliminated.

- Step 20.** Remove wire #8 from the top of the terminal strip. Measure the ohmic value from wire #8 to #2.
- If the meter still reads 0 Ω , then wire #8 is shorted inside the panel.
 - If the meter reads the expected ohmic value (open loop), then wire #8 is eliminated.

- Step 21.** Remove wire #9 from the top of the terminal strip. Measure the ohmic value from wire #9 to #2.
- If the meter still reads 0 Ω , then wire #9 is shorted inside the panel.

We now know that wire #9 is shorted to wire #2 somewhere inside the panel. We now have to find it through visual inspection. Once the fault is found, then repaired and verified, reconnect all wires, replace the fuse, remove the locks, and turn on the power. The machine should be ready to check out.

Scenario B is the motor does not start when the start button is pressed. The **correct voltage is present at X1 and X2**, the contactor is not energized and the problem is in the control circuit. For Scenario B, the fault is a **ground fault** from wire #9 to ground and **outside the panel**.

Remember the first three steps will always be the same. You should have read the voltage at terminals X1 and X2 and the correct voltage is present (120 volts).

Since the correct voltage is present we must troubleshoot the system in a logical order until we lose the correct voltage. The measurements made in Step 4 through Step 6 will be the exact same as with Scenario B. They are just like open circuit troubleshooting in the control circuit until we find that **a fuse is open**.

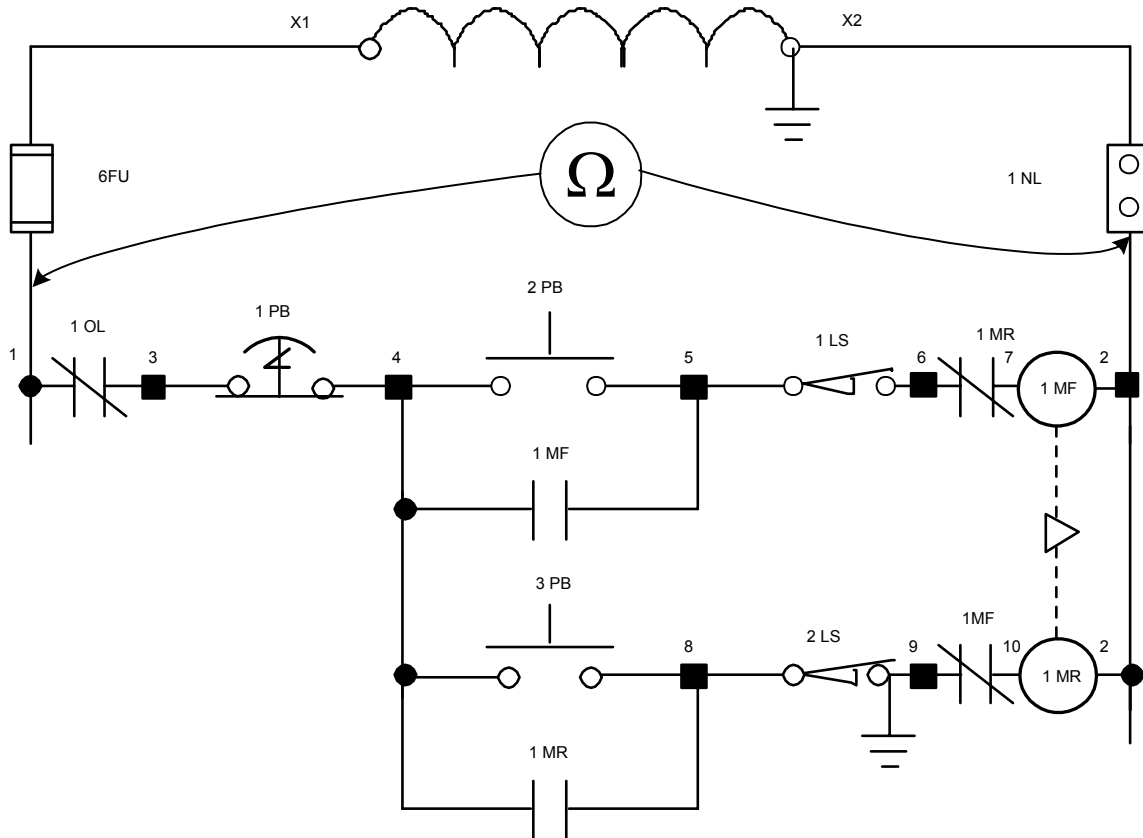
Once we have determined that a fuse has opened, voltage readings can not be used. We must find out the cause. It could be a **short circuit or a ground fault**. We don't know which yet but both give the same indication (**0Ω**).

We will use the ohmmeter and use logical troubleshooting from left to right, top to bottom.

We will be using wire #2 as a reference for the following measurements.

We will, first, find the 0 Ω reading and then determine if it is a short circuit or a ground fault.

You should follow the appropriate lockout procedure.



We will use the same method with Scenario B. The steps up through opening the neutral link will be the same as Scenario A. Let's review those steps:

Step 7. Measure the ohmic value from wire #1 to #2.

- If the meter reads 0 Ω , then wire #1 and everything connected to it are either shorted or grounded.
- If the meter reads the expected ohmic value (open loop), then wire #1 is OK. Go to Step 8.

Step 8. Measure the ohmic value from wire #3 to #2.

- If the meter reads 0 Ω , then wire #3 and everything connected to it are either shorted or grounded.
- If the meter reads the expected ohmic value (open loop), then wire #3 is OK. Go to Step 9.

- Step 9.** Measure the ohmic value from wire #4 to #2.
- If the meter reads 0 Ω , then wire #4 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (open loop), then wire #4 is OK. Go to Step 10.
- Step 10.** Measure the ohmic value from wire #5 to #2.
- If the meter reads 0 Ω , then wire #5 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (**100 Ω**), then wire #5 is OK. Go to Step 11.
- Step 11.** Measure the ohmic value from wire #6 to #2.
- If the meter reads 0 Ω , then wire #6 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (**100 Ω**), then wire #6 is OK. Go to Step 12.
- Step 12.** Measure the ohmic value from wire #7 to #2.
- If the meter reads 0 Ω , then wire #7 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (**100 Ω**), then wire #7 is OK. Go to Step 13.
- Step 13.** Measure the ohmic value from wire #8 to #2.
- If the meter reads 0 Ω , then wire #8 and everything connected to it are either shorted or grounded.
 - If the meter reads the expected ohmic value (**100 Ω**), then wire #8 is OK.

Wire #8 read 0 Ω and should have read 100 Ω . We have located the problem area, but there are still many different possibilities, wire #8, 9, 10 are either shorted or grounded.

- Step 14.** Measure the ohmic value from wire #8 to #2 again. It should still be **0 Ω**. Now open the neutral link.
- If the meter still reads 0 Ω, then wire #8 and everything connected to it are **shorted**.
 - If the meter reads the expected ohmic value (**100Ω**), then wire #8 is **grounded**. To verify, measure the ohmic value from wire #8 to earth ground. The reading should be **0 Ω**.

The 0 Ω reading to earth ground proves to us that the fault is a ground fault and is not a short circuit. This neutral link is provided for that specific reason. Since our fault is a ground fault and could be inside or outside of the panel, we know that wire #8, 9 or 10 is touching earth ground or something connected to earth ground. We must now eliminate the possibilities and use earth ground as our reference with the neutral link open.

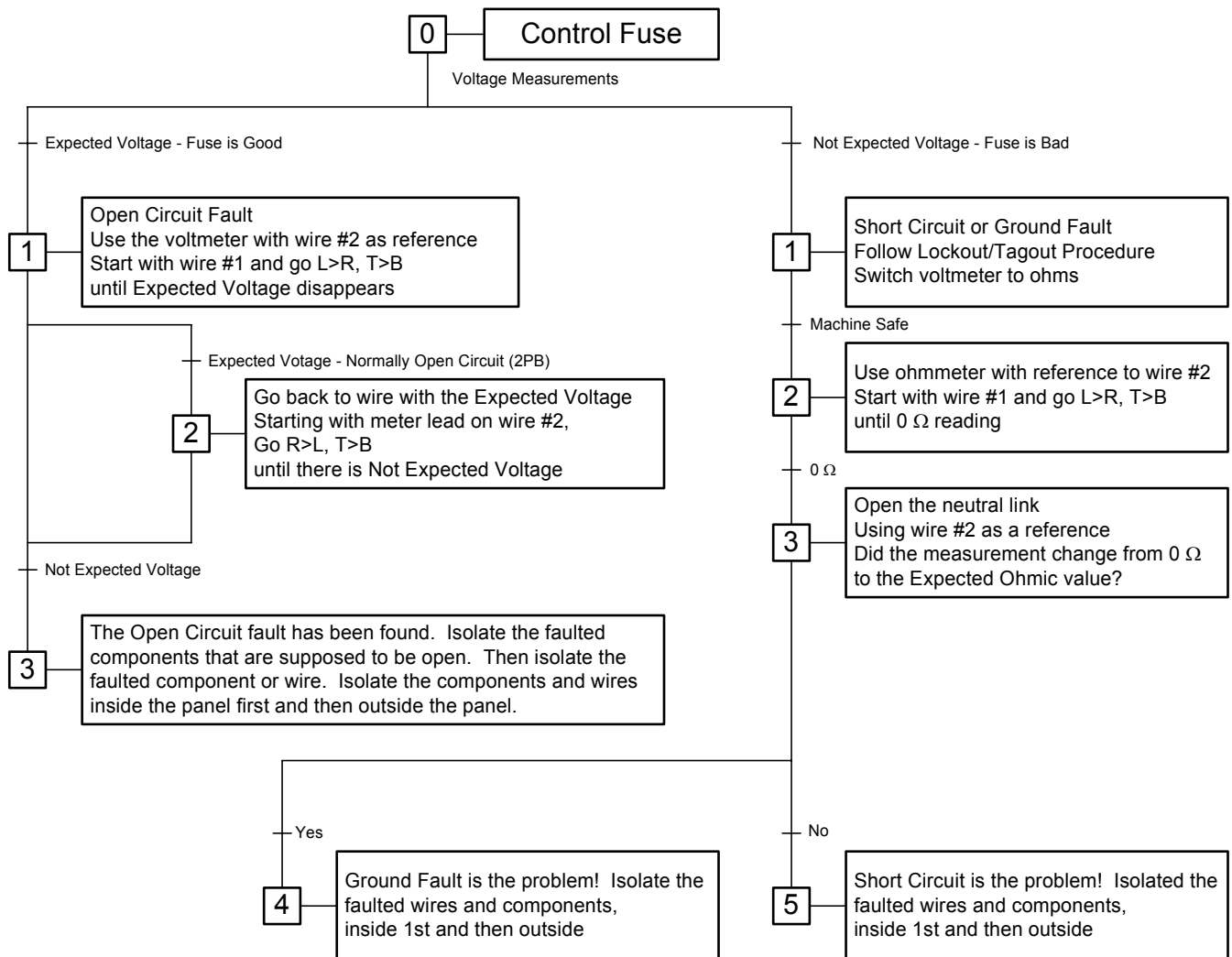
- Step 15.** Push 1MF in to open the normally closed contacts with wire #9 and #10 connected. Measure the ohmic value from wire #10 to earth ground.
- If the meter still reads 0 Ω, then wire #10 is grounded.
 - If the meter reads the expected ohmic value (open loop), then wire #10 is eliminated.
- Step 16.** Remove wire #8 from the top of the terminal strip. Measure the ohmic value from wire #8 to earth ground.
- If the meter still reads 0 Ω, then wire #8 is grounded inside the panel.
 - If the meter reads the expected ohmic value (open loop), then wire #8 inside the panel is eliminated.
- Step 17.** Remove wire #8 from the bottom of the terminal strip. Measure the ohmic value from wire #8 to earth ground.
- If the meter still reads 0 Ω, then wire #8 and #9 are grounded outside the panel.
 - If the meter reads the expected ohmic value (open loop), then wire #8 outside the panel is eliminated and the terminal is grounded.
- Step 18.** Remove wire #9 from the top of the terminal strip. Measure the ohmic value from wire #9 to earth ground.
- If the meter still reads 0 Ω, then wire #9 is grounded inside the panel.
 - If the meter reads the expected ohmic value (open loop), then wire #9 inside the panel is eliminated.

Step 19. Remove wire #9 from the bottom of the terminal strip. Measure the ohmic value from wire #9 to earth ground.

- If the meter still reads 0 Ω , then wire #8 and #9 are grounded outside the panel.
- If the meter reads the expected ohmic value (open loop), then wire #9 outside the panel is eliminated and the terminal is grounded.

Step 20. Go to 2LS and check wire #8 and #9, removing them from the terminals of the limit switch. You should visually find wire #9 grounded to the chassis of the switch or to the ground wire for the switch. Once the fault is found, repaired and verified, reconnect all wires, replace the fuse, remove the locks, and turn on the power. The machine should be ready to start.

Control Circuit Troubleshooting Flow Diagram





CONTROL DEVICES

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PUSH BUTTON CONTROL STATIONS

A push button station is a device that can provide control of a motor with the pressing of the appropriate push button. With push button stations a motor can be controlled from any one of several locations while only using one magnetic starter. The start, forward, reverse, fast, slow and stop operations of a motor may be controlled by push buttons. Auxiliary push buttons are used to control the motor from remote points. The auxiliary control may be a simple stop or start button, or the same controls as the main station. Industrial push buttons are used in control circuits to actuate magnetic contactors or remote-operated controllers which handle power circuits.

Push buttons are pilot devices and must be ruggedly constructed to withstand operator and mechanical abuse. They are frequently exposed to oils, coolants, chemicals, dusts, and various foreign elements. Heavy electrical loads are sometimes carried by the contacts of the push button because of the high inrush current drawn by larger contactors. Push buttons are classified as standard-duty or heavy-duty, according to their current handling capabilities. Heavy-duty oil tight, and multi-light-control oil-tight are classified according to their ability to withstand these conditions. The terms standard-duty and heavy-duty describe only the contact capacity of the push button in its making and breaking ability. These designations have no reference to the service conditions or frequency of operation.

STANDARD DUTY PUSH BUTTONS

Most systems use standard duty push button stations to control A-C or D-C starters. General-purpose push button stations are designed for operating flexibility and ease of wiring. Padlocking attachments are sometimes added to the push button stations. These padlocking attachments are added to lock the "stop" button in the depressed position.

SINGLE CONTACT RATINGS

Standard-duty units have contacts rated for pilot duty, typically as follows:

A-C

3.0 Amperes, 120 volts

1.5 Amperes, 240 volts

0.75 Ampere, 480 volts

0.6 Ampere, 600 volts

HEAVY DUTY PUSH BUTTONS

Heavy-duty push button stations are found in many industrial applications. They have approximately twice the current rating of the standard-duty station. They come with any combination of push buttons, selector switches, jogging buttons, and pilot lights. Push buttons are available with flush, extended, or mushroom heads. They may have either momentary or maintained contacts. Heavy-duty push button units have double-break contacts rated for pilot duty, typically as follows:

A-C

6 Amps, 120 Volts

3 Amps, 240 Volts

1.5 Amps, 480 Volts

1.2 Amps, 600 Volts

D-C

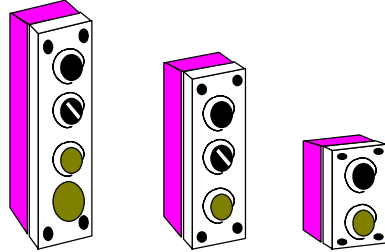
1.1 Amps, 120 Volts

0.55 Amps, 230 Volts

0.2 Amps, 550 Volts

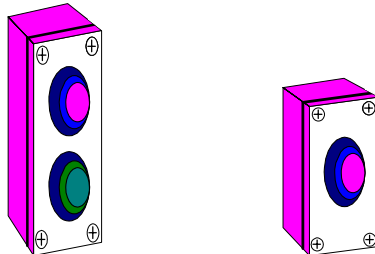
PUSH BUTTON STATION DESCRIPTIONS

General-purpose stations have steel bases and steel wraparound covers that fit tightly to exclude dirt and dust, as illustrated below.



Watertight and **dust tight** stations have a stainless steel enclosure with a gasket between the cover and base.

Water tight, **corrosion-resistant** stations are intended for applications where they are subject to corrosive fumes or liquids. The enclosure is made of nonmetallic material, and synthetic rubber boots protects the push buttons. This is illustrated below.

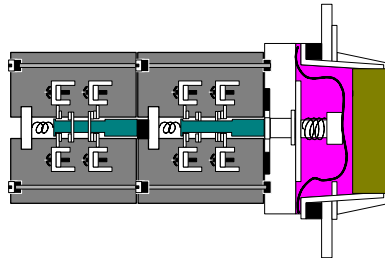


Push button stations for hazardous locations are suitable for hazardous gas and hazardous dust locations. A machined surface is provided between the cover and base.

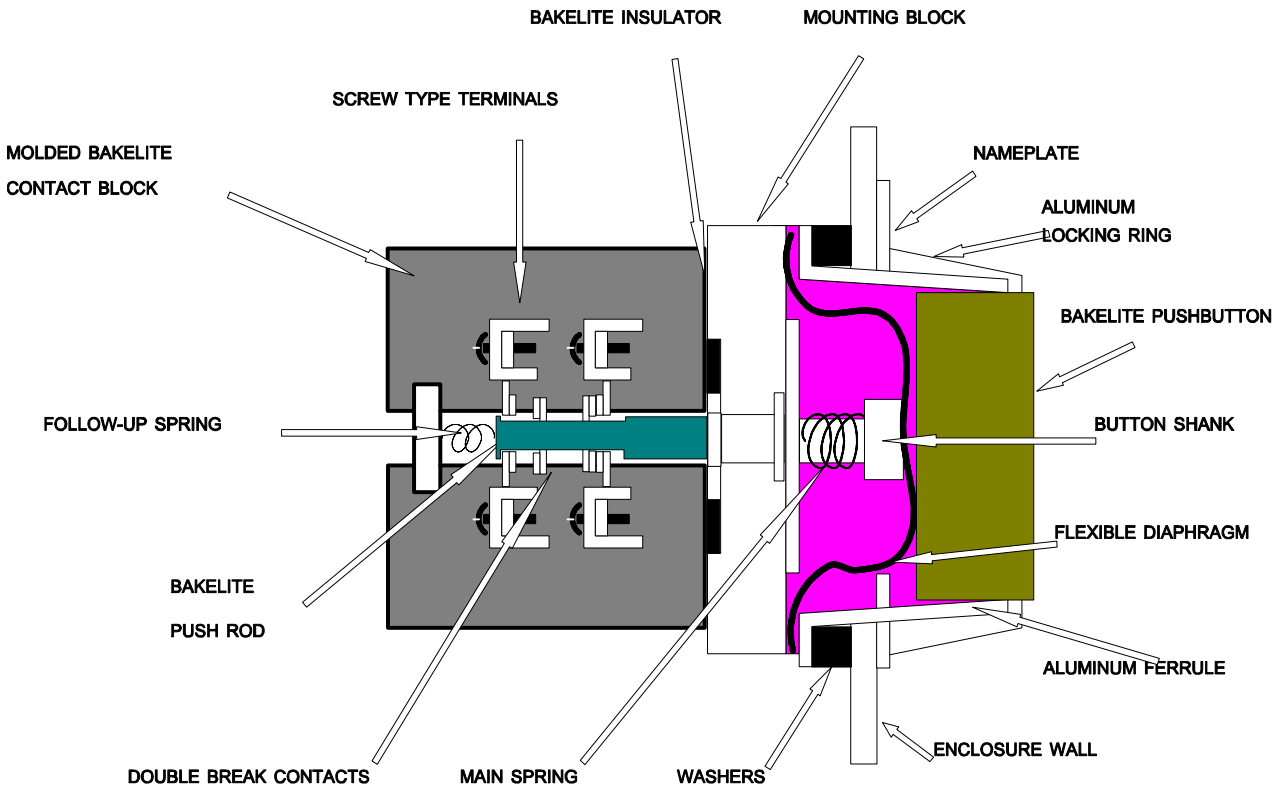
Oil tight push button control stations are used wherever there is presence of oil, coolant, and other noncorrosive industrial liquids. These control stations may be the surface mounted, flush mounted or pendant types. These stations have an enclosure that is sealed with a neoprene gasket. One or more neoprene washers tightly seal individual oil tight units.

All these control units may include momentary or maintained contact push buttons. The contacts are usually the double-break type. These contact blocks can be assembled in numerous contact arrangements.

Single and double circuit constructed contact blocks are frequently used in any combination of "normally open" or "normally closed" circuits. Double circuit blocks have an individually operated contact plunger for each circuit made from high strength phenolic to resist cracking and warping. Several contact blocks can be stacked behind the push button operator, as illustrated below.



Each unit usually consists of two parts, the operator and the contact block. The bodies of the operators are die-castings, the operating buttons are molded plastic, and the locking rings are usually aluminum. One or more synthetic rubber washers provide the oil tight seal between the panel and operator.



ACCESSORIES

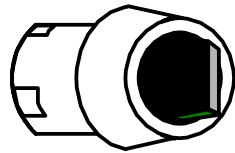
Some types of push button stations may be supplied with a padlocking attachment that locks the **stop** button in the depressed position. Some push button stations may have pilot lights on them that indicate their particular function. Push button stations usually use mushroom heads as an **E-stop** button.

PUSH BUTTON OPERATORS

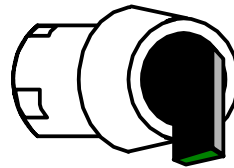
Different types of push button and cylinder lock operators are used. Some of these are flush button, extended button, mushroom head, and jumbo mushroom head. The buttons are a solid color usually made of molded plastic. The cylinder lock type push button can be locked in various positions and the key can be removed from the lock. A keyhole "dust cover" prevents dirt and other foreign matter from entering. Key operators may be used with identical locks, dissimilar locks, or with dissimilar locks having a master key system.

SELECTOR SWITCH OPERATORS

Selector Switches can be obtained in two, three, four, and etc. position types. Cams in the operator sleeve actuate the contact blocks. These selector switches can provide *maintained* or *spring return* contact operation. Many circuit combinations can be made since there is a number of different operating cams available and a variety of contact blocks.



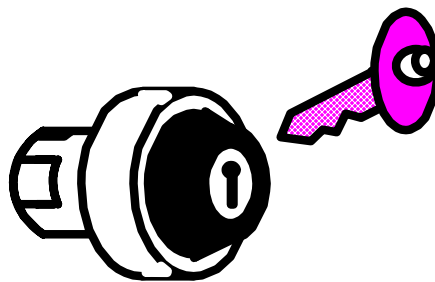
Standard Lever



Extended Lever

KEY OPERATED SELECTOR SWITCH

Key operated selector switches work just like normal selector switches plus a key locking feature to prevent unauthorized change or accidental tripping from a selected position. These switches also provide maintained or spring return momentary cam action on the contact plungers.



Key Operator

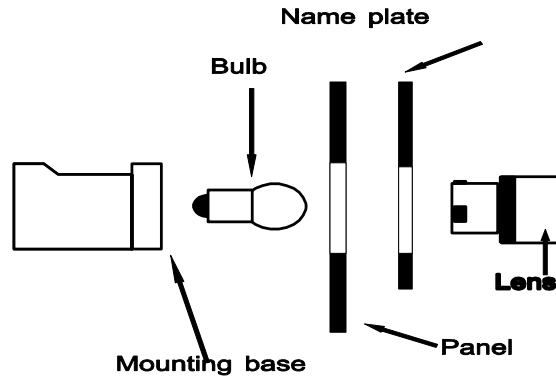
ILLUMINATED PUSH BUTTONS

These devices combine the functions of both a push button operator and an indicating light in a single unit and require only half the space of two separate units. The light unit may be either a resistor type or an encapsulated transformer. These units are usually designed to give illumination from all angles. The contact blocks can still be used for circuit control as before. A rubber diaphragm in the operator, a rubber lens gasket, and a rubber panel gasket can provide oil tight assembly.

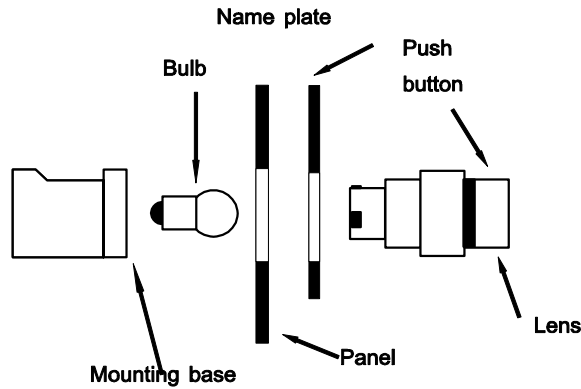
INDICATING LIGHTS

Indicating lights can tell you at a glance what is happening. They indicate if everything is ready for operation or operating smoothly. They also can warn of possible trouble and malfunction. Indicating lights also alert the attendant of the next operation for their machine. Therefore, it is important that indicating lights function accurately.

Standard indicating lights can have either a transformer built in to change the voltage or the lamps are rated for the exact voltage. Indicating lights are available for both AC and DC voltages. They are also available in color with plastic or glass lenses.



The press-to-test type indicating lights can test to see if the lamp is burned out.



LIMIT SWITCHES

Limit switches are devices used for interlocking a mechanical motion or position with an electrical circuit. The selection of a limit switch involves both electrical application requirements and mechanical placement.

Limit switches are normally in the control circuit and can start a machine in motion or stop its motion. They can also restrict the travel of a machine between two points or possibly initiate a separate action at a pre-determined point of machine travel.

Limit switches are also often used in safety devices for the protection of both personnel and equipment.

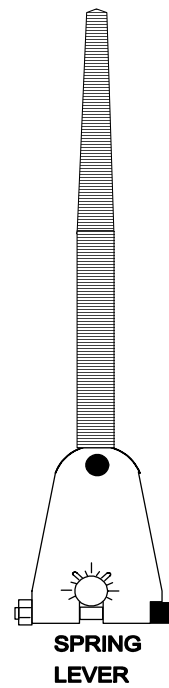
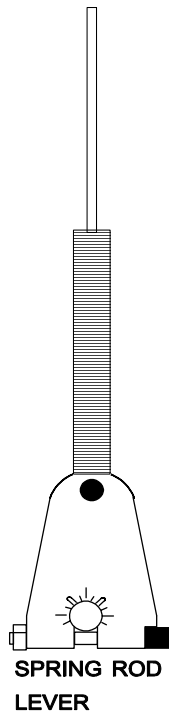
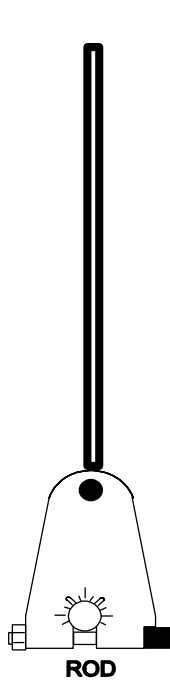
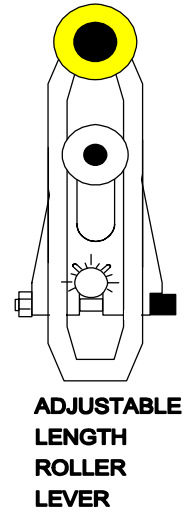
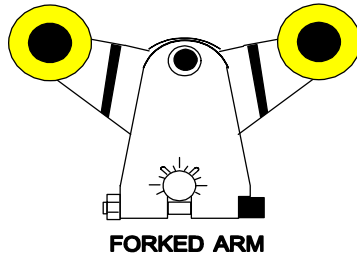
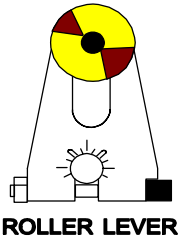
TYPES OF LIMIT SWITCHES

The function performed by limit switches is similar no matter how complex the design of the electrical circuit. The main differences are the mechanical design and the means by which the switch is actuated.

ACTUATORS

An actuator is the external linkage that detects the mechanical movement of the machine. This actuates an internal mechanism that results in contacts opening or closing.

EXAMPLES OF ACTUATORS





OVERCURRENT RELAY TECHNOLOGY

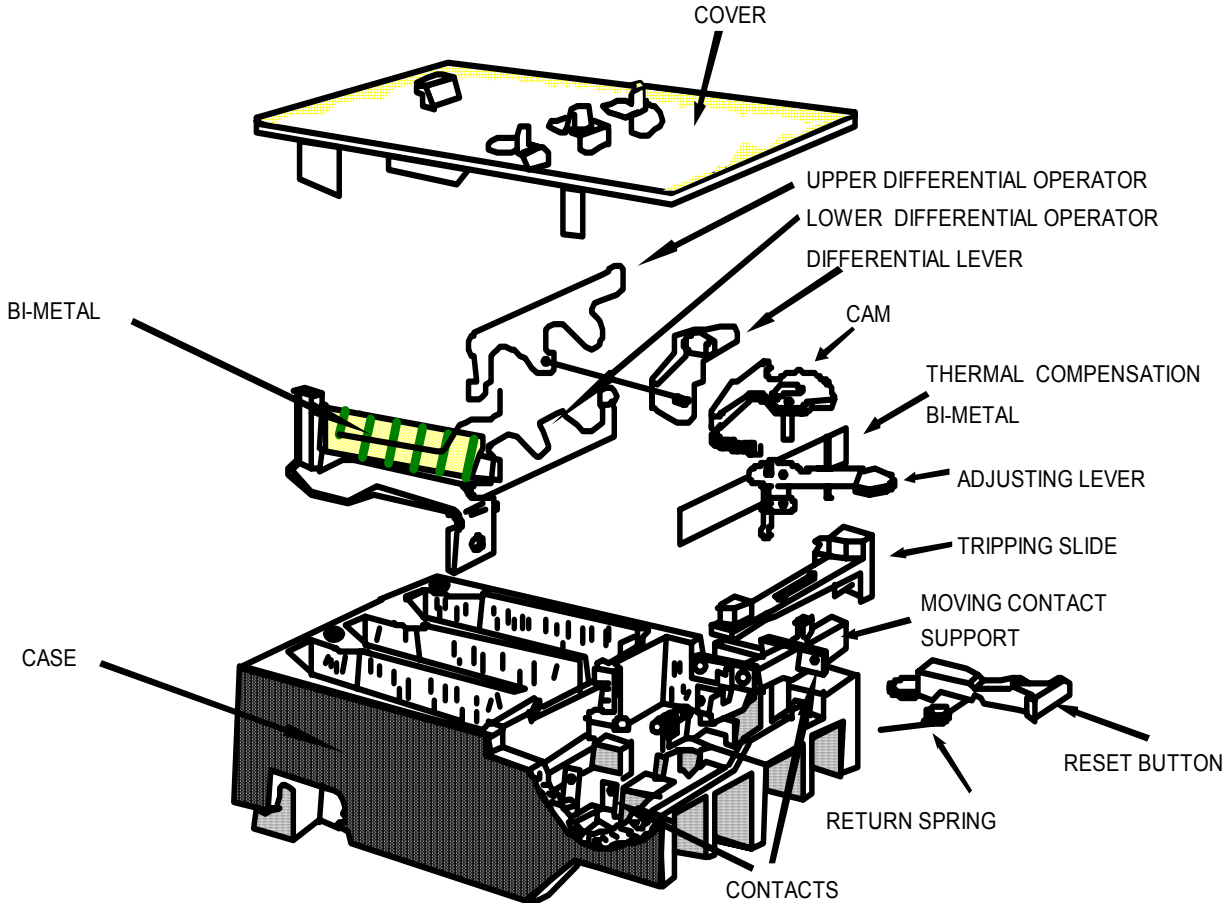
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CONSTRUCTION

TELEMECANIQUE
LR1-D



O/L SPECIFICATIONS

OPERATING RANGES

LR1-DO9		LR1-D12	LR1-D16	LR1-D25	LR1-D40	LR1-D63
0.1-0.16A 0.16-0.25A 0.25-0.4A 0.4-0.63A 0.63-1.0A	1-1.6A 1.6-2.5A 2.5-4A 4-6A 5.5-8A 7-10A	10-13A	13-18A	18-25A	23-32A 30-40A	38-50A 48-57A 57-66A

Maximum Voltage: 600V AC or DC

Frequency Range: up to 400 Hz

CONTACTS

1 Normally Open and 1 Normally Closed

AMBIENT TEMPERATURE COMPENSATION

From - 4 to 140 °F
-20 to 60 °C

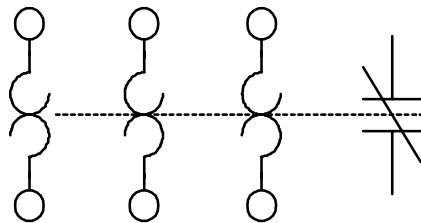
DIFFERENTIAL

Phase loss and phase unbalance detection

FUNCTION - The overcurrent relay is used to protect motors in case of:

- Prolonged Overcurrent (**105 to 125% Full Load Current**)
- Phase Unbalance
- Phase Loss

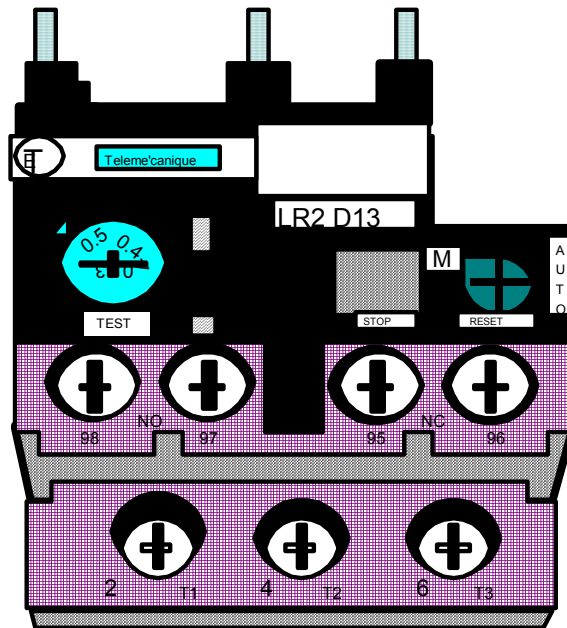
SYMBOL



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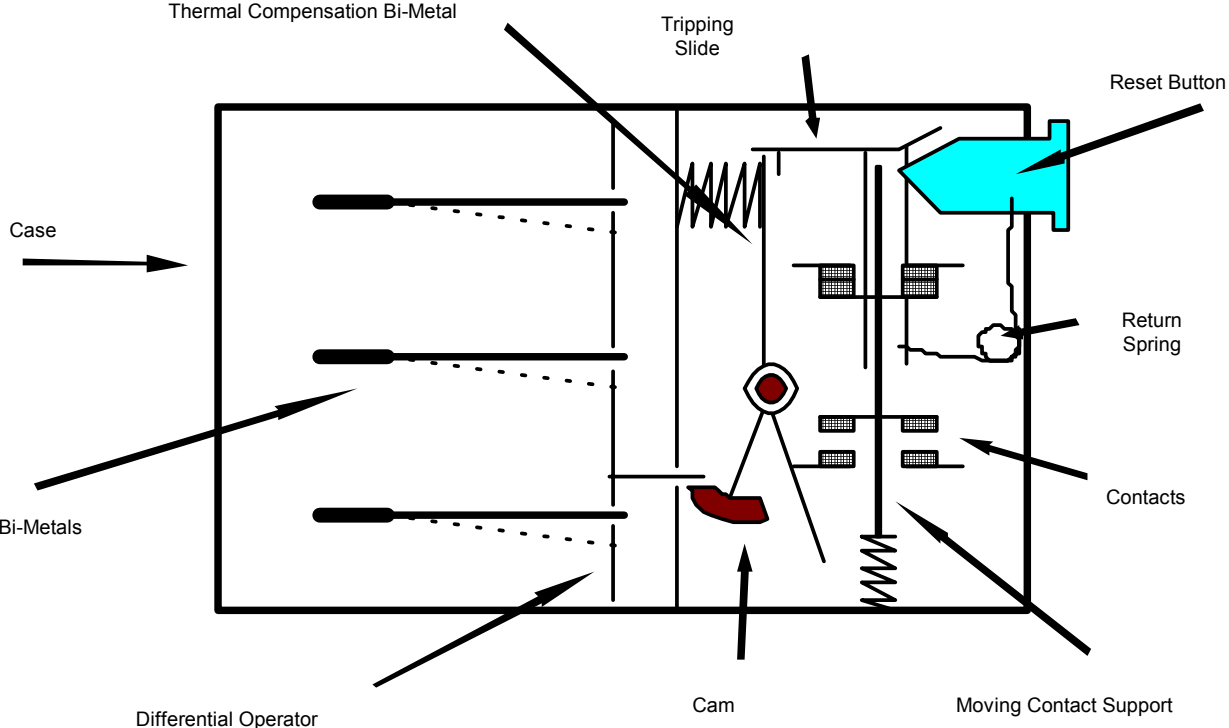
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ADJUSTMENT and RESETTING

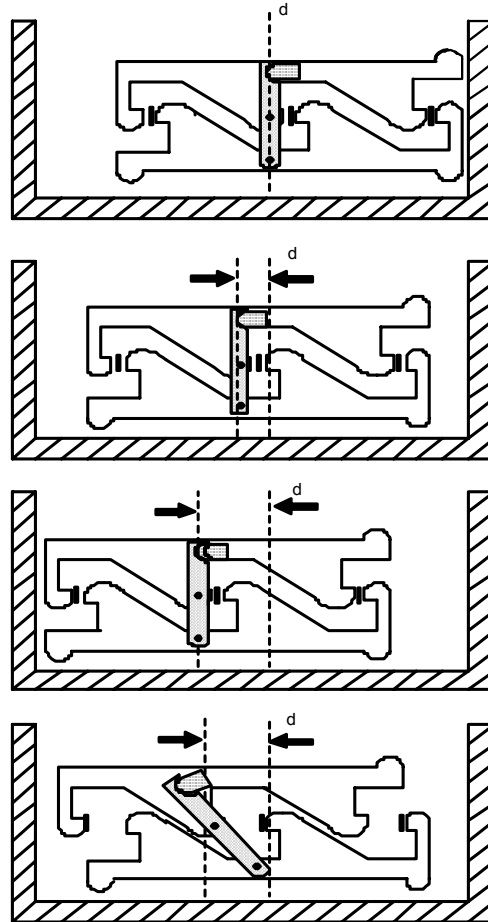


- ADJUSTMENT - **Adjusting dial must be set to read the full load current of the motor (FLC).**
- RESETTING - **Resetting is done by pressing the blue reset button after the bi-metal elements have been allowed to cool down.**

MECHANICAL OPERATION



DIFFERENTIAL OPERATION



- COLD POSITION - The differential operators are hard over to the right.
- WARM POSITION - **NORMAL BALANCED CURRENT** - The 3 bi-metals and the operators move to the left the same distance **d**.
- WARM POSITION - **BALANCED OVERCURRENT** - The 3 bi-metals and the operators move over to the left the same distance which trips the overcurrent relay. Tripping current is 125% of the actual adjusting dial value.
- WARM POSITION - **UNBALANCED CURRENT** - The unbalanced current causes unequal deflection of the 3 bi-metal strips. The differential lever amplifies this unequal deflection. The distance **d** is also amplified and causes the mechanism to trip. **The tripping current for an unbalanced current is equal to 80% of the current for 3 balanced phases.**



FUSES AND CIRCUIT BREAKERS

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INTRODUCTION TO FUSES

I. **Purpose** - A fuse is intended to safely isolate a fault preventing damage to equipment. Current resulting from an overload or short circuit fault will damage or completely destroy system components if not quickly interrupted. A fuse provides reliable circuit protection preventing or minimizing damage to components such as conductors, transformers, motors, motor starters, etc. Without adequate protection of electrical distribution systems, a fault can result in severe damage to equipment and significant monetary loss due to machine or manufacturing plant downtime.

II. Definitions

A. **Overcurrent** - An overcurrent is excess current resulting from either a short circuit or an overload.

B. **Overload** - An overload is a current that is in excess of normal current but confined to normal conducting paths. An overload current is typically **one to six times the normal current**. It is usually associated with the normal start up of motors or inrush current to a transformer. Provided that the overload current is not continuous, any temperature rise of components will be small and have no harmful effects. An overload current becomes harmful only when it is **sustained**.

An example of a sustained overload is a defective or overloaded motor. If an overload is sustained beyond several seconds, components will begin to overheat due to the excess current that they are required to pass. This excess heat will damage or degrade the components and could lead to further problems such as short circuits due to melting insulation.

C. **Short Circuit** - Unlike an overload current, a short circuit current is not confined to normal conducting paths. Also, an overload current is relatively small being only one to six times that of the normal level. A short circuit current can be **several hundred times greater than normal current levels**.

A short circuit current can have very destructive effects totally destroying distribution equipment and causing fires. The heat energy produced by a short circuit current can be great enough to vaporize metal, melt conductors, and cause severe insulation damage. Arcing produces ionized gases that result in other conductive paths and additional short circuits.

Short circuit currents can result in destroying cable trays, warping bus bars and completely disconnecting the bus bars from their retaining supports. Any conductor that carries current will have a magnetic field around the conductor. When conductors are subjected to short circuit currents, the forces produced by the interaction of conductor magnetic fields are very destructive. The forces can typically be several hundred pounds per linear foot of the conductor.

- D. **Voltage Rating** - The voltage rating of a fuse is the **maximum circuit voltage in which the fuse can be safely applied**. If the voltage rating is exceeded, re-strike is possible across the open fuse element. The fuse also may not safely clear the fault. For instance, a 250volt fuse could safely be used in a 208volt system but not in a 480volt system. The voltage rating is marked on the fuse and is usually related to its physical length within the manufacturer's specifications. This is not to say that all 600volt fuses are all the same length, but that most manufacturers have length specifications for their 600 volt fuses within its applications.
- E. **Continuous Current Rating** - The continuous current rating on the fuse is the current that the fuse is intended to normally carry. The fuse will carry this current indefinitely. In selecting the continuous current rating, consideration must be given to the type of load, application and code requirements. The continuous current rating is marked on the fuse and is usually related to its physical diameter. This is not to say that all 30 ampere fuses are the same diameter, but that most manufacturers have diameter specifications for their 30 ampere fuses within its applications.
- F. **Interrupting Rating** - A fuse must be able to withstand the destructive energy of a short circuit current and be able to interrupt the current without **rupture**. **The interrupting rating is the maximum short circuit current that a fuse can safely interrupt without rupturing**. The National Electric Code, Section 110-9, requires equipment intended to break current at fault levels to have an interrupting rating sufficient for the current that must be interrupted. Analysis of a distribution system must be made to estimate available short circuit fault currents. Upon completed analysis, fuses with an adequate interrupting rating can be selected. A typical short circuit current available from a 500KVA, 480 Volt transformer is approximately 50,000 amperes.
- G. **Current Limitation** - The term current limitation is associated with short circuit conditions, not overloads. **A fuse is said to be current limiting if it operates quickly under short circuit conditions, typically in less than one half of a cycle**. By opening quickly, the instantaneous peak short circuit current is **limited** to a value much less than the peak that would otherwise occur. This greatly reduces the heat energy that would otherwise be let-through to circuit conductors and components. The total energy let-through by a fuse is a function of the product of the current squared and time in seconds (I^2t). A circuit breaker being an inherently slow device will subject a circuit to the full peak short circuit current for several cycles before opening. During this period of time, circuit conductors and components are being subjected to an enormous amount of heat energy. A fuse being a fast acting current limiting device can be used in combination with a breaker to overcome the breaker's limitation.
- H. **Selective Coordination** - Selective coordination concerns the need to prevent facility blackouts. **If distribution systems protective devices are selective, only the protective device nearest the faulted circuit will open**. Devices upstream remain intact, supplying other feeders. For a system to be selective, a minimum ratio must be maintained between upstream and downstream continuous current ratings. The ratio is specified by the fuse manufacturer and depends on the type of fuse.

III. Fuse Classification

- A. **Safety/Standards Organizations** - Various safety and standard organizations exist which assign classifications to fuses based on the criteria of safety and performance. The most predominant of these organizations is Underwriter's Laboratories, Inc. Underwriter's Laboratories evaluates fuses under specific conditions, regulatory codes and other standards

including international standards. Based upon the results, U.L. may "list" the fuse and assign the fuse a class such as RK1, H, or J. There are U.L. standards that define the criteria that a fuse must meet to be considered belonging to a particular class.

- B. **U.L. Classifications for Low Voltage Fuses** - A low voltage fuse is a fuse with a voltage rating of 600 volts or less. Illustrated on the following pages are charts. These charts list fuses by U.L. classification and their corresponding characteristics.
- C. **Class Types** - Fuses are available with different interrupting ratings which makes misapplication possible. For instance, UL class K5 and class H fuses are both available with the same physical dimensions. Although each fuse has the same physical dimensions, voltage rating and continuous current rating, their interrupting ratings are significantly different. **The class K5 fuse has an interrupting rating of 50,000 to 200,000 amperes** where **the class H fuse has a rating of 10,000 amperes**. If the class H fuse is used in place of the class K5 fuse and a short circuit occurs resulting in a fault current in excess of 10,000 amperes, the class H fuse will rupture possibly injuring nearby personnel. To overcome this problem a **rejection feature** is built into the end ferrules of class RK1 and RK5 fuses. The **"R"** in the class designation indicates a rejection type fuse with a minimum **interrupting rating of 200,000 amperes**. Rejection type fuses will fit only into fuse blocks intended to receive the modified end ferrule. The fuse block rejects a class H fuse, as it will not fit, since it is missing the special end ferrule.

A. **Motor Branch Circuits with Overcurrent Relays**

1. Class RK series dual element time delay fuses (5 inch).
2. Sized to 125% times FLC of the motor and go up to next available nominal size.

$$\text{If FLC of the motor} = 18.7A$$

$$\text{Fuse size} = 18.7A \times 1.25 = 23.375A$$

$$\text{Actual fuse size} = 25A$$

B. **Control Circuit Transformer Primary and Secondary Fuses**

1. Both primary and secondary windings will be fused.
2. Primary fuses - class RK series dual element time delay.
3. Secondary fuses - class K5 single element non-time delay.
4. Primary fuses sized to 125% times the primary current of the transformer and go up to next available nominal size.

$$\text{If primary current} = 5A$$

$$\text{Fuse size} = 5A \times 1.25 = 6.25A$$

$$\text{Actual fuse size} = 7A$$

5. Secondary fuses sized to 125% times the secondary current of the transformer. **Don't exceed the 125%, if needed go down** to next nominal size.

$$\text{If secondary current} = 2.5$$

$$\text{Fuse size} = 2.5A \times 1.25 = 3.125$$

$$\text{Actual fuse size} = 3A$$

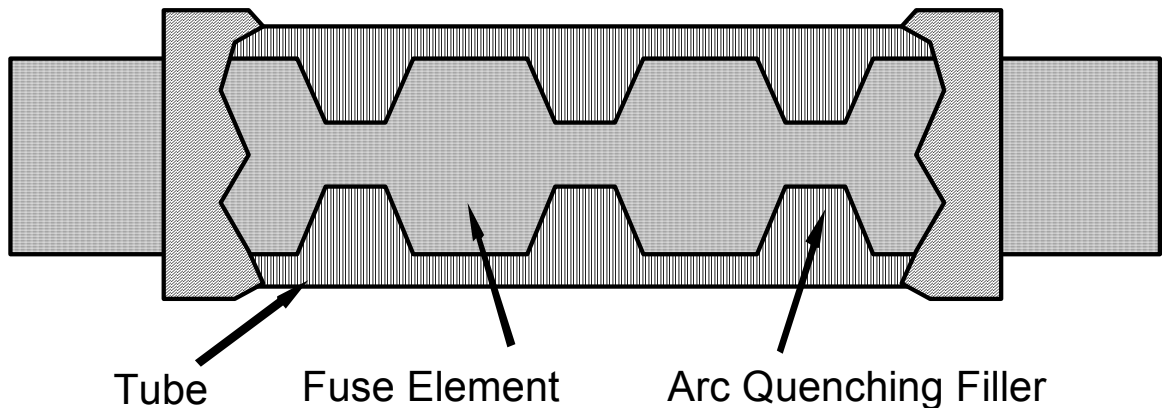
OPERATING PRINCIPLES OF FUSES

High interrupting rated; current-limiting fuses provide safe and reliable protection for electrical distribution systems. They can be used with complete confidence in their performance. Fuses operate from increased fuse element temperature caused by an overcurrent flowing through them. Since the functioning of fuses does not depend on the operation of intricate moving mechanical parts, fuse performance characteristics are reliable. Fuses remain safe and accurate since age does not increase their current carrying capacity nor lengthen their opening time. After a fuse has been used to clear a short-circuit or overload, it is replaced by a new safe, factory calibrated unit, as accurate and dependable as the original. The two basic types of current-limiting fuses are **single element** and **dual element** fuses. Each type has a simple, reliable operation principle.

Semiconductor or Rectifier type fuses are used for special applications on electronic equipment such as power supplies. These fuses are very fast acting and are sized just like the single element type used for a control transformer secondary.

SINGLE ELEMENT FUSES

A single-element fuse consists of a link or several links contained in a tube filled with arc-quenching filler.

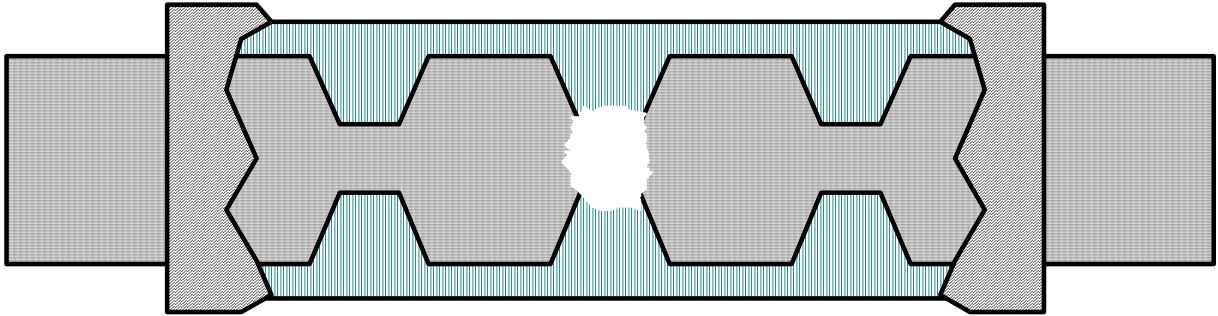


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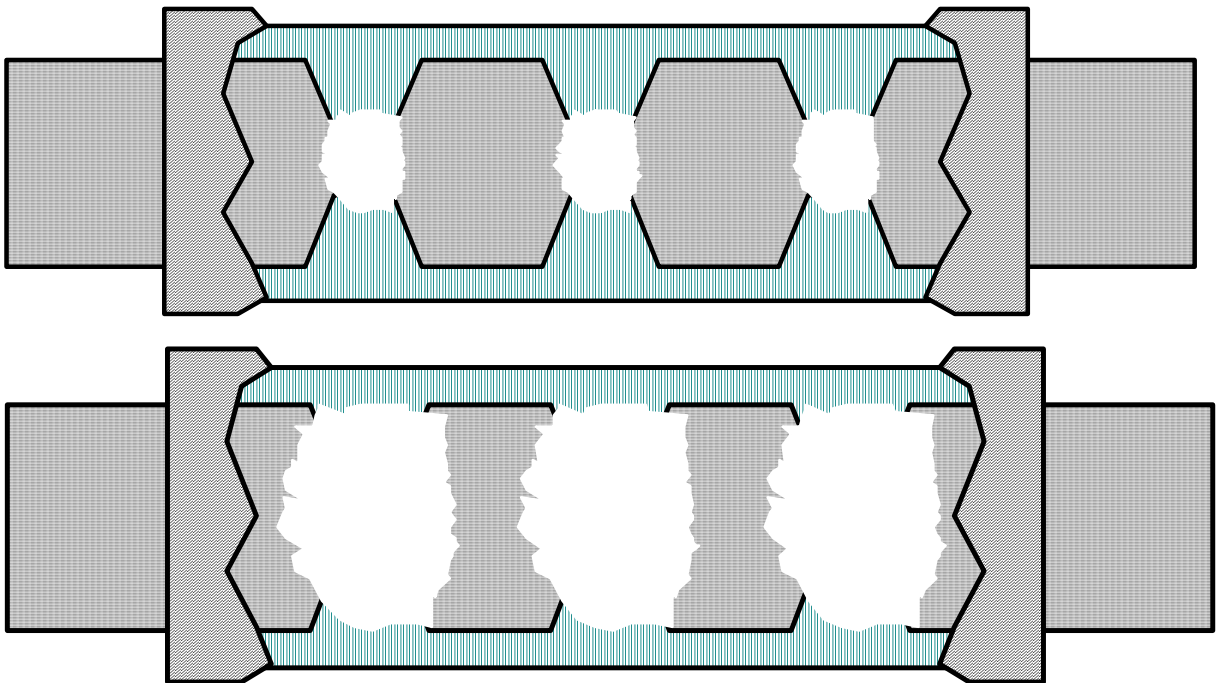
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Overload Operation - If an overload current of more than rated current is continued for a sufficiently long period of time, the fuse link melts. An arc across the resulting gap burns back the metal, lengthening the gap. The arc is quenched and the circuit interrupted when the break is of sufficient length. The surrounding filler aids the arc quenching process.

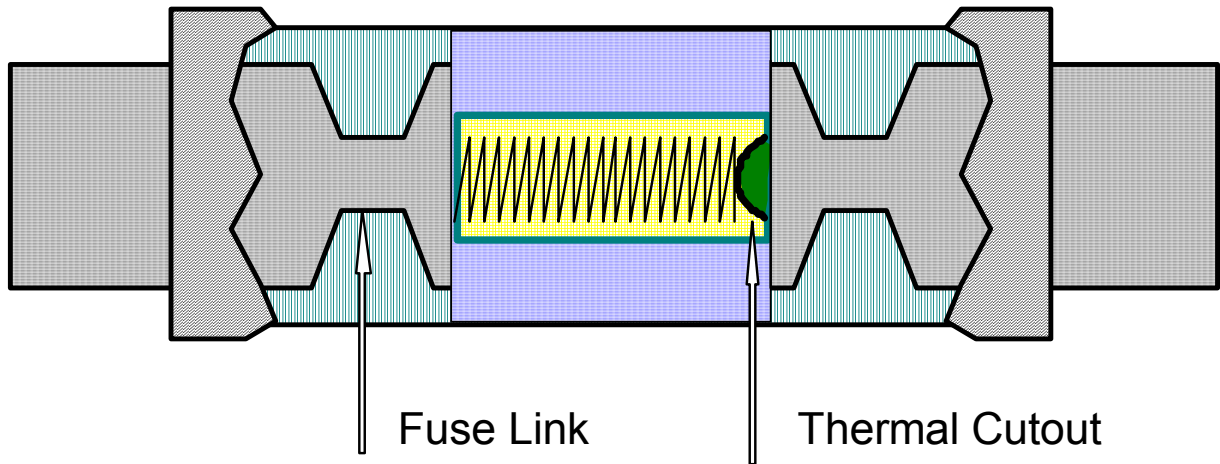


SI

portions of the link commences, and the arc extinguishing filler quickly aids in quenching these arcs, and thus clearing the circuit. Although the fuse opening operation is caused by an increase in the link temperature, the fusing opening operation is safely contained in the fuse casing and the circuit is interrupted in a fraction of a second. The total operating time of current limiting fuses during short circuit conditions can be less than a half cycle (less than 8/1000 of a second). For high short circuit currents the total clearing time can be less than a quarter cycle. It is this fast clearing speed which enables current limiting fuses to protect system components from damage due to high short circuit currents that may occur.



DUAL ELEMENT FUSES



The thermal cutout gives dual element fuses a time delay on overloads, such as motor starting current. This delay allows the motor starting current to be disregarded during that time as long as the current is within five to six times normal running current. The fuse link in dual element fuses provides current limiting, short circuit protection just as single element fuses.

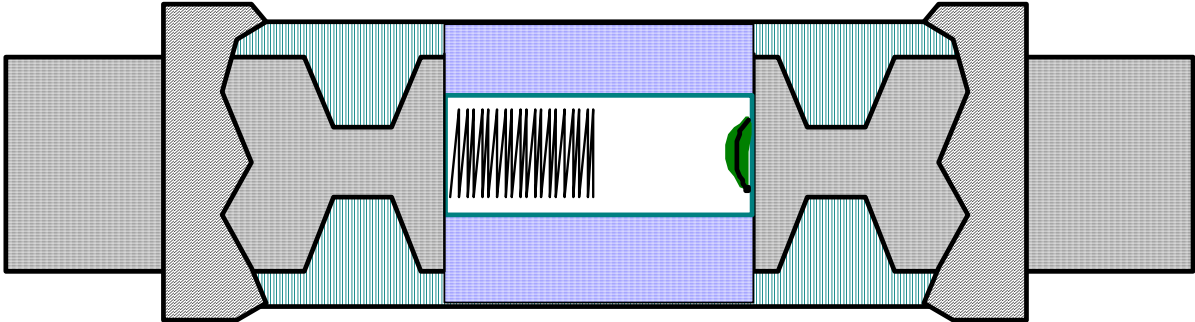
Dual element, time delay fuses utilize this time delay in the low overload range to eliminate needless opening on harmless overloads and transient conditions. These fuses are extremely fast opening and current limiting on short circuit currents. This beneficial time current characteristic is obtained by using two fusible elements (thus the name dual element) connected in series and contained in one tube:

- (1) The thermal cutout element and,
- (2) The fuse link element surrounded with arc extinguishing filler.

The magnitude of the overcurrent determines which element functions. The thermal cutout element is designed to open on overcurrents of up to approximately 500% of the fuse ampere rating. The fuse link or short circuit element is designed to open on heavier overloads and short circuit currents. Typical dual element, time delay fuses by manufacture.

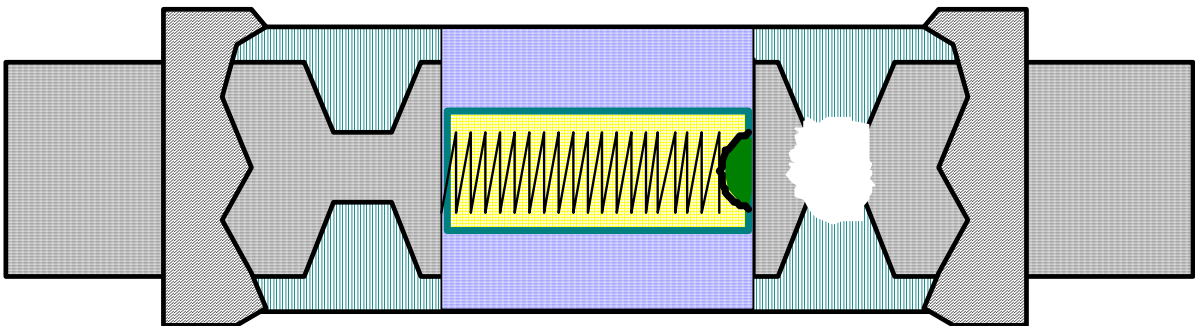
Manufacture	Name	Class
Bussman _____	KTS-R _____	RK1
Bussman _____	DLS-R _____	RK5
Bussman (<i>Fusetron</i>) _____	FRS-R _____	RK5
Gould Shawmut _____	TRS1R _____	RK5
Gould. Shawmut (<i>Amp-Trap</i>) _____	A6D1R _____	RK1

Overload Operation - On a low overload current the short circuit fuse link remains entirely inactive. The overload element consists of a center mass of copper on which is mounted a spring and a short connector. This connector is held in place by a low melting point solder joint, which connects the center mass of copper to the fuse link. When overload current flows long enough to raise the temperature of the center mass to the melting point of the solder, this connector is pulled out of place by the spring, thereby opening the circuit.



The thermal cutout element has a built in time delay which permits momentary harmless surge currents such as motor starting current to flow without opening the fuse. If the overload current persists too long, the thermal cutout element clears the circuit, thus protecting the components and equipment. These fuses are ideal for motor, transformer and other circuits with harmless start-up current.

Short Circuit Operation - During a short circuit condition the fuse link acts as described for a single element fuse. A portion of the link vaporizes and the surrounding filler aids in extinguishing the arc. This fuse element has current-limiting ability for short circuit currents thereby reducing the mechanical, thermal, and arcing stress which system components would have to withstand.



CIRCUIT BREAKERS

OVERVIEW

The function of the circuit breaker corresponds basically to that of a switch in combination with a fuse.

When the current is above the normal rating, either on overload or short circuit current, the circuit breaker is an automatic overcurrent protective device.

A circuit breaker (CB) will automatically interrupt current flow when the conditions are abnormal without damage to itself. The circuit breaker mechanism is set to interrupt the current at a particular overload value and it can interrupt a short circuit current.

The automatic circuit opening action of a circuit breaker is accomplished in several ways. Some of these are by thermal release, magnetic action, the combination of thermal release and magnetic actions, hydraulic means, and pneumatic means.

Advantages and Disadvantages - Comparison to Fuse Protection

A. Advantages

- Breakers can be reset after trip and need not be replaced normally.
- Breakers can be used as a switching device.
- In the case of air circuit breakers (ACB's) trip elements are adjustable (current and time)

B. Disadvantages

- Cost
- Size
- Handling and Weight

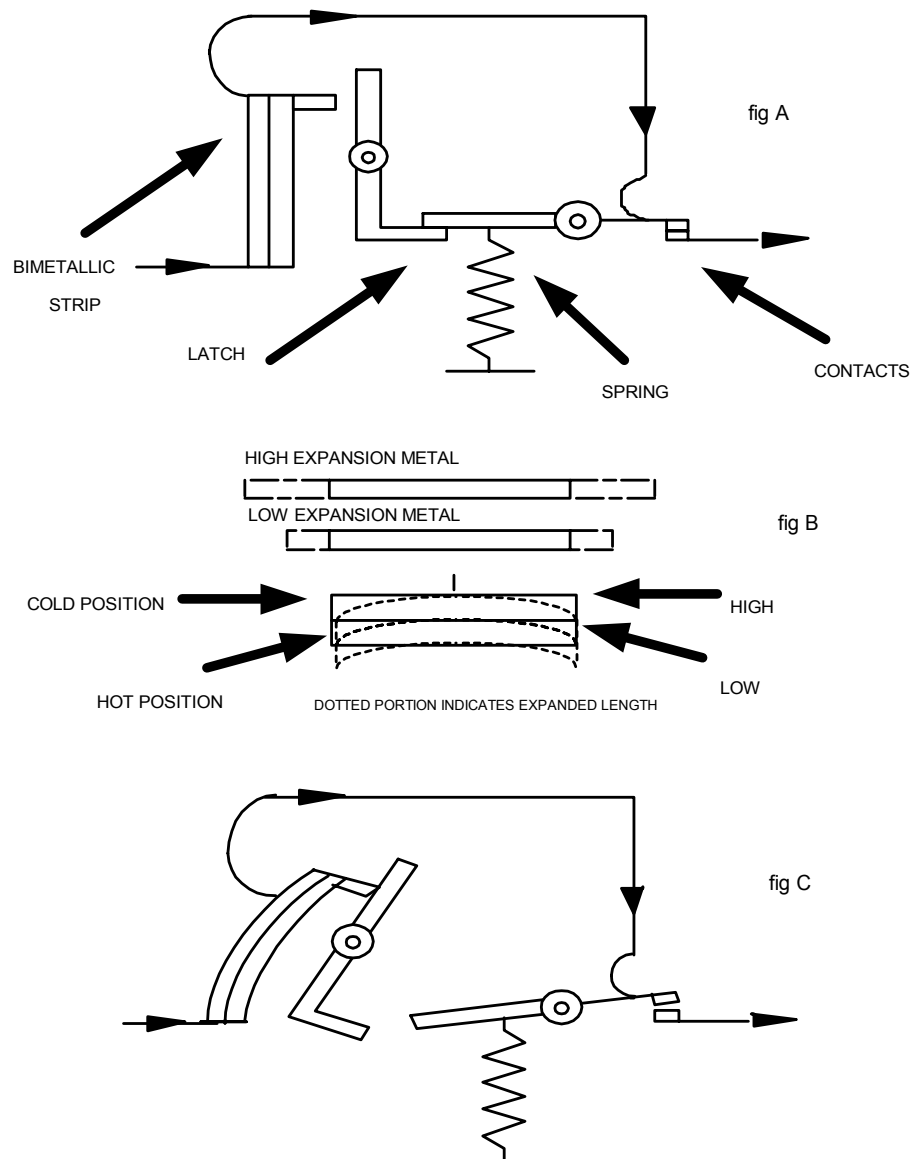
Circuit Breakers would be used in preference to fuses when a disconnect means is required. An example of this is motor control systems. Circuit breakers would also be used if sufficient space is available and if standard current ratings are required, such as, 20 A, 30A etc.

Fuses would be used in preference to circuit breakers where accurate current values are required, such as, 1.6A, 10.4A. Fuses (Rectifier/semi-conductor) would also be used in rapid response situations such as electronic circuits or Silicon Controlled Rectifier (SCR) Circuits found in D.C. Drives and other precise control circuits. Fuses are normally used when no disconnect means is required.

Thermal Circuit Breakers

Thermal (heat) type air circuit breakers are used primarily for protection against overcurrent. A typical thermal circuit breaker operates on the principle of metal expanding when heated. In Figure A, a mechanism holds the contacts closed with a latch. The thermal element is a bimetallic strip made of two different metals bonded together as illustrated in Figure B. The bimetallic strip, having resistance, heats in proportion to the line current. If the current becomes excessive for a prolonged period of time, the bimetallic strip becomes hot and bends because of different expansion rates of the two metals as illustrated in Figure B. When the strip bends sufficiently, it trips the latch and opens the contacts as illustrated in Figure C.

Thermal circuit breakers provide overload protection at voltages up to 600 volts A-C and 250 volts D-C, from 10 to 60 amperes.

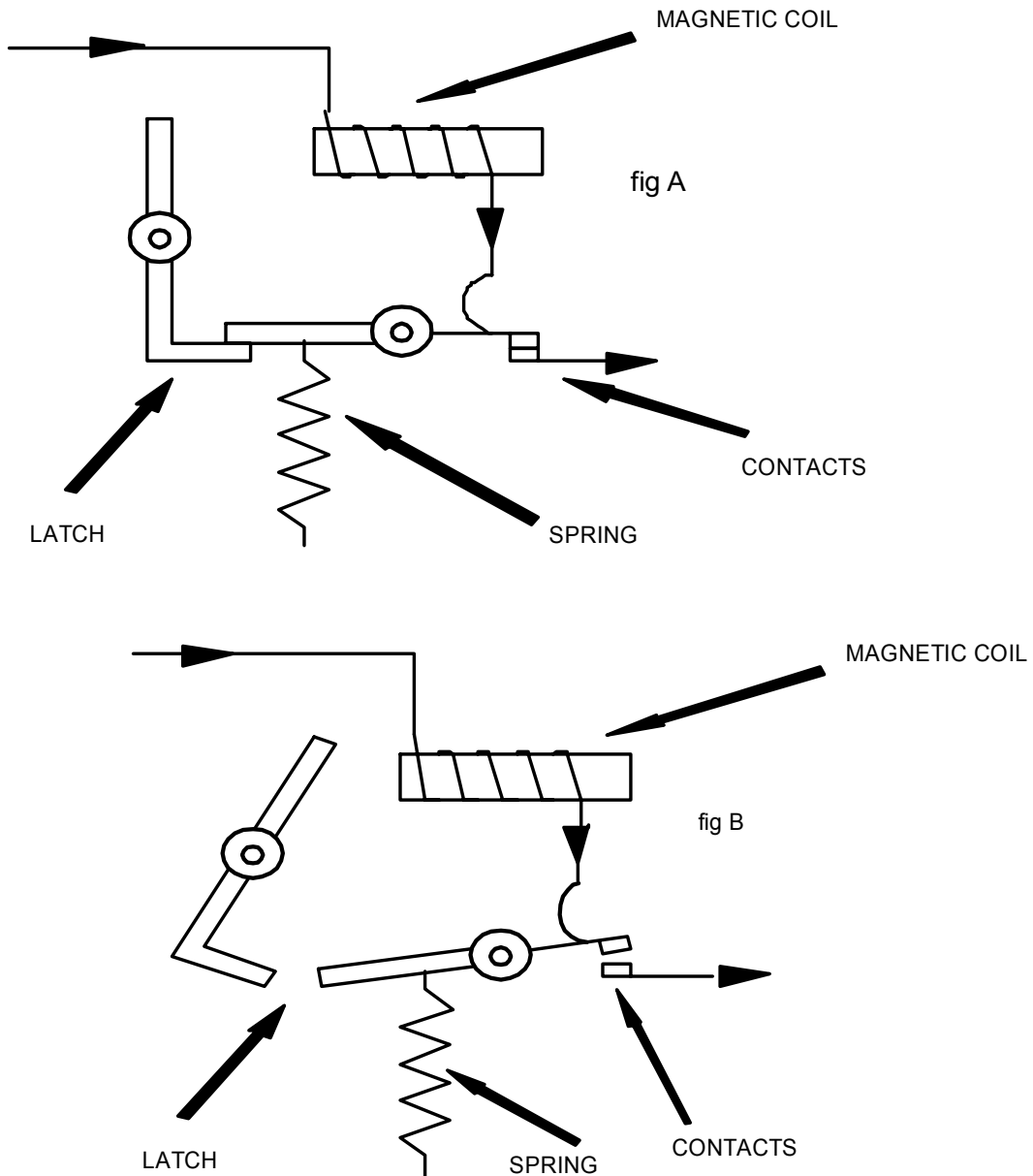


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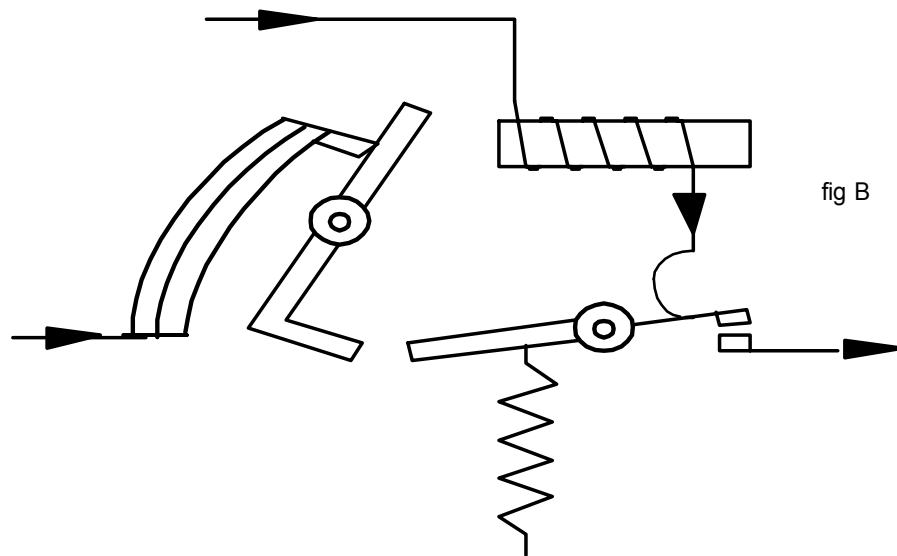
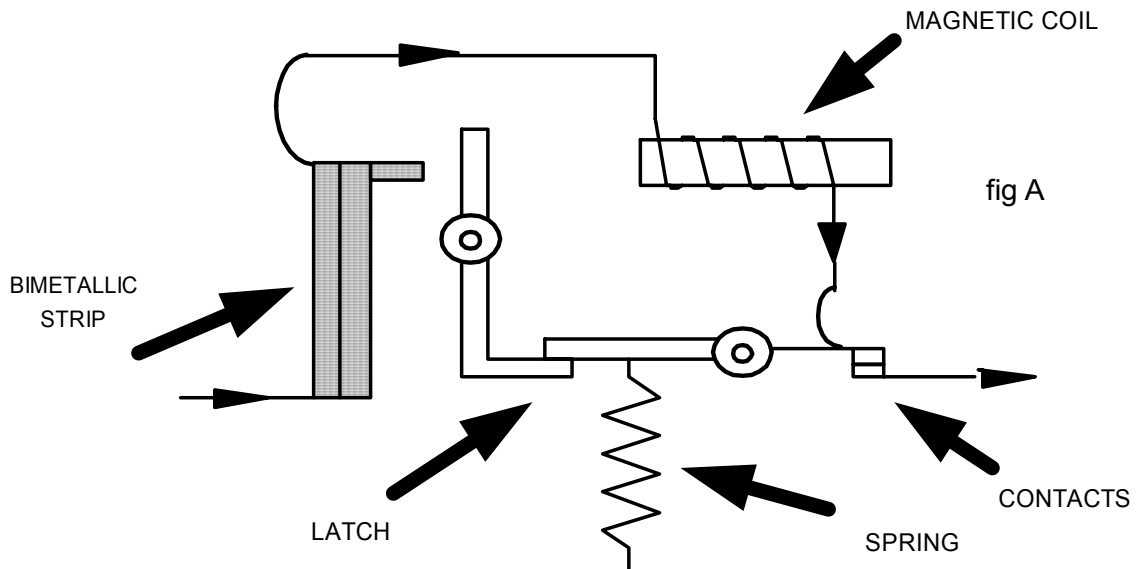
Magnetic Circuit Breaker

A magnetic circuit breaker has no thermal device. It is used whenever instantaneous action is required to open a faulted circuit. Figure A illustrates a magnetic circuit breaker under normal conditions. Figure B shows the circuit breaker in a tripped position.



Thermal-Magnetic Circuit Breaker

A thermal-magnetic circuit breaker incorporates both a thermal strip and a magnetic coil. The thermal strip provides a time delay for momentary overloads. The magnetic coil provides instantaneous trip on high or short circuit currents. The magnetic trip also protects the bimetallic strip from excessive overheating that can destroy it. Figure A illustrates normal operation and Figure B illustrates the tripped position of a thermal-magnetic circuit breaker.



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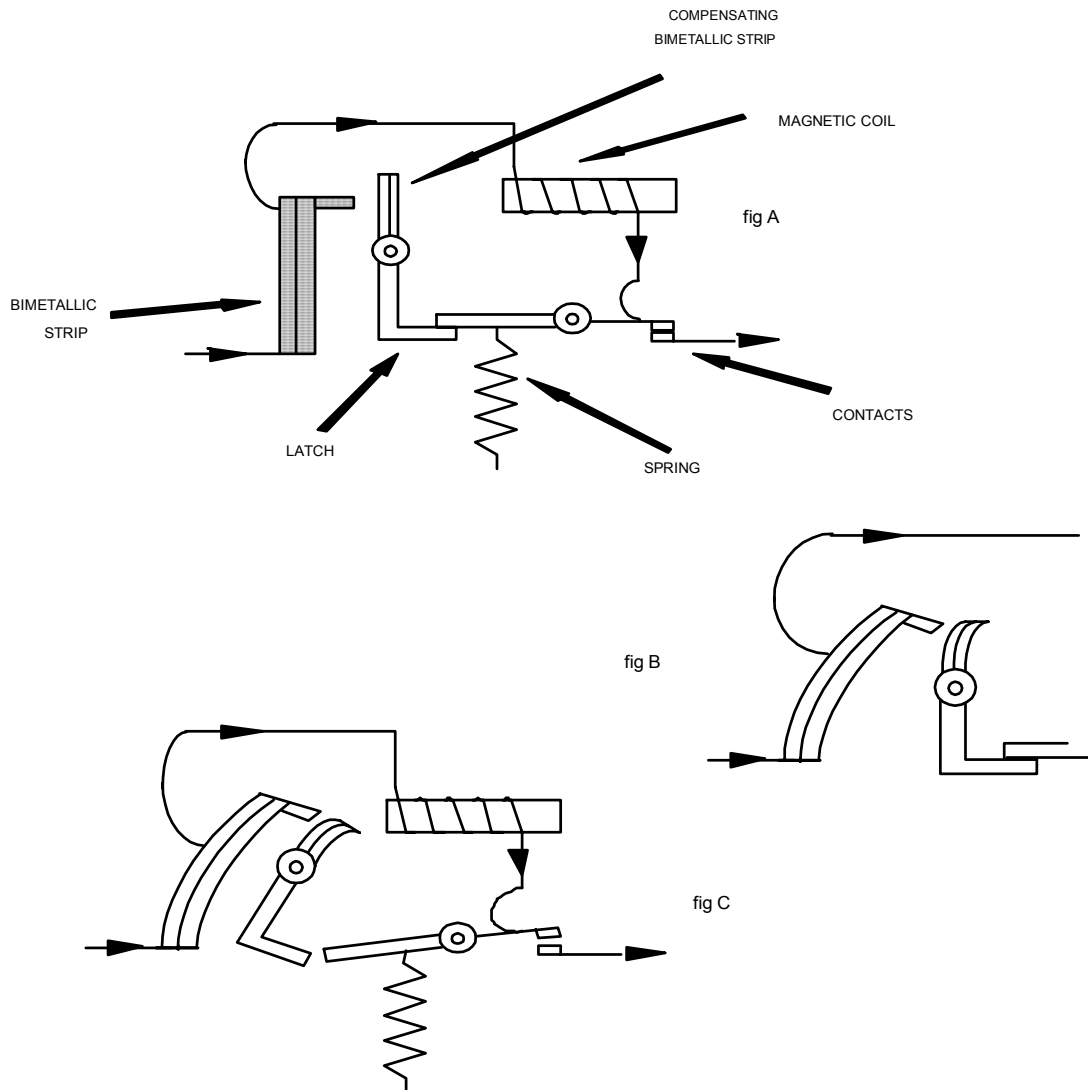
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Ambient Compensating Circuit Breaker

The ambient-compensated circuit breaker has an overload bimetallic strip, and a compensating bimetallic strip.

Both elements bend with an increase in ambient heat but only the overload element responds to the current. Figure A illustrates the ambient compensating circuit breaker in a normal ambient temperature of 18 to 21 degrees C. Figure B illustrates the two bimetallic strips bending because of an increase of ambient temperature. This does not trip the breaker. The breaker trips only when the excessive current through the overload strip causes it to bend more than the compensating strip.

The ambient-compensated circuit breaker is used in areas where high temperatures are encountered.



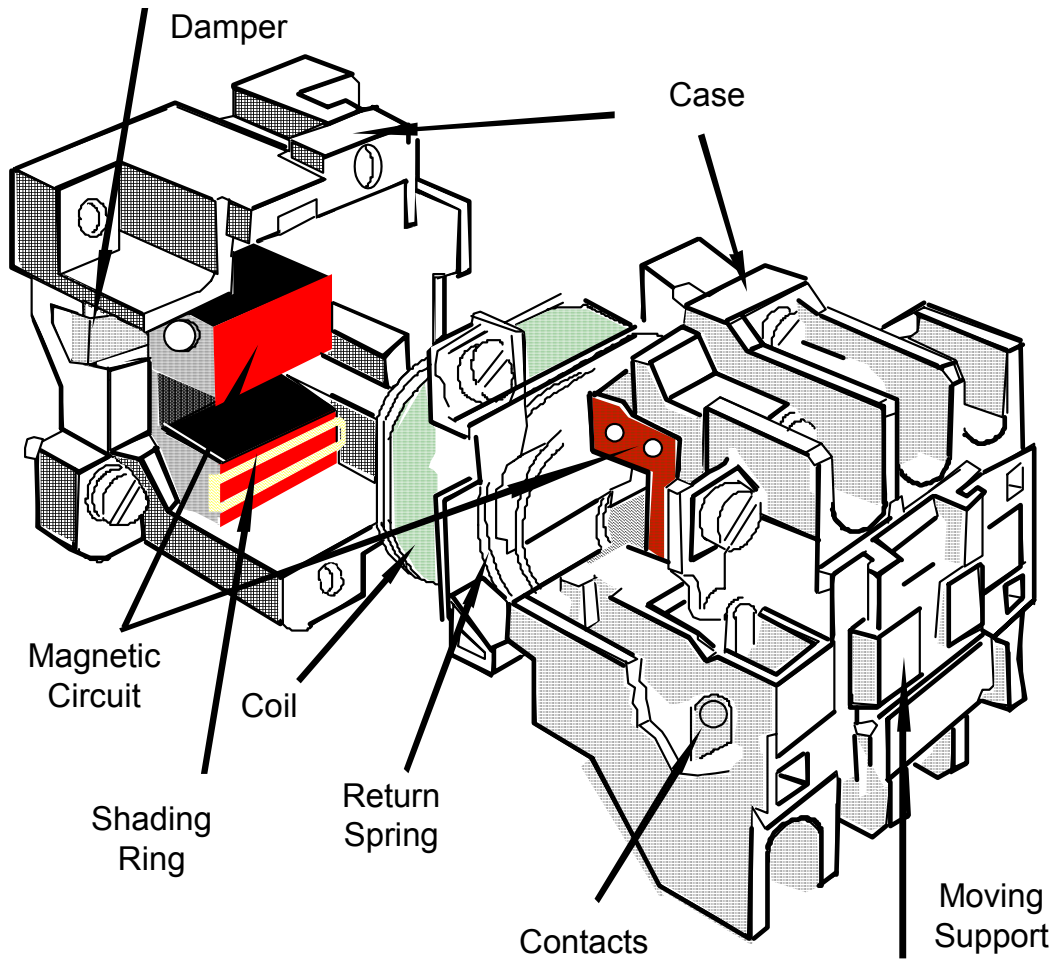


ELECTRICAL PRINCIPLES FOR CONTACTORS AND RELAYS

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PURPOSE

Both relays and contactors provide a means of automatic operation of a machine from a remote location.

A contactor belongs to both the control circuit and the power circuit. The contactor coil and auxiliary contacts such as those required to seal-in or provide electrical interlock are found in the control circuit. The remaining main contacts are used to switch loads in the power circuit.

A relay is always used in the control circuit. It is used to remember machine events such as the momentary closure of a limit switch contact. It is also used to overcome contact constraints, such as, incorrect type or not enough normally open or normally closed contacts available on a particular device.

OPERATION AND CONSTRUCTION

CASE or HOUSING

Contains all the parts and provides the insulation necessary to isolate individual contacts.

CONTACTS

Main contacts, usually three and each of them having

- Fixed contact

- Movable contact

- Sometimes an arc blow-out device

Auxiliary contacts, usually on the device or added and having

- Fixed contact

- Movable contact

Different types

- Normally open contact

- Normally closed contact

These contacts should open and close at the same time as the main contacts and can be used to control various other circuits.

RETURN SPRING

This spring insures that the moveable core rapidly moves away for the stationary core when the coil is de-energized. This rapid opening insures that the contacts, both main and auxiliary open as quickly as possible.

ELECTROMAGNET

The main feature of a contactor that distinguishes it from a manual starter is the use of an **electromagnet**. The electromagnet is ultimately responsible for switching the state of the contacts. The electromagnet consists of the following:

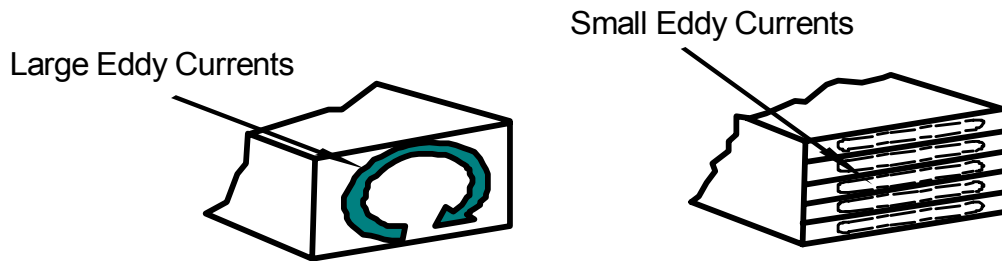
Coil: The coil produces magnetic flux as the result of current flow. The **impedance of the coil limits the current in an AC circuit**. The coil's impedance is mainly inductive reactance since the coil usually has a very low internal resistance. **Only the DC resistance of the coil limits the current in a DC circuit.**

Stationary Core: The **stationary core concentrates magnetic flux**. In doing so, this core's surface, which mates with the moveable core, is polarized and attracts the moveable core. This core is constructed of laminated steel to reduce Eddy currents.

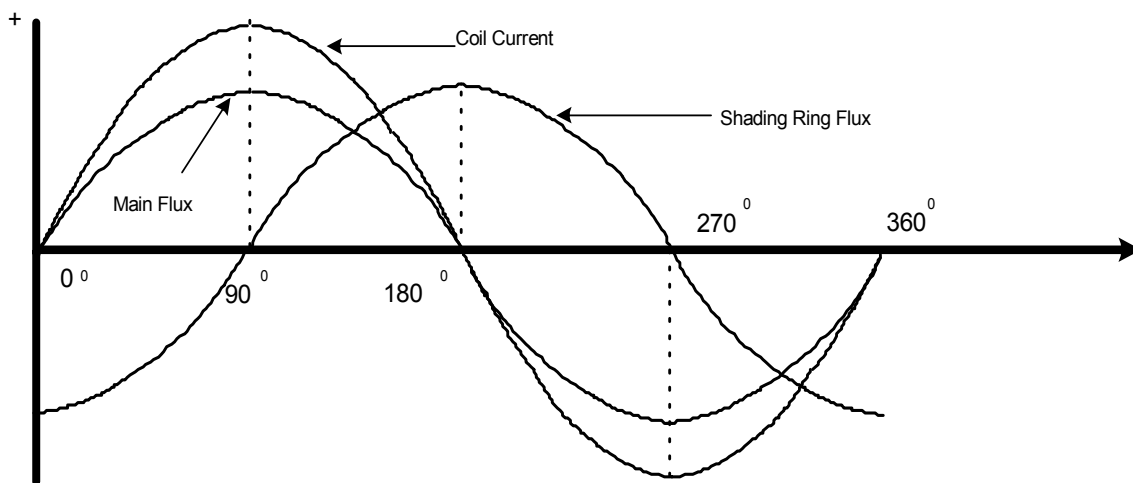
Movable Core: The **moveable core also concentrates magnetic flux**. The moveable core concentrates magnetic flux radiating from the mating surfaces of the stationary core. As a result, the mating surfaces of the moveable core are attracted to the stationary core resulting in the movement of the moveable core against the stationary core. The moveable core is attached through a plastic or insulated assembly to the contacts. As the moveable core is pulled against the stationary core, **the contacts change state**. Since the moveable core is made to move, it is often referred to as the armature. This core is also constructed of laminated steel to reduce Eddy currents.

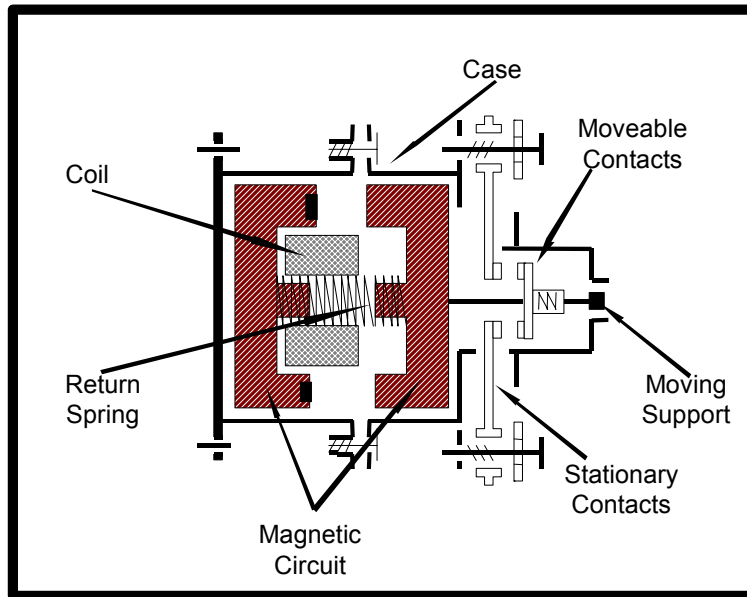
There are two inherent problems when an AC voltage is applied to a relay or contactor coil.

1. The change in magnetic flux with respect to time induces a voltage in the core resulting in undesirable induced currents called **eddy currents**. The **core is constructed of laminated steel to reduce these eddy currents**. Laminations serve to increase the electrical resistance of the core. If the resistance of the core is doubled, the current is halved. Then from Watt's Law, we see that a reduction in current results in a significant reduction in power since $P = I^2R$. Eddy currents are undesirable because they result in power dissipated by the core in the form of **heat**.



2. The magnetic flux produced by the coil also goes to zero twice per cycle due to the alternations of the sinewave. Since there is no magnetic attraction, the two cores try to pull apart during these two instants in time. Since this pulling apart would cause the relay or contactor to **chatter**, something must retain the magnetic attraction during these times. **Shading rings** are embedded in the surface of the stationary core. These rings retain magnetic flux as the coil current passes through zero. The amount of magnetic flux produced by the coil is proportional to the current through the coil. As coil current passes through zero, it is making its greatest change with respect to time. Since the flux and current are in phase, flux is also making its greatest change with respect to time. This rapid change in flux causes an induced voltage and thus current to flow in the shading ring. As the result of current flow in the shading ring, a small magnetic field is created. The strength of this magnetic field is sufficient to retain the attraction of the two cores during the instant the main magnetic field passes through zero.



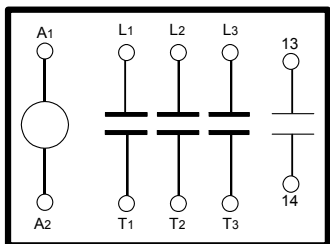


Mechanical Drawing Cross-Section

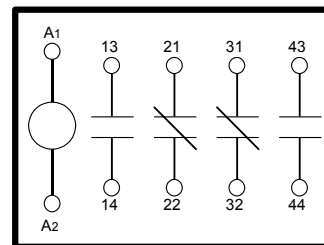
The contactor and relay functions mechanically exactly the same. The cross-section drawing above shows how the moveable contacts are mechanically connected to the moveable part of the magnetic circuit. When the moveable part of the magnetic circuit is pulled against the return spring, the moveable part of the contacts either closes or opens relative to the stationary set of corresponding contacts. This is a mechanical representation of the contactor. The moveable and stationary contacts must be electrically insulated and isolated from each other, the magnetic circuit and the coil. There are many different variations of contact configurations.

There is not just one symbol for a contactor or a relay. These devices are a combination of many symbols, such as contacts and coils. Below is an electrical representation for a contactor and a relay.

Both contain a coil that has terminal numbers A1 and A2. The contactor has three main contacts numbered L1 – T1, L2 – T2, L3 – T3, which are designed to carry heavy loads to motors, heaters, etc. The darker lines show these main contacts. The contactors auxiliary contacts are shown with smaller lines and numbered 13 – 14. The relay has all smaller auxiliary type contacts with different numbers. The numbers will be different for different configurations of contacts. The one shown is two normally open and two normally closed.



Electrical Representation for a Contactor



Electrical Representation for a Relay



TROUBLESHOOTING SAFETY AND TEST INSTRUMENTS

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TROUBLESHOOTING SAFETY

In this section we will look at the safety aspects associated with troubleshooting. Safety is always important. Safety is especially important when troubleshooting because conditions are unusually hazardous. The fact that a fault has occurred means that circuit conditions are **abnormal, unpredictable, and dangerous**. Also, there is added pressure sometimes to expedite the repair to save production time. The tendency to hurry, coupled with the abnormal, unpredictable, and dangerous conditions, greatly increases the chances for serious mistakes.

Always keep in mind that no equipment is so important and no service so urgent that we cannot take the time to do the job safely.

Safety is basically using good judgement. You must be alert to the hazards that are peculiar to each particular machine. There are, however, a few general rules that apply to most situations:

- **Always verify your test instruments.**
- **Isolate power personally if repair is necessary.**
- **Verify that no voltage is present before making any repairs.**
- **Think about what you are testing and what you expect to find. Random probing with the test instruments can cause serious mistakes for personnel and equipment.**
- **Be aware of the mechanical dangers. What may happen when the machine is energized either normally or abnormally?**
- **Be certain any temporary work is absolutely safe.**
- **Verify safe working order after completion. Remove all test jumpers and device defeats. Check all safety circuits before returning the machine to normal service.**

Troubleshooting Aids Used in Fault Finding

There are several important aids available to the troubleshooter.

- **Operations Diagram** which gives the sequence of operation of machine functions.
- **Electrical Schematic** which gives the correct electrical sequence of circuit components.
- **Wiring Diagram** which shows physical location of circuit components.
- **Computerized Reports** which will assist in evaluating the trouble history of the machine.

The more familiar a troubleshooter becomes with each of these aids, the better he is prepared to repair any machine. The operations diagram, electrical schematic, and wiring diagram were presented earlier.

The computerized reports are a valuable aid in evaluating recurring problems. The report should contain the machine description and location, time the fault occurred, the fault symptoms, the actual fault, probable cause, corrective action taken, and time to complete.

Fault Diagnosis

All faults, whether electrical or mechanical, normally require quick action to correct the fault. This should always be carried out in a safe and correct manner.

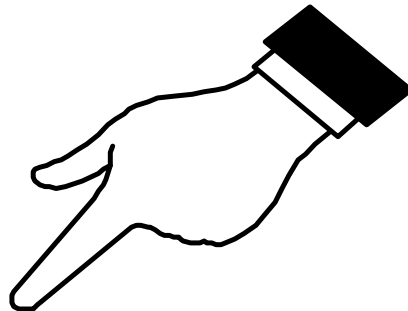
The techniques employed by different troubleshooters will vary according to circumstances. The four senses are usually needed in all circumstances. It is not necessary to touch something to prove that it is **Hot**. Close proximity gives adequate information or **Warning**. It is also not necessary to inhale toxic smoke to detect that there is a fire. Use your senses individually or as a combination, but always use care.



SIGHT



HEARING



TOUCH



SMELL

TEST INSTRUMENTS

Test instruments come in various types, shapes and sizes. The most common types of volt-ohm-meters are grouped in two categories, analog and digital. There is also a type of ohmmeter called a meg-ohm-meter that will be discussed later in this chapter.

The Analog Volt-Ohm-Meter (VOM)



Troubleshooting with an Analog VOM

The analog VOM is frequently used in conventional trouble-shooting but is becoming more obsolete due to digital multi-meters. The VOM can tell the trouble-shooter if voltage is present or not, and can also tell how much is present. At times this additional information can be helpful. There are some concerns to be aware of when using test instruments such as the VOM.

- Meter Damage** - It is easy to overlook the range and function selected on a VOM. If the wrong range or function is selected, incorrect readings and/or meter destruction can occur.
- Calibration Errors** - Most instruments of this type need periodic calibration. An instrument that is out of calibration can cause lost time and wasted efforts due to the incorrect readings.
- Expense** - Initial cost of industrial quality VOM's is quite high. As with any precision instrument, extra care must be taken to protect it.

The Digital Multi-Meter (DMM)



Fig. 1

Digital multimeters (DMM) have generally replaced the analog-type multimeter (VOM) as the test device of choice for maintainers because they are easier to read, are often more compact and have greater accuracy. The DMM performs all standard VOM measurement functions of a-c and d-c. Some offer frequency and temperature measurement. Many have such features as peak-hold display that provides short-term memory for capturing the peak value of transient signals as well as audible and visual indications for continuity testing and level detection.

To compare these two types of multimeters, let us examine their pros and cons in more detail:

Ease of reading. One of the greatest problems with an analog meter is the errors that occur due to the human factor when reading off the value from the many different scales. The thin analog needle against a calibrated scale is similar to the hands of a clock against the number scale indicating the hours. When you look at an analog clock, you have to determine where the hands are, which number the hand is nearest to, and so on. With a digital clock, however, the time is read directly from a display. With the analog meter, the decoding of the scale is necessary, while the digital multimeter displays the magnitude, polarity (+ or -), and the units (V, A, or Ω) on typically a four- or five-digit readout. A disadvantage of the digital multimeter is its slow response to display the amount on the readout once it has been connected in the circuit. To compensate for this disadvantage, most DMMs have a bar graph display below the digital readout, as shown in Fig. 2, showing the magnitude of the measured quantity using more or less bars. A bar graph reading is updated 30 times per second while the digital display is updated only 4 times per second. The bar graph is used when quickly changing signals cause the digital display to flash or when there is a change in the circuit that is too rapid for the digital display to detect. For example, a contact's resistance changes momentarily from zero to infinity when a contact "bounces". A DMM cannot indicate contact bounce because the digital display requires more than 250 milliseconds to update.

A DMM set to measure voltage may display a reading before the leads are connected to a powered circuit. This is known as a "**ghost voltage**" and is produced by magnetic fields, fluorescent lights and such which may be in close proximity. These voltages enter the meter through the open test leads which act as antennae. These voltages are very low and will not damage a meter but can be confusing as to their source.

Accuracy - DMMs are typically accurate to 0.01 % and have no need for a zero-ohms adjustment. Returning to the example of the analog and digital clock, a person reading the time from the traditional analog clock would say that the time is almost 12:30. The wearer of the digital watch, however, will be totally specific and give the time as 12:27. Similarly, an analog reading on a meter of about 7 V becomes 7.15 V with the far more accurate DMM.

Price - Digital meters have complicated internal circuitry that is why the digital readout meters usually have a more expensive price tag than the analog readout multi-meters.

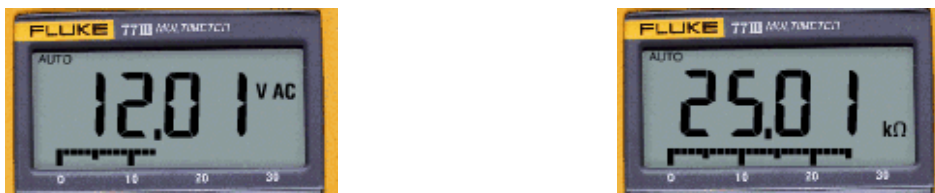


Fig. 2

When troubleshooting with the digital multimeter, the maintainer is able to “see” the situation and the problem within the circuit or system. Fig. 3 illustrates a typical autoranging digital multimeter. Of course for the meter to be of any use it must first be connected to the circuit or device to be tested. Both leads, one red and the other black, must be inserted into the correct meter lead jacks. The black lead is connected to the meter jack marked COM or common. It is usually the lower right jack as in this illustration. (Be aware that not every meter has the same jack configuration.) The red lead is connected to either of the appropriate jacks depending on what the maintainer wants to measure; ohms, volts or amperes. The two jacks on the left are utilized when measuring current, either in the 300mA or the 10 ampere range.

The display shows other functions as well.

- Low battery indicator
- Annunciators show what is being measured (volts, ohms, amps, etc.)
- Autopolarity indicates negative readings with a minus sign when the leads are connected incorrectly without any damage
- Autoranging automatically selects proper measurement range
- One selector switch makes it easy to select measurement functions
- Overload protection prevents damage to the meter and the circuit, and protects the user



Fig. 3

Measuring resistance – Fig. 4 shows the steps that should be followed when measuring resistance. Remember that resistance measurements are carried out without the power being applied to the component under test, and resistance values can vary by as much as 20% due to the tolerance of certain resistors. Do not be misled if your meter reading is slightly different from the color band on the resistor. If a resistor's value is off and exceeds the tolerance, the resistor should be replaced. A resistor will rarely short, but typically will open. If a resistor does open, the DMM display will flash on and off or display OL (open line) because the resistor has an infinite resistance.

1. Turn off power to the circuit
2. Select resistance Ω
3. Plug the black test lead into the COM jack and the red test lead into the Ω jack
4. Connect the probe tips across the component or portion of the circuit for which you want to determine the resistance
5. View the reading and be sure to note the unit of measure, Ω , $K\Omega$, $M\Omega$, etc.



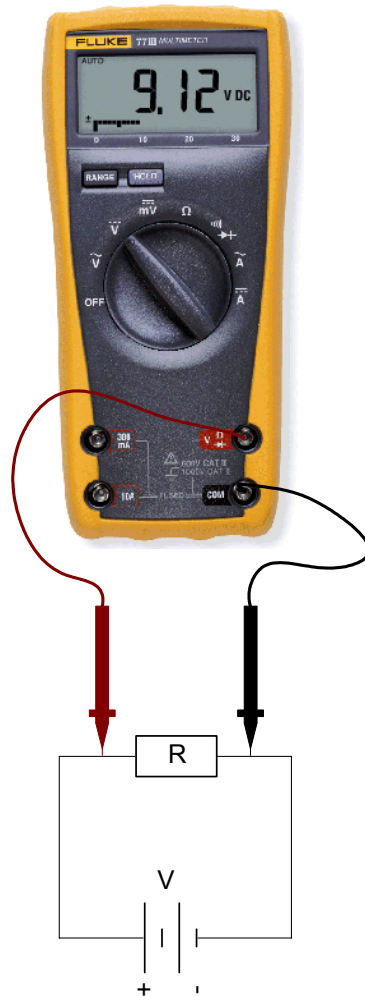
Fig. 4

Measuring voltage – **Fig. 5** shows the steps that should be followed when measuring voltage. The measurement of both voltage and resistance is where the DMM finds its greatest utilization. For voltage and resistance measurement, the red lead is inserted into the V – Ω (volt or ohm) meter jack.

1. Select volts AC (V~), volts DC (V---), mvolts (V---) as desired
2. Plug the black test lead into the COM jack and the red test lead into the V jack
3. Touch the probe tips to the circuit across a load or power source as shown (parallel to the circuit to be tested)
4. View the reading being sure to note the unit of measure

Note: For DC readings of the correct polarity (+ or -), touch the red test probe to the positive side of the circuit, and the black test probe to the negative side of the circuit ground. If you reverse the connections, a DMM with auto-polarity will merely display a minus sign indicating negative polarity. With an analog meter you risk damaging the meter.

Fig. 5



Measuring current – Fig. 6 shows the steps that should be followed when measuring current. The measurement of current is rarely performed when troubleshooting, as the circuit path has to be opened to insert the DMM in series with the current flow. However, if current is to be measured, the red lead is inserted into one of the ampere jacks, 10 amp (10A) or 300 milliamp (300 mA) input jack depending on the expected value of the reading.

1. Turn off the power to the circuit
2. Disconnect, cut or unsolder the circuit, creating a place where the meter probes can be inserted
3. Select amps AC (A~), or amps DC (A---) as desired
4. Plug the black test lead into the COM jack and the red test lead into 10 amp (10A) or 300 milliamp (300mA) jack depending on the expected value of the reading
5. Connect the probe tips to the circuit across the bread as shown so that all current will flow through the meter (a series connection)
6. Turn the circuit power back on
7. View the reading being sure to note the unit of measure

Note: If test leads are reversed a negative (-) sign will be displayed

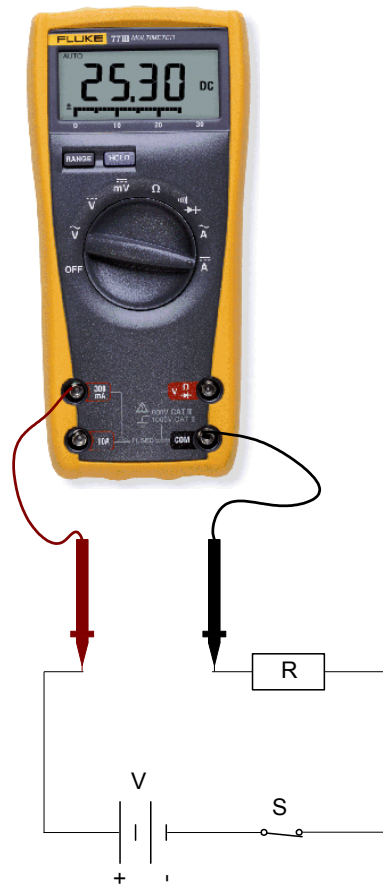
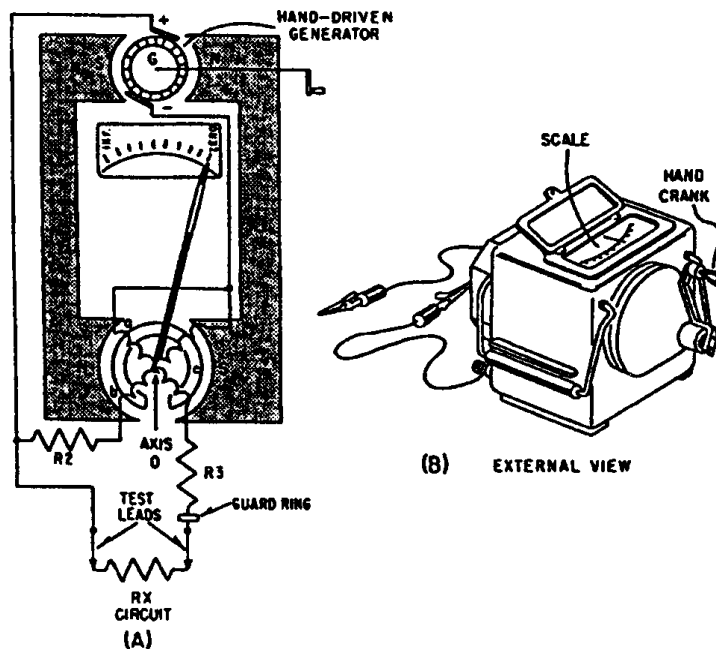


Fig. 6



Megohm meter

An ordinary ohmmeter cannot be used for measuring resistance of multi-millions of ohms, such as conductor insulation. To adequately test for insulation breakdown, it is necessary to use a much higher potential than is furnished by an ohmmeter's battery. This potential is placed between the conductor and the outside surface of the insulation.

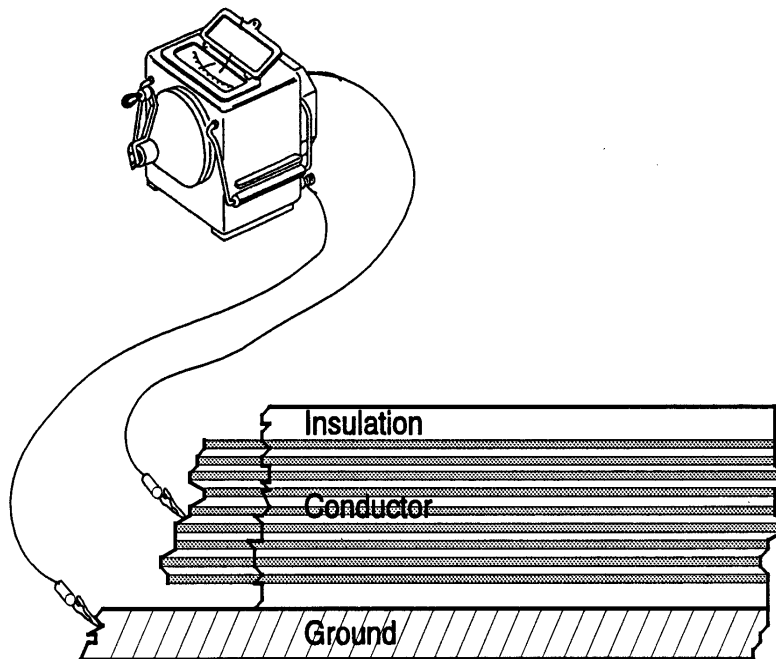
An instrument called a megohmmeter is used for these tests. The megohmmeter is a portable instrument consisting of two primary elements.

1. A hand-driven DC generator G, which supplies the necessary voltage for making the measurement
2. The instrument portion, which indicates the value of the resistance being measured
The instrument portion is of the opposed-coil type as shown above. Coils a and b are mounted on the movable member c with a fixed angular relationship to each other, and are free to turn as a unit in a magnetic field. Coil b tends to move the pointer counterclockwise, and coil a clockwise.

Coil a is connected in series with R_3 and the unknown resistance R_x to be measured. The combination of coil R_3 and R_x form a direct series path between the positive (+) and negative (-) brushes of the DC generator. Coil b is connected in series with R_2 and this combination is also connected across the generator. There are no restraining springs on the movable member of the instrument portion of the megohm meter. Therefore, when the generator is not operated, the pointer floats freely and may come to rest at any position on the scale.

The guard ring intercepts leakage current. Any leakage currents intercepted are shunted to the negative side of the generator. They do not flow through coil a; therefore, they do not affect the meter reading.

If the test leads are open-circuited, no current flows in coil a. However, current flows internally through coil b, and deflects the pointer to infinity, which indicates a resistance too large to measure. When a resistance such as R_x is connected between the test leads; current also flows in coil a, tending to move the pointer clockwise. At the same time, coil b still tends to move the pointer counterclockwise. Therefore, the moving element, composed of both coils and the pointer, comes to rest at a position at which the two forces are balanced. This position depends upon the value of the external resistance, which controls the relative magnitude of current in coil a. Because changes in voltage affect both coil a and coil b in the same proportion, the position of the moving system is independent of the voltage. If the test leads are short-circuited, the pointer rests at zero because the current in coil a is relatively large. The instrument is not injured under the circumstances because the current is limited by R_3 .



To avoid excessive test voltages, most megohm meters are equipped with friction clutches. When the generator is cranked faster than its rated speed, the clutch slips and the generator speed and output voltage are not permitted to exceed their rated values. For extended ranges, a 1000-volt generator is available. When extremely high resistances, such as 10,000 megohms or more, are to be measured, a high voltage is needed to cause sufficient current flow to actuate the meter movement.

A good rule of thumb for megging motors, conductors, etc. is to use a voltage level twice the voltage insulation rating of the device to be checked.

Another rule of thumb is a $1\text{M}\Omega$ value of motor insulation is considered to be acceptable. Anything below this value is considered to be suspect.

Note: Always discharge the megohm meter after taking readings. The dielectric can act like a capacitor and hold a charge, especially for higher voltages.



AC DRIVES

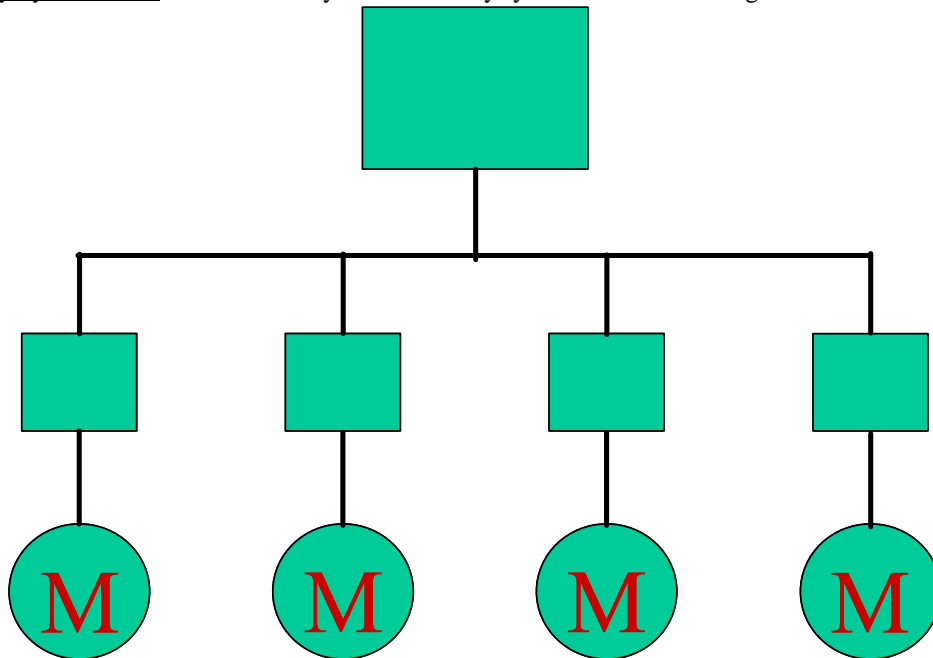
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AC Drive Advantages

1. Cost - Three phase AC motors are much cheaper than DC motors of the same horsepower. AC controllers also increase the efficiency of an AC motor.
2. Maintenance - AC motors are virtually maintenance free.
3. Speed Control - AC motors have a wide range of speed control (up to 20 to 1).
4. Fully Regenerative - Four-quadrant control is easily achieved.
5. Good Open Loop Control - Typical open loop speed regulation is less than 5%.
6. Quick Response - AC motors have a relatively low inertia, which provides better response.
7. Easily Synchronized - Multi-motor systems are easily synchronized with a single AC Drive controller.

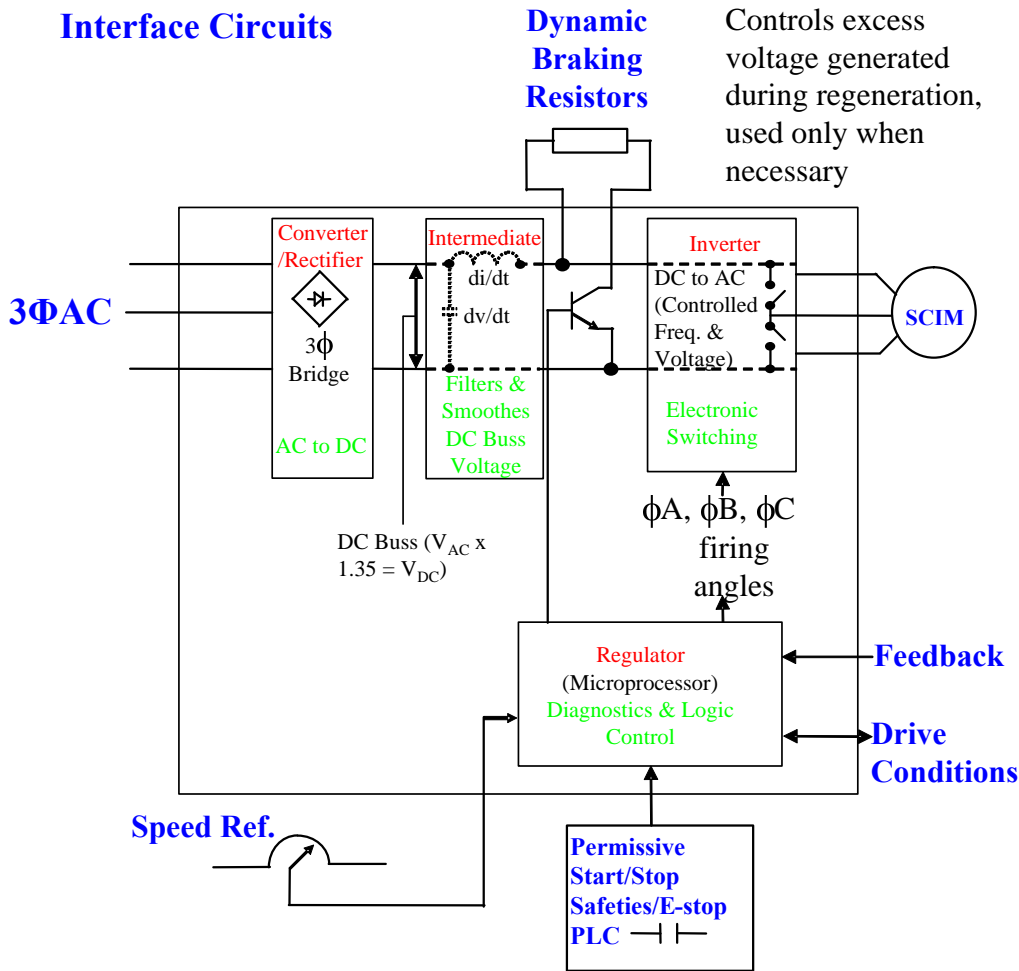


8.

Selection of Motors - Wide range of standard three phase motors are available.

AC Drive Interface Circuits

Typical interface circuits that can be applied to AC drives are shown in the figure below.



The most recognized AC drive interfaces are the AC supply, and the stator.

The feedback circuit can be a tachometer or it can be an optical encoder, an AC generator, a linear voltage displacement transformer, and even a current transformer.

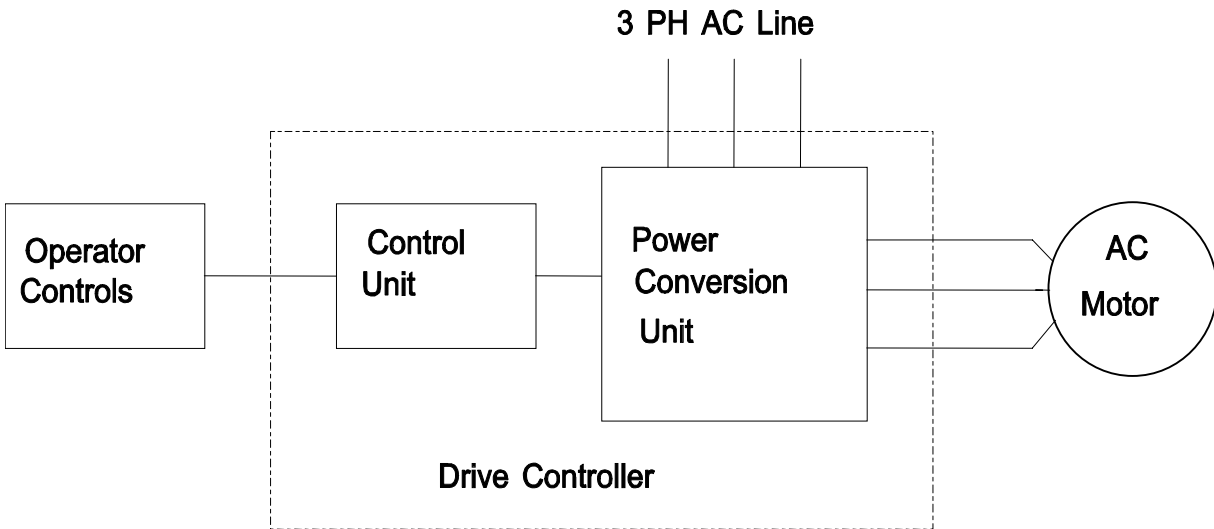
The drive condition circuit varies from a simple LED, to selectable conditions that will cause an output to change state. These can be conditions such as "drive at speed" or "drive in current limit". These conditions are outputs from the drive that can be used in external circuits.

The run permissives include all of the external circuits that enable the drive. These can be safety gates, interlocks or contacts from another drive showing that it is "running at speed".

The speed reference circuit is shown as a three-wire connection. The most common manual configuration is a three-wire pot used to manually set the speed reference. Other sources for the speed reference are an analogue output card from a PLC or a motion controller like the Allen Bradley IMC 121. These basic interface circuits can be identified on almost all drives. Recognizing them and being able to verify their function is a prime responsibility of troubleshooters.

Basic AC Drive System

An AC adjustable frequency drive typically consists of three basic parts: operator controls, drive controller (often referred to as an inverter) and an AC motor. The figure below shows a block diagram of these components.



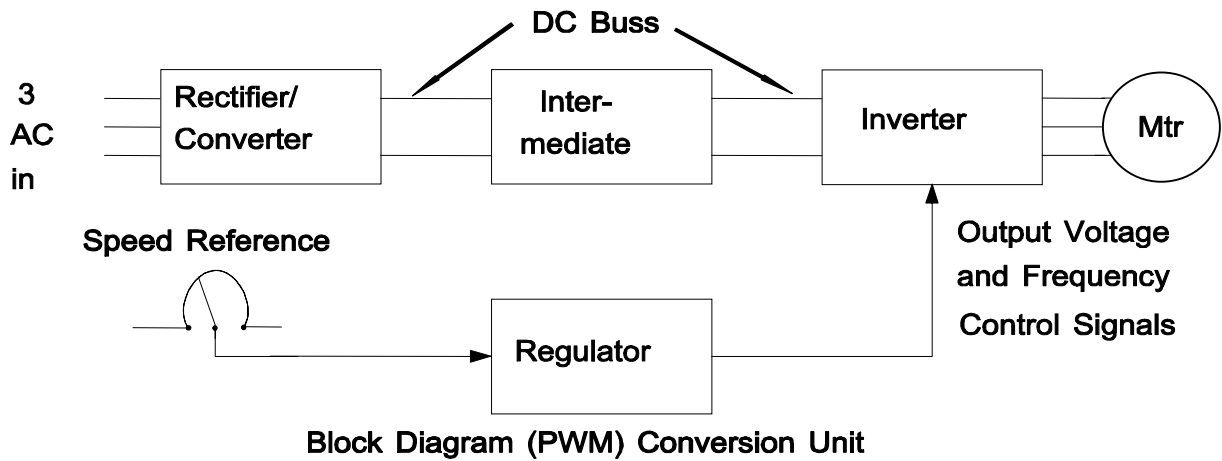
AC Adjustable Frequency Drive System

The operator controls allow the operator to start, stop, and change direction and speed of the controller by simply turning potentiometers or other operator devices. These controls may be an integral part of the controller or may be remotely mounted. Programmable controllers are often used for this function.

The Drive Controller converts a fixed voltage AC to an AC waveform with adjustable frequency and voltage. It consists of a Control Unit and a Power Conversion Unit as seen in the figure above.

The Control Unit oversees the operation of the drive and provides valuable system diagnostic information.

The figure below shows a block diagram of the Power Conversion Unit with the regulator shown as part of the control unit and the speed reference as part of the operator controls.



The Power Conversion Unit performs several functions. In the converter block, it rectifies the incoming fixed AC voltage (changes AC to DC). The resultant DC voltage is then filtered through an LC low pass filter to obtain a DC voltage bus in the intermediate block. The inverter block then produces an AC current and voltage output having the desired frequency to control the motor.

The AC Motor converts the adjustable frequency AC from the drive controller to rotating mechanical energy.



FEEDBACK DEVICES

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CenTec, Inc. P.O.Box 5127, Greenville, S.C. 29606

Name: DC Tachometer/Generator

Type of Signal: Pulsing DC w/polarity

Type of Information: Speed → Amplitude V_{DC}
Direction → Polarity

Rating: Volts/RPM

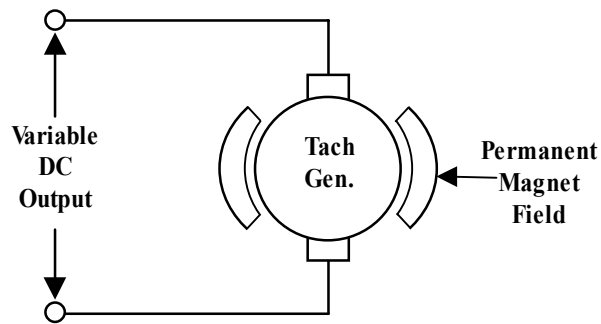
Examples: 6v/1000RPM
50v/1000RPM
100v/1000RPM

-Maximum Speed Rating

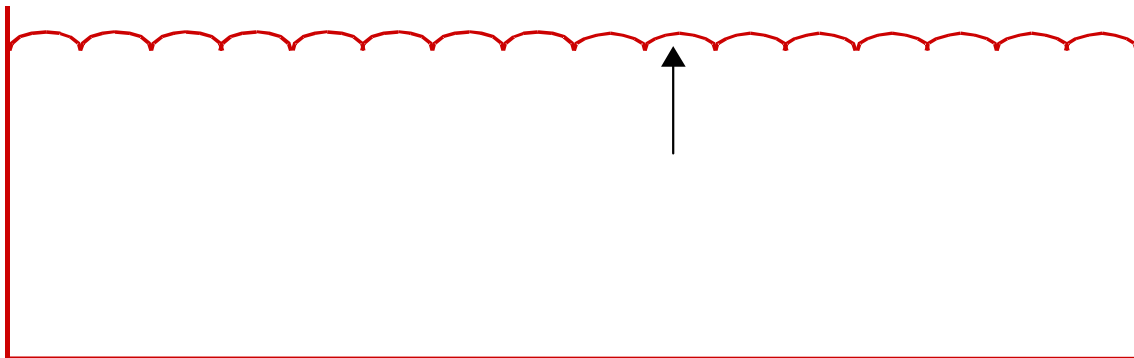
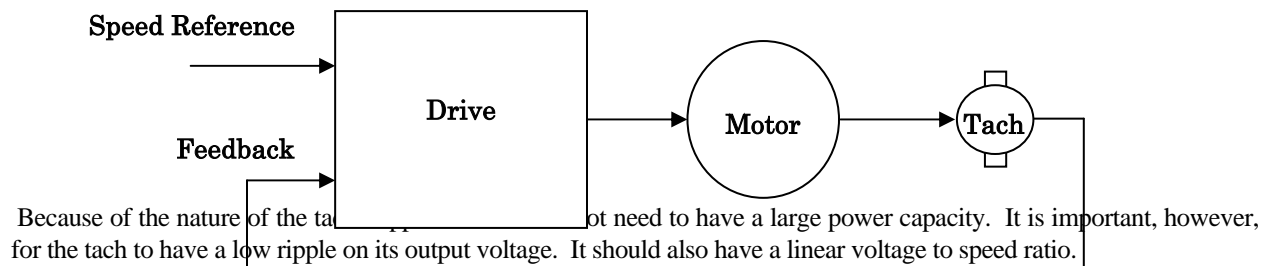
Maintenance: High

Examples: -Clean
-Replace brushes
-Must be PM'ed

Tachometer

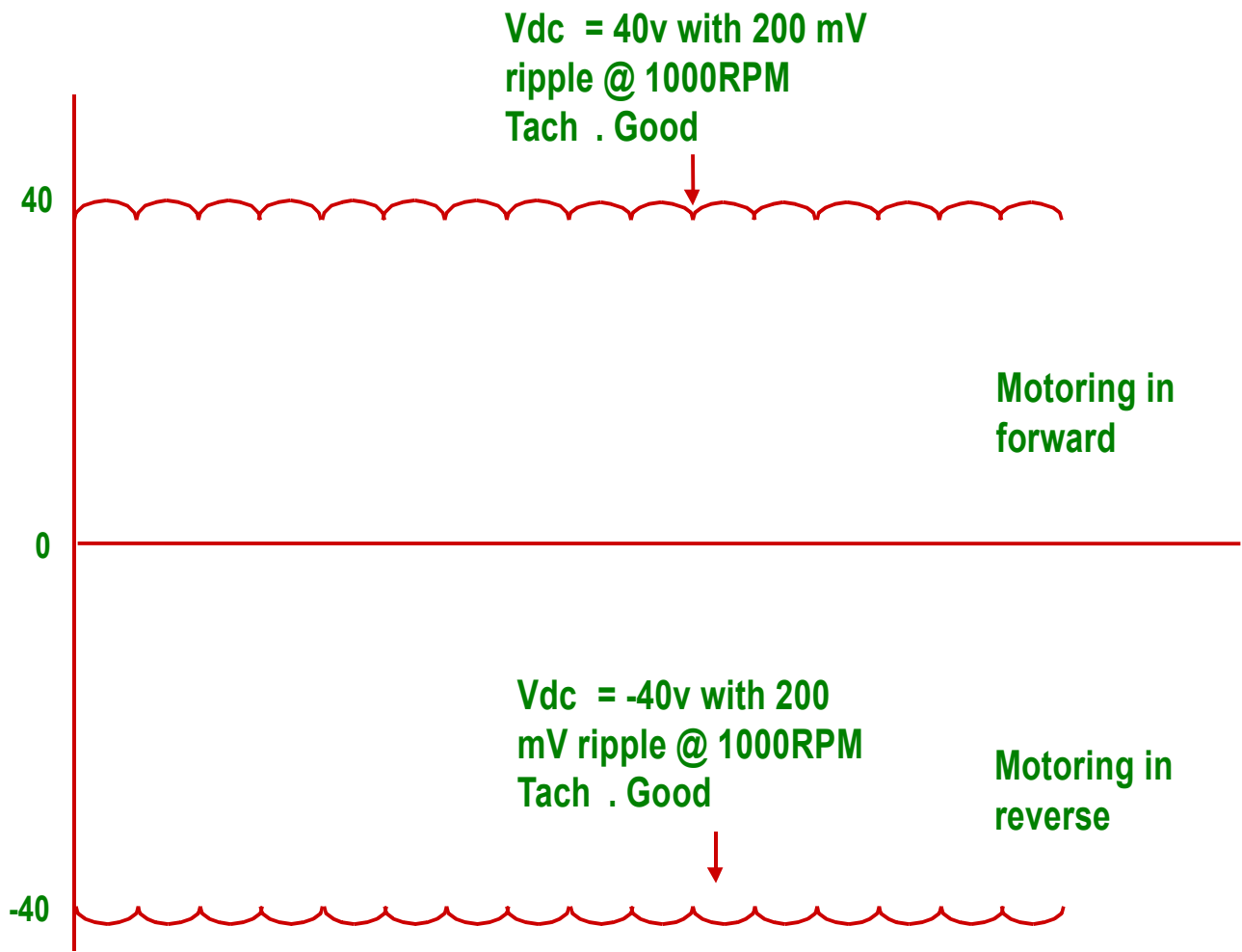


A tachometer generator, or tach generator, is a machine that generates a voltage that is used as a signal rather than a power source. The signal output from the tach is intended to be directly proportional to the speed of the motor. The output of the tach can be fed back to the drive controller providing the controller with a measure of the motor's speed. The controller can then regulate the speed using the voltage feedback. This would represent a closed loop control system as shown below.



The ripple in the output of the tach is set by the number of coils and commutator segments determined by its construction. An average tach would have 32 segments in its commutator. A more expensive and accurate tach could have as high as 100 segments.

In order to achieve good linearity, a tach generator must have a constant field strength. The majority of tachs used are now constructed with a permanent magnet field. This makes sure the voltage at a given RPM is always the same, and so the generated voltage is in direct proportion to the speed. The polarity of the generated signal is an indication of the direction of the rotation of the motor.



Name: Incremental Encoder

Type of Signal: Digital Signal (Binary) Pulse train
(Squarewave)

Type of Information: Speed = Freq.
Direction = Phase Relationship
Angular Position = Count & Marker

Rating: Windows/turn or
Pulses/turn
#Channels
Maximum frequency

Maintenance: Replace as needed, critical alignment, fragile

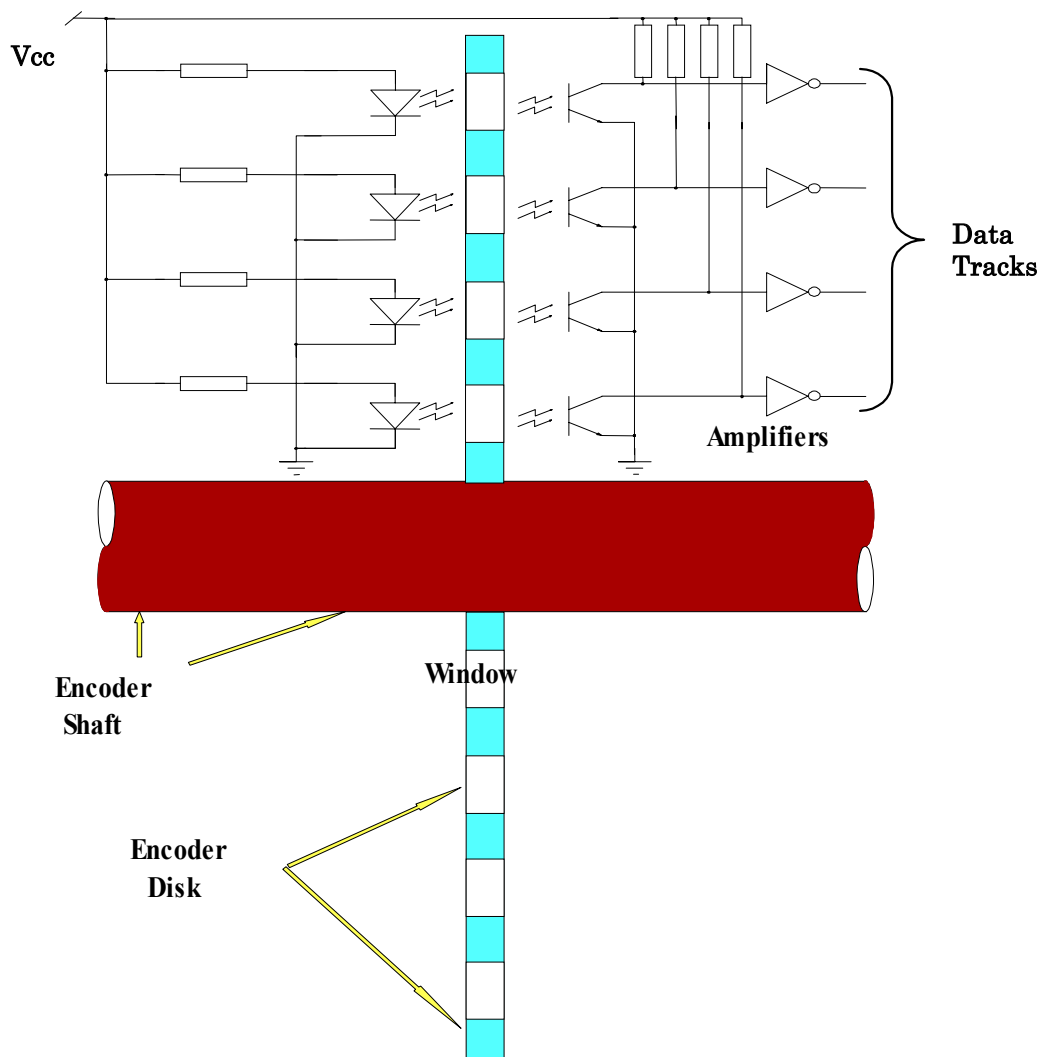
Note: Encoder must be clean
Properly align
No preload on the bearing

Incremental Encoders

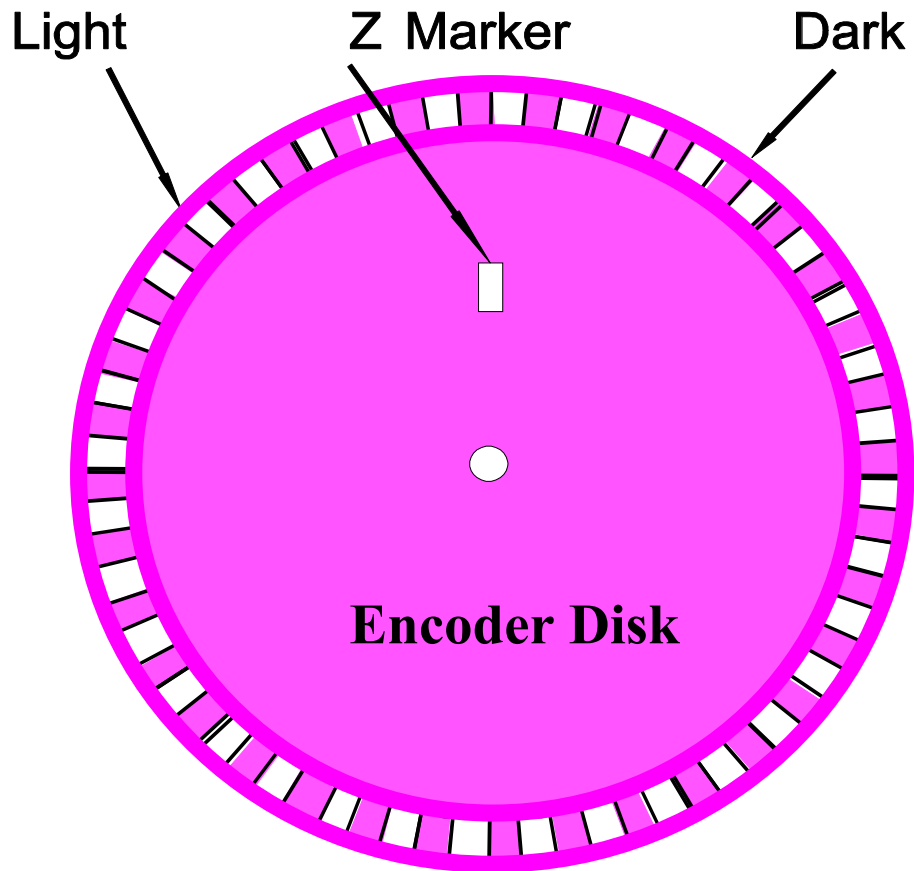
Incremental encoders are position verification devices that indicate rotary or linear motion and the direction of movement. An encoder plus a counting device make up an incremental system. The counting device will sum the positive and negative increments allowing the user to detect the net amount of movement at any point in time. Linear incremental encoders should be applied to traverse operations. Rotary encoders are the best choice for angular applications.

Basic Operation of a Rotary Encoder

A rotary incremental optical encoder consists of five basic components. The light source (LED or incandescent), the encoder disc, grid assembly, photo-detector, and amplification electronics. These are shown below.



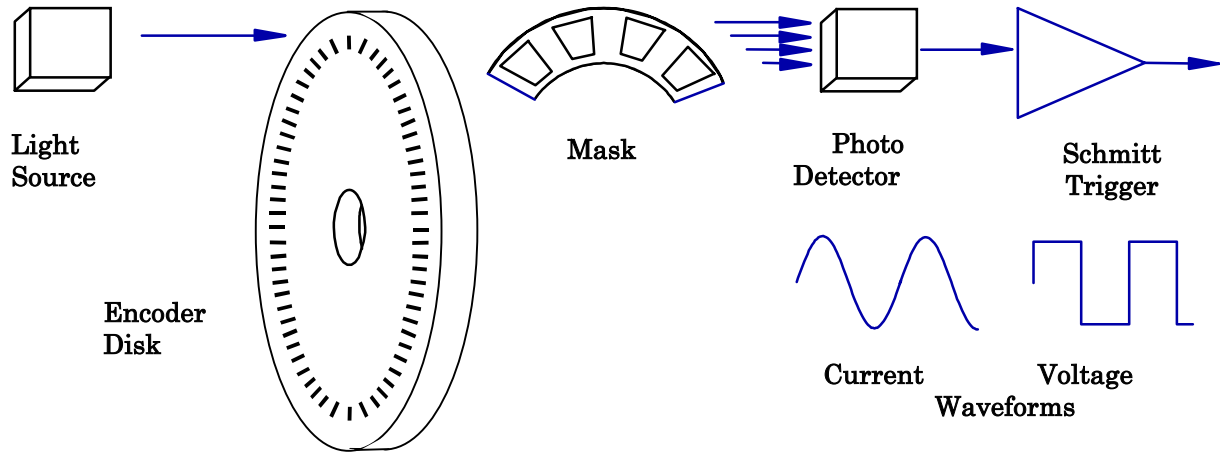
The disc is one of the key elements of the encoder. A simplified disc is shown below.



It is typically a glass material with imprinted marks of metal with slots precisely located. The quantity of marks or slots is equivalent to the number of pulses per turn. A typical resolution is 500 or 1000 pulses per revolution. For example, a glass disc with 1000 marks imprinted would have moved 180° after 500 pulses. The maximum resolution of the encoder is limited by the number of marks or windows that can be physically located on the disk, which determines the number of pulses per revolution.

Most rotary encoders also provide a single mark on the disk called the Z channel or marker. The pulse from this channel provides a reference once per revolution to detect errors within a given revolution.

The LED or incandescent light source is constantly enabled. As the disk rotates, light reaches the photo-detector as each slot or window passes as shown below.



Rotary Incremental Optical Encoder

As the photo-detector senses light it allows current to flow and produces a current sine wave. The frequency of the sine wave is controlled by the alternations of light and dark from the disk's movement.

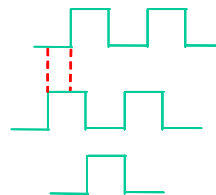
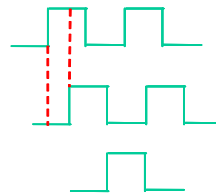
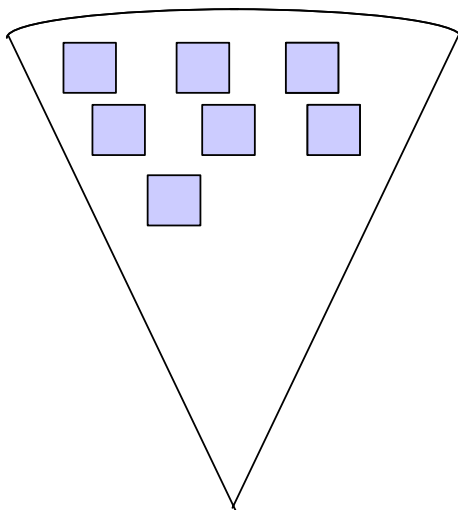
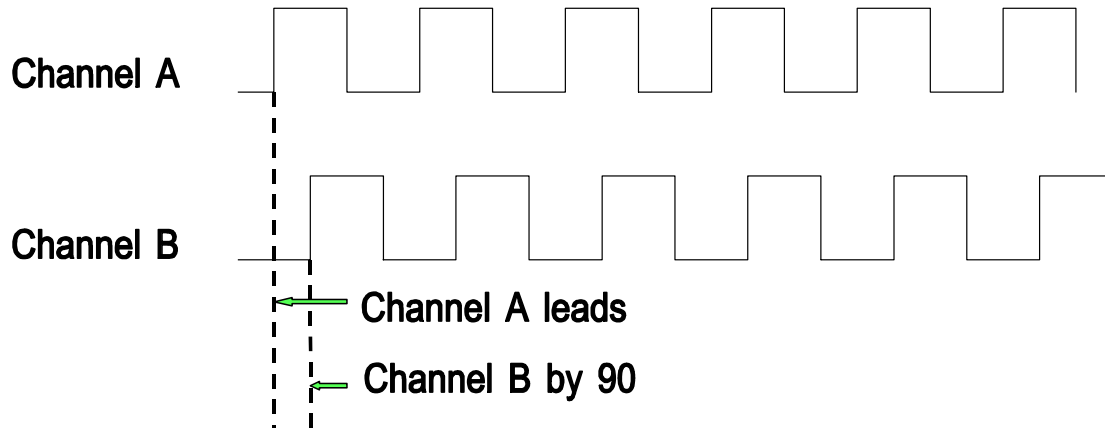
The outputs from the photo-detector are then converted into a square waveform and supplied to a counting device.

All incremental encoders rely on a counter to determine position and a stable clock to determine velocity. These systems use a variety of techniques to separate "up" counts from "down" counts, and maximize the incoming pulse rate. Correct position information is dependent on accurate counting and proper transmission of pulses. The use of complementary outputs will prevent false counting due to electrical noise developing stray electrical pulses.

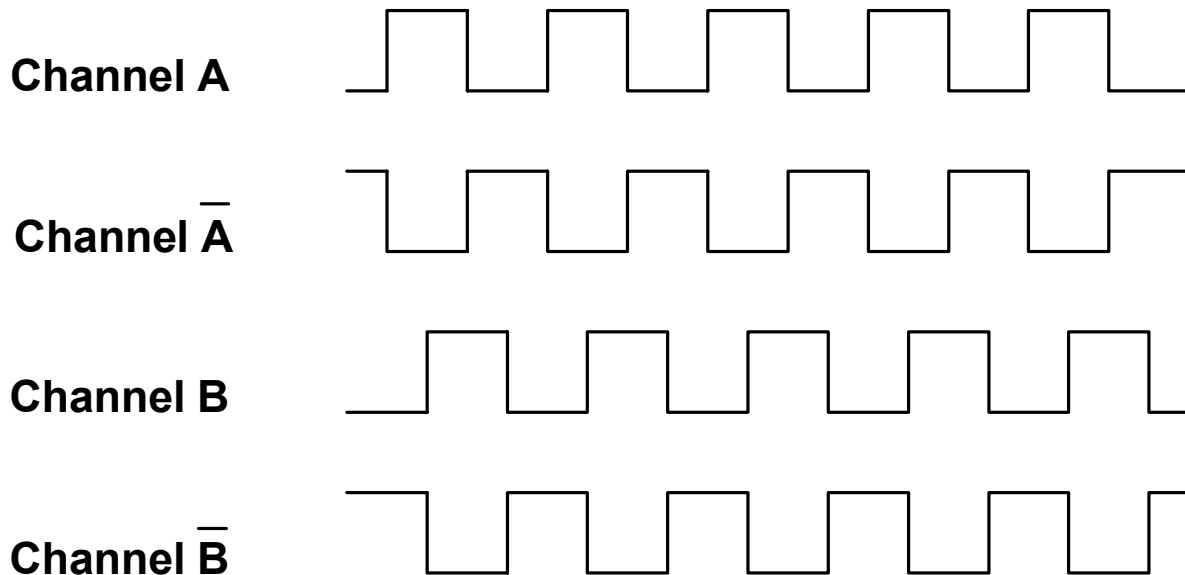
Incremental Encoders

The majority of all incremental encoders have a second light source and sensor (Channel B) located over the windows on the disk. Channel B is mechanically offset one half window from Channel A's light source and photo-detector.

Channels A and B will produce two square waves that are 90 electrical degrees apart. By monitoring the phase shift of both channels A and B one can determine direction. For example, if channel B leads channel A, that could indicate counter clockwise rotation. If channel A was to lead channel B, the opposite would be true. The waveform shown below is considered standard for **forward rotation**.



Quadrature Encoder with Complementary Outputs



An additional benefit of a quadrature encoder is the ability to multiply the encoder disk resolution by four. By counting the leading and trailing edge of each window on both channels, each slot of window now gives four counts. Using this procedure, a 1000 window disk can have a resolution of 4000 counts per revolution.

User Abuse

Even with the appropriate package, shaft, bearings and disc, the user must exercise care to avoid undue shock and abuse. In particular, the glass code disc can be damaged if the encoder is dropped or if a pulley is hammered onto the shaft. The typical shock and vibration specification for an industrial encoder is 50 grams of shock of 11 msec, as well as a vibration of 20 grams from 2-2000 Hz. In applications utilizing gears or drive belts, excessive radial (side) loading on the shaft can shorten bearing life. Therefore great care should be taken when tensioning an encoder's drive belt.

Name: Absolute Encoder

Type of Signal: Grey code

Type of Information: Position verification

Rating: Counts/turn

#Disks

#Turns

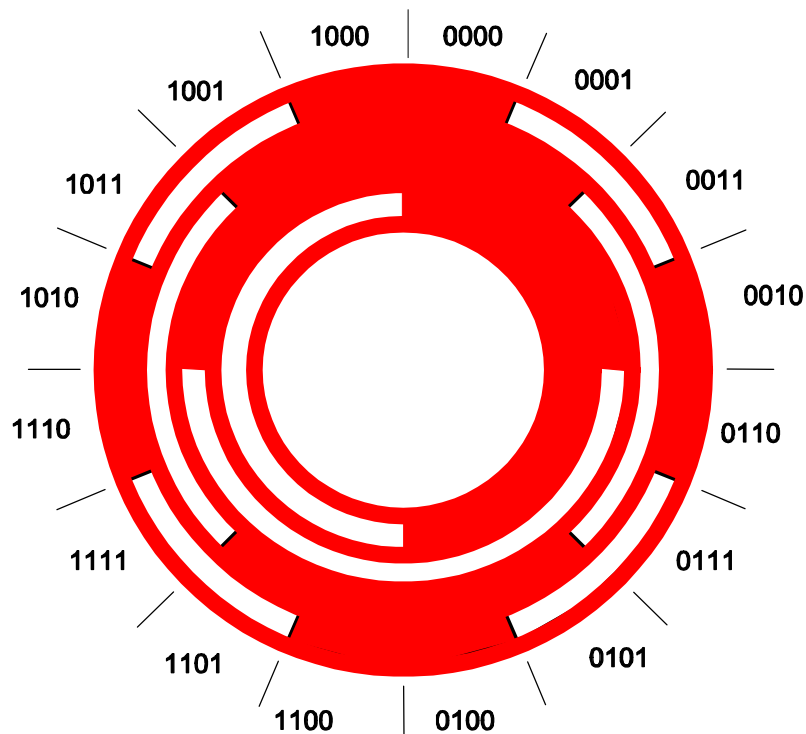
Maintenance: Replace as needed, Breakout box (grey code interpreter, PLC display)

Absolute Encoders

Basics of Absolute Encoders

An absolute encoder is a position verification device that provides unique position information for each shaft location. The location is independent of all other locations, unlike the incremental encoder, where a count from a reference is required to determine position.

In an absolute encoder, there are several concentric tracks, unlike the incremental encoder, with its single track. A simplified absolute encoder disk is shown below.



Grey Code for an Absolute Encoder Disk

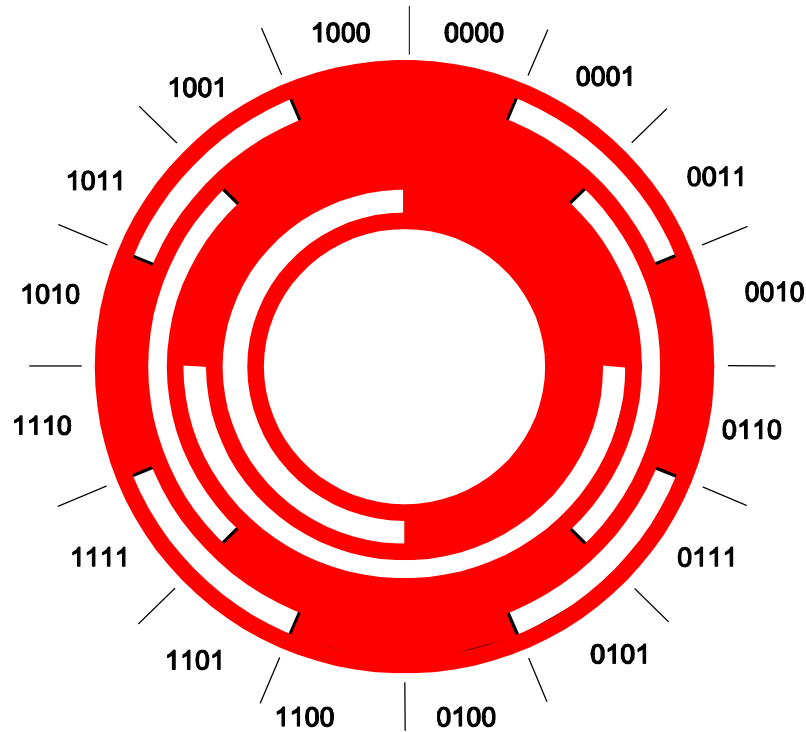
Each track has a separate and independent light source. As the light passes through a slot a high state (true "1") is created. If light does not pass through the disk a low state (false "0") is created. The position of the shaft can be identified through the pattern of "1's" and "0's".

The tracks of an absolute encoder vary in slot size, moving from smaller at the outside edge to larger towards the center, the pattern of slots is also staggered with respect to preceding and succeeding tracks. The number of tracks determines the amount of position information that can be derived from the encoder disk-resolution. For example, if the disk has ten tracks, the resolution of the encoder would be 2^{10} or 1,024 positions per revolution.

For reliability, it is desirable to have the disks constructed of metal rather than glass. A metal disk is not as fragile, and has a lower inertia.

Absolute Encoder Output

The disk pattern of an absolute encoder is in machine-readable code, usually binary, grey code or a variant of grey.



Grey Code for an Absolute Encoder Disk

The figure above represents a simple binary output with four bits of information if the current location was at the equivalent to the decimal 2 (0-0-1-0 binary). Moving clockwise from the current position, the next decimal number is not 3 but 6 (0-1-1-0 binary). Moving counter-clockwise from the current position, the next decimal number would be 3(0-0-1-1). For this reason the output of the absolute encoder is usually decoded by a microprocessor.

Multi-turn Absolute Encoders

Gearing an additional absolute disk to the primary high-resolution disk provides for turns counting, so that unique position information is available over multiple revolutions. Here is an example of how an encoder with 1,024 discrete positions per revolution becomes an absolute device for 524,288 discrete positions.

The primary high-resolution disk has 1,024 discrete positions per revolution. A second disk with three tracks of information will be attached to the high-resolution disk with a gearing ratio of 8:1. The absolute encoder now turns 8 complete rotations for each rotation of the shaft, or 8,192 discrete positions. Adding a third disk geared 8:1 and a fourth disk geared 8:1 would provide 512 turns of the high-resolution disk to each turn of the shaft and therefore, 524,288 discrete absolute positions. Encoders using this technique are called multi-turn absolute encoders.

Name: Resolver

Type of Signal: AC/Amplitude Modulated

Type of Information: Speed = Freq.
Direction = Phase
Angular position = Sin/Cos

Rating: Voltage of carries
poles (up to 4)

Maintenance: Calibration
Alignment

Resolvers

The resolver is a form of synchro (resolvers are very often called synchro resolvers) in which the sine-cosine windings on the stator are displaced mechanically at 90° from each other instead of 120° as in synchros. The resolver therefore exploits the sinusoidal relationship between the shaft angle and the output voltage. The primary or source winding is placed on the rotor.

In outward appearance, resolvers are very similar to synchros and are produced in the standard synchro frame diameters.

Internally, resolvers come in many forms with a wide variety of winding configurations and transformation ratios. The simplest resolver would have a rotor with a single winding and a stator with two windings at 90° to each other. It would be represented as shown in the figure below.



DC DRIVES

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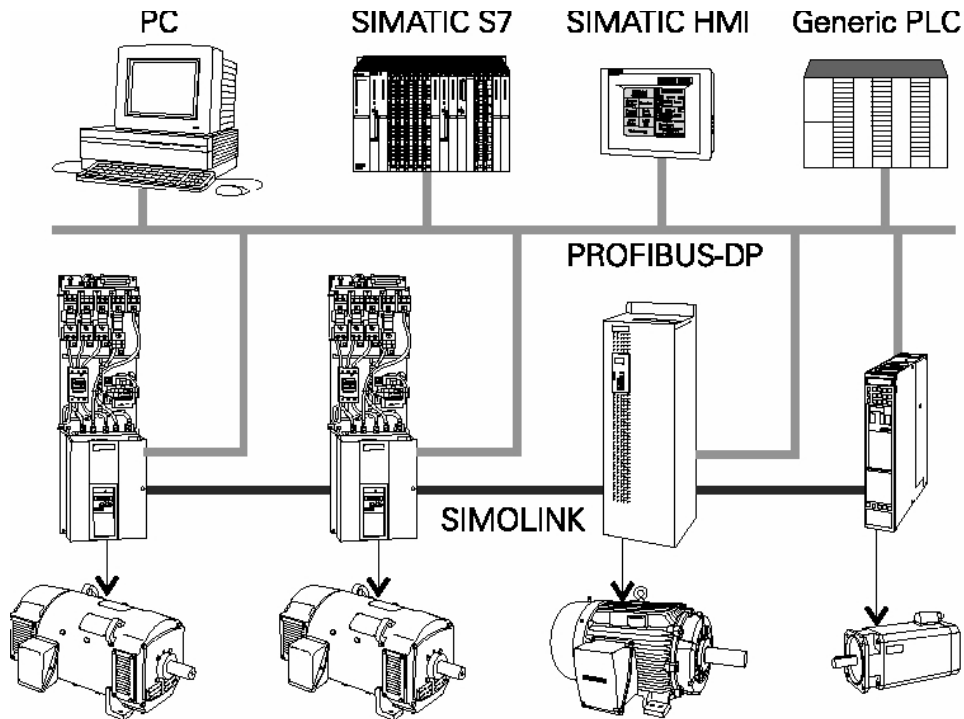
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Analog DC Drives

One of the mainstays of DC Drives is the analog drive. The analog drive does not use a microprocessor or other forms of digital processing. The transistor and the operational amplifier are the active components in the drive. The analog drive is cheaper to build which is why it is still being made today.

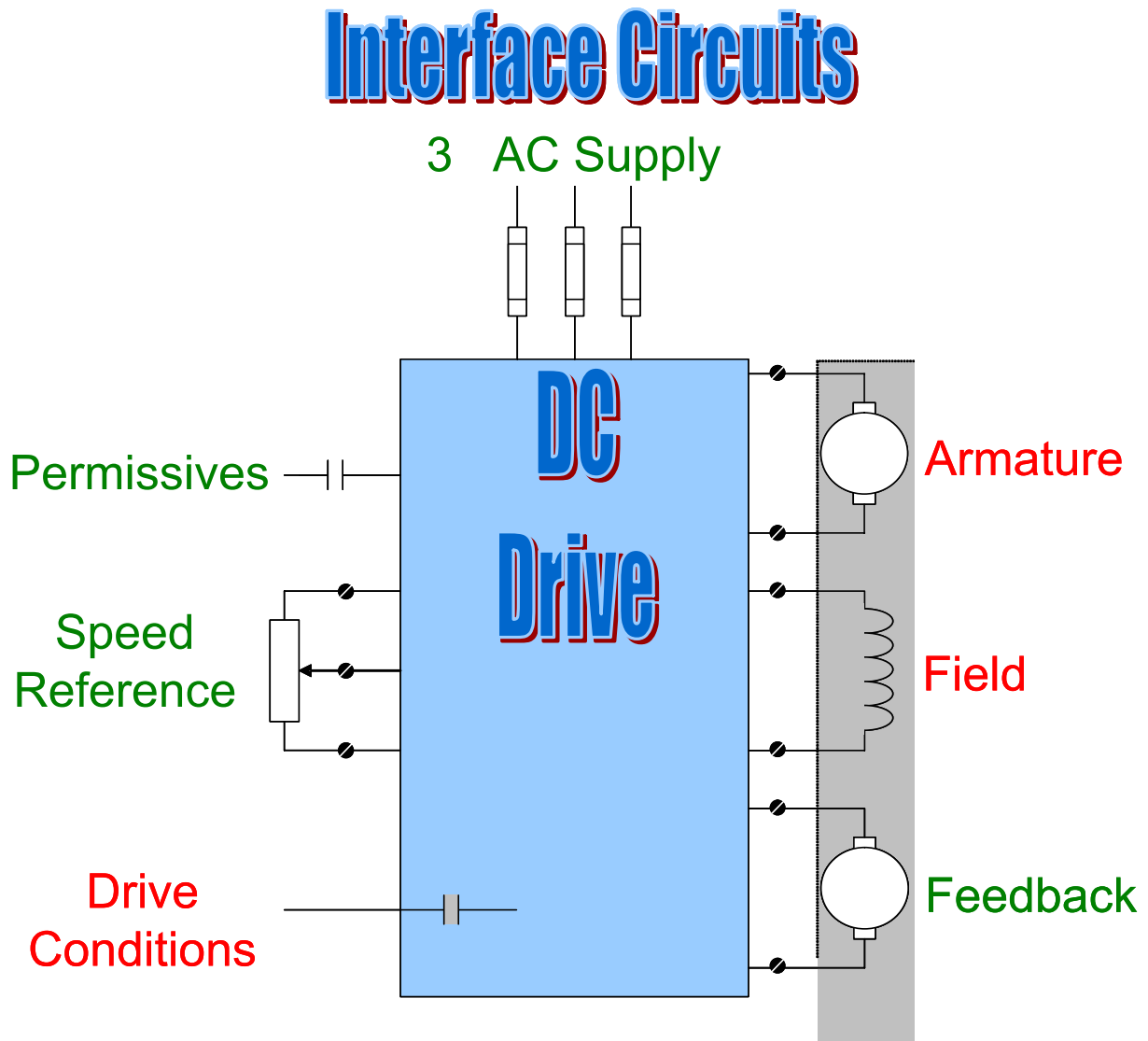
Digital DC Drives

The analog drive used transistors and op amps to perform its control functions. The digital drive is different in that it uses a microprocessor to bring about its control functions. The typical digital drive will have a logic and control board as the center of its drive control system. One of the benefits gained through the use of digital drives is their ability to communicate with other digital systems as shown below.



DC Drive Interface Circuits

Typical interface circuits that can be applied to either analog or digital drives are shown in the figure below.



The most recognized DC drive interfaces are the AC supply, the armature (A1 - A2), and the field (F1 - F2).

The feedback circuit can be a tachometer or it can be an optical encoder, an AC generator, a linear voltage displacement transformer, and even a current transformer.

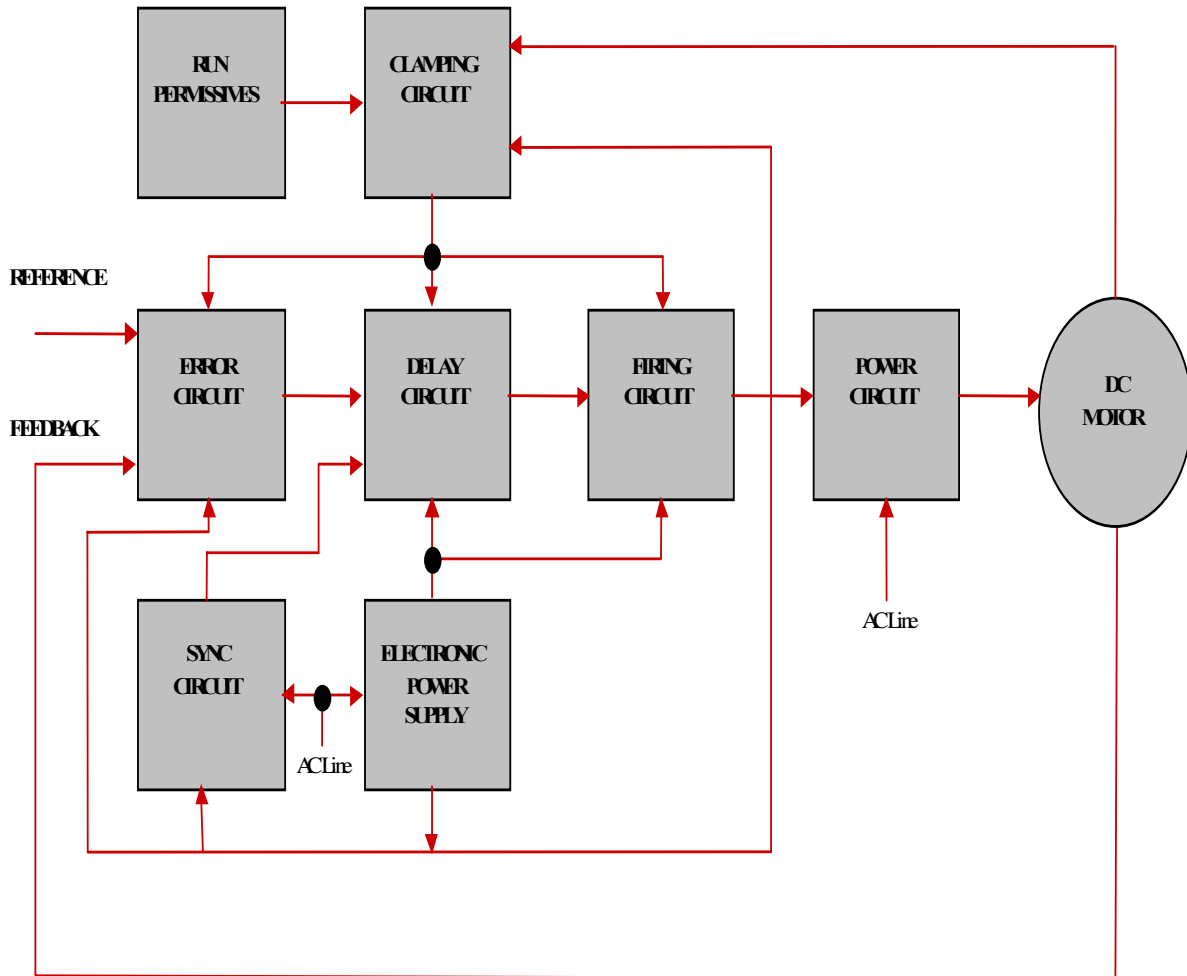
The drive condition circuit varies from a simple LED, to selectable conditions that will cause an output to change state. These can be conditions such as "drive at speed" or "drive in current limit". These conditions are outputs from the drive that can be used in external circuits.

The run permissives include all of the external circuits that enable the drive. These can be safety gates, interlocks or contacts from another drive showing that it is "running at speed".

The speed reference circuit is shown as a three-wire connection. The most common manual configuration is a three-wire pot used to manually set the speed reference. Other sources for the speed reference are an analogue output card from a PLC or a motion controller like the Allen Bradley IMC 121. These basic interface circuits can be identified on almost all drives. Recognizing them and being able to verify their function is a prime responsibility of troubleshooters.

DC Drive Block Diagram

A typical block diagram of a DC drive's circuits which, can be applied to either analog or digital drives is shown in the figure below.



DC Drive Block Descriptions

Error Circuit - Compares reference and feedback signals and produces an error signal for any correction needed. Usually contains two loops.

- (1) **Major loop** - the regulation loop
- (2) **Minor loop** - the current loop (much faster than the major loop)

Sync Circuit - Provides a time frame or "window" where the gate pulse may be developed. It synchronizes the drive with the incoming line voltage.

Delay Circuit - Produces a signal that triggers the firing circuit exactly where the gate pulse is to be placed within the sync window. This is the timing function of the drive. Usually produces a ramp voltage that will trigger the firing circuit at a particular level.

Firing Circuit - Uses the signal developed by the Delay Circuit to generate a pulse with proper voltage, current, and time so that the pulse will fire the SCR's.

Power Circuit - Contains the power devices, SCR's, and diodes to drive the motor.

Electronic Power Supply - Supplies all the necessary D.C. voltages to the electronic circuits.

Clamping Circuit - Limits the drive in some manner. It may not allow the drive to run at all or may limit the drive in current, speed, etc.

Run Permissives - Any conditions that must be met to run the drives, such as close to run circuits, E-stops, safeties, etc. Usually external inputs to the drive.



BASIC DC MOTOR PRINCIPLES

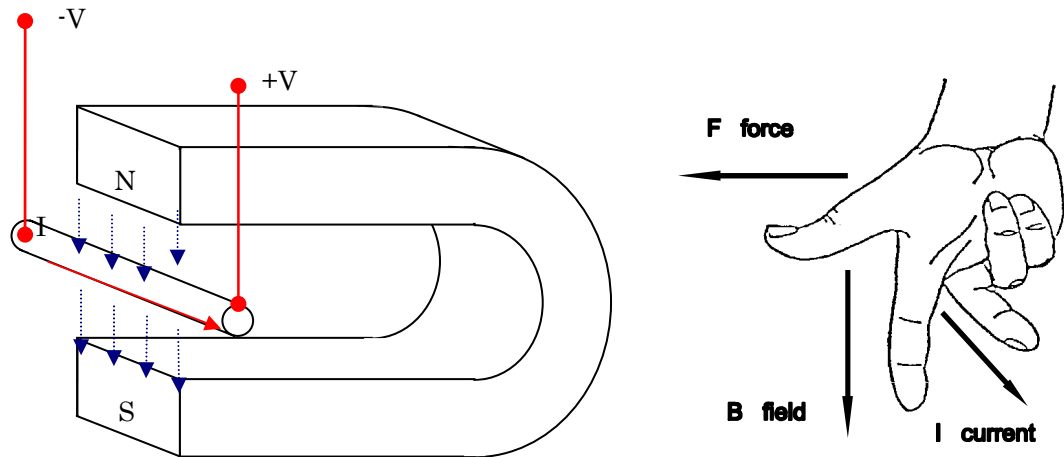
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Electromotive Force

When a current carrying conductor is placed in a magnetic field it is subjected to an electromotive force. The direction of the force is given by the **right hand rule**.



F = Force on the conductor in newtons.

B = Flux density.

I = Current in amperes.

The electromotive force is a result of the two magnetic fields and their interaction. The right hand rule is one way to establish the direction of force, another is the basic magnetic laws. Like poles repel and opposite poles attract. The permanent magnets flux lines travel from north to south. The left hand rule would indicate the flux lines around the wire.

Once the flux lines from both sources are established the direction of force is known, flux lines traveling in opposite directions-attract.

Torque

Torque is produced when a force exerts a twisting action on a body, tending to make it rotate.

$$T = Fr, \text{ where } T = \text{Torque, } F = \text{Force, and } r = \text{radius}$$

The developed torque is directly proportional to:

B: the flux density set up by the permanent magnet.

L: the effective length of the current carrying conductor.

I: the amount of current in the conductor.

N: the numbers of loops.

D: the distance between the two opposite live conductors.

$$\text{Torque} = BLIND \quad (\text{unit for torque} = \text{Nm})$$

Since B,L,N, and D are constants, the torque depends only on I, the amount of current in the conductor.

Torque is produced in a DC Motor through the interaction of two magnetic fields.

This force is the result of Field Flux (ϕ_f) and Armature Flux (ϕ_{arm}).

$$T = k \phi_f \phi_{arm}$$

To change the speed of a DC Motor, you must affect the torque equilibrium.

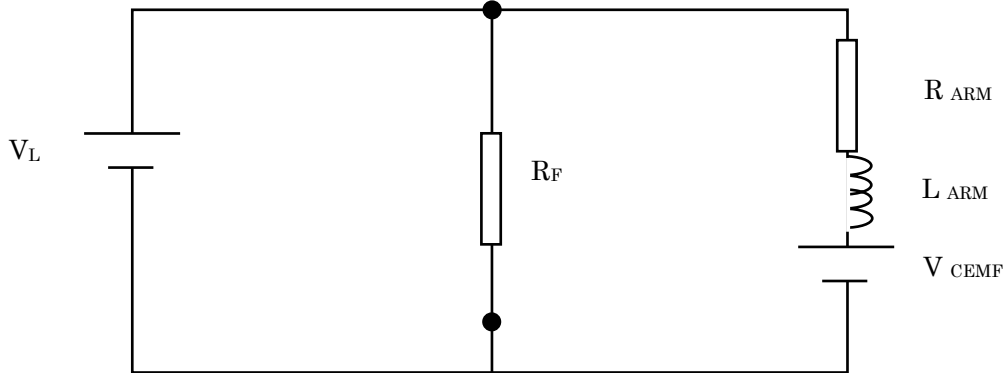
If a motor is at constant speed:

$$T_{mv} = T_{load}$$

To accelerate, this relationship must be taken out of equilibrium:

$$T_{mv} > T_{load}$$

Shunt DC Motor



Equivalent circuit of a D.C. Shunt Motor

By using Mesh analysis, we can obtain the following equation describing a Shunt Wound DC Motor:

$$V_{\text{line}} = V_{\text{cemf}} + I_{\text{arm}} R_{\text{arm}} \quad (\text{neglecting } L_{\text{arm}})$$

V_{line} is the instantaneous voltage potential from the DC Drive Controller that is applied directly to the armature. As we have seen before V_{cemf} can be expressed as:

$$V_{\text{cemf}} = k\phi_f S$$

k = motor constants

ϕ_f = field flux

S = speed

Increasing V_{line} will increase the amount of I_{arm} that will flow. This will likewise increase the torque delivered to the motor increasing its speed. The V_{cemf} will naturally increase with speed causing I_{arm} to decrease. However, I_{arm} will settle to a value that is higher than its original value. Therefore, the end result is an increase in motor speed. A similar statement could be made for a decrease in V_{line} . It can therefore be seen that the speed of a Shunt Wound DC Motor is controlled by manipulating V_{line} .

Combining the two above equations, we can obtain an expression describing the speed of a Shunt Wound DC Motor.

$$S = \frac{V_L - I_{\text{arm}} R_{\text{arm}}}{k \Phi_F}$$

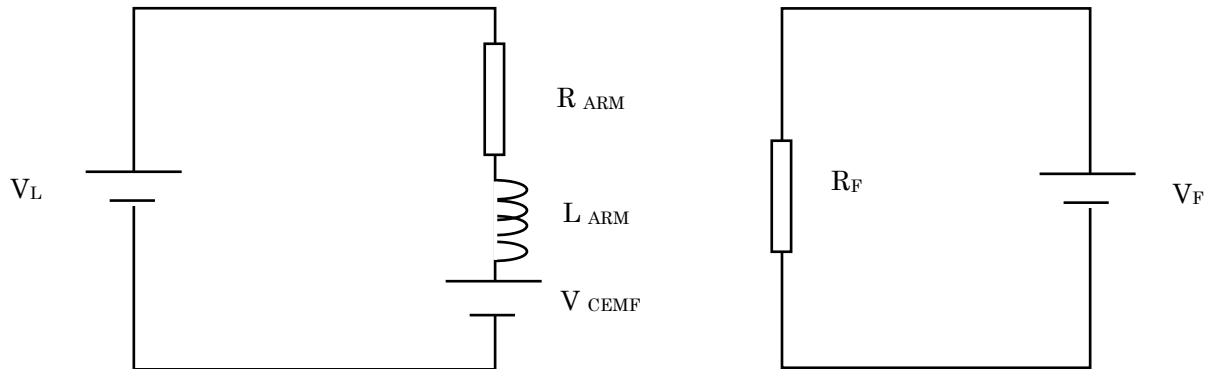
To avoid confusion let's reiterate that we control the speed of a DC Motor by controlling I_{arm} . This may seem to contradict our last statement, which said that we vary V_{line} to control the speed. However, our previous discussion also revealed that a change in V_{line} would produce a similar change in I_{arm} .

It can therefore be concluded that both arguments are true since they both make the same statement.

Our equation for the speed of a DC Motor also reveals another method of controlling speed, through the variation of ϕ_f . This may seem odd at first, so let's consider a scenario. Let's say we decreased ϕ_f . This would cause a decrease in V_{cemf} , which in turn would cause an increase in I_{arm} . The result would be an increase in motor speed. As stated in an earlier discussion, this is referred to as Field Weakening.

In an effort to reduce its inertia, as little wire as possible is used during the winding of the armature. This means that the resistance of the armature is very low, usually less than 1 Ω . This low resistance, combined with the absence of V_{cemf} , requires that V_{line} be reduced during starting in order to keep I_{arm} from reaching dangerously high levels. With the field connected in parallel with the armature, a reduction of V_{line} will also reduce the magnetic flux produced by the field windings. Without the presence of field flux the motor will exhibit poor starting torque.

To improve the starting torque of a Shunt Wound DC Motor, the field is excited by a different source than of the armature. This allows the field to be at full strength at starting and greatly improves the starting torque. This configuration is referred to as the Separately Excited DC Shunt Motor and is the most common type found in industry. The equivalent circuit is shown below.



Equivalent circuit of a Separately Excited D.C. Shunt Motor

The low resistance of the armature (1 to 3 ohms), combined with its low inductance, does allow it to be very responsive.

$$S = \frac{V_L - I_{arm} R_{arm}}{k \Phi_F}$$

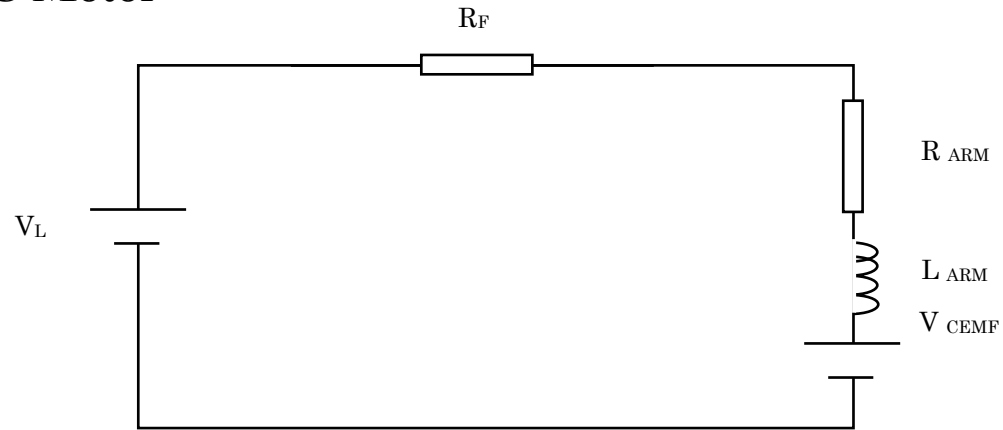
In the above equation, $I_A R_A$ is at maximum only 5% of V_L , because R_A is so small. Therefore, the most effect on speed a change in current from no load to full load can have is 5%.

$$SR\% = \frac{\text{No Load Speed} - \text{Full Load Speed}}{\text{Full Load Speed}} \times 100$$

The small armature resistance and the small effect armature current has on speed makes the Shunt Motor the best of all DC Motor configurations in the area of speed regulation.

The separately excited DC shunt wound motor is by far the most utilized DC motor in industry; therefore, it will be the only one we discuss in detail.

Series DC Motor



Because the field is now in series with the armature, the current in each will be equal. Therefore, some of the equations describing the motor operation will change slightly.

For example, the equation for speed now becomes:

$$S = \frac{V_L - I_{arm}(R_{arm} + R_f)}{k I_{arm}}$$

The expression for torque will also change:

$$T = k I_{arm}^2$$

The series motor will also exhibit its own unique characteristics. One of these characteristics is its high starting torque. Because the field is now in series with the armature, reduced voltage starting is no longer necessary. The resistance of the field winding will prevent the armature current from reaching a level that would prove destructive.

A less desirable characteristic of the series motor is its poor speed regulation. The field winding possesses a very high inductance. Since inductance opposes a change in the magnitude or direction of current flow, the motor cannot respond to quick load changes. This obviously affects its ability to maintain a constant speed over a varying load.

As seen from the speed formula above, as I_{arm} decreases, speed increases. Therefore, care must be taken to never operate the motor unloaded, or it will run away.



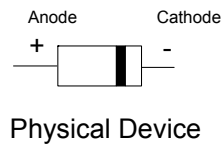
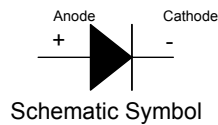
POWER SUPPLIES

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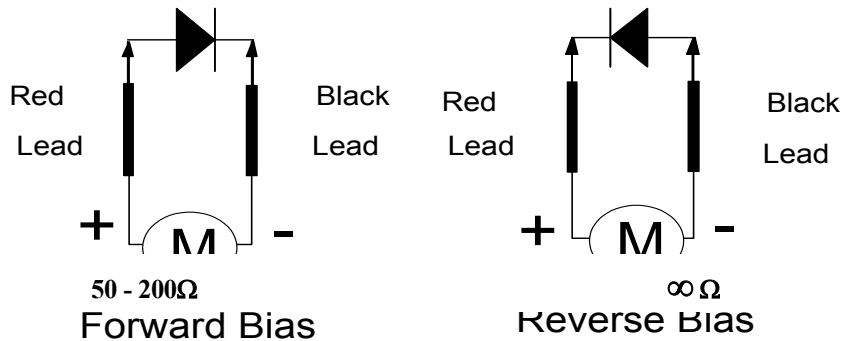
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DIODES



1. The diode acts like a check valve, allowing current flow in one direction and restricting it in the other direction.
2. Current flows from cathode to anode (electron current flow).
3. Germanium Diodes are normally low current, used on signal type circuits with about .3 volt drop when forward biased.
4. Silicon Diodes are normally high current, used on power supply type circuits with about .7 volt drop when forward biased.

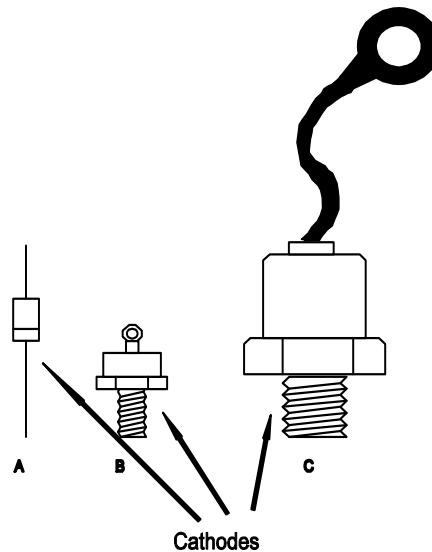
HOW TO CHECK WITH AN OHMMETER USING R1 SCALE



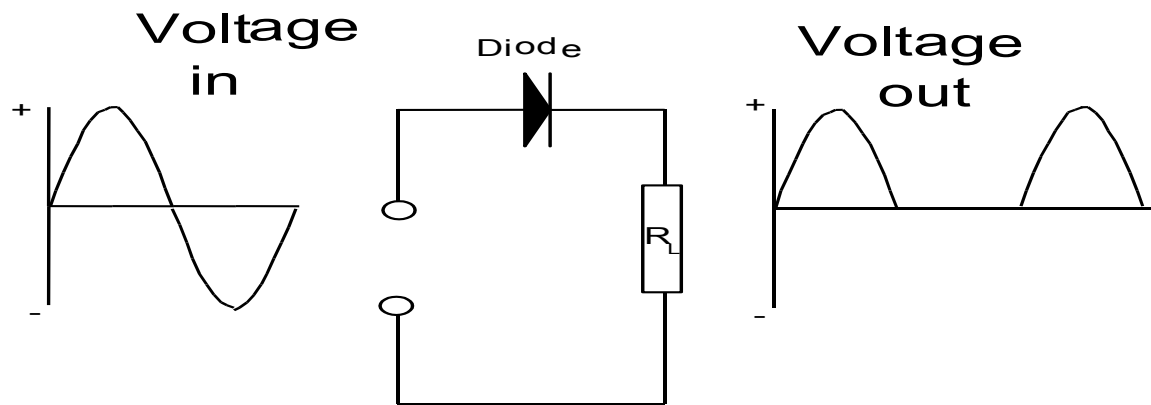
Note: This value

ctions.

- A. Low power devices
- B. Medium power devices
- C. High power devices



HALF WAVE RECTIFICATION



Shown above is a diode connected in an AC circuit. Current can flow only from the cathode to the anode. With an AC voltage source applied, the diode will conduct when the supply voltage connected to the anode is positive. During the positive half cycle, the diode conducts and the supply voltage is delivered to the load. Since the diode is a semiconductor device, there is a voltage drop across it while it is conducting. The two main types of materials used for diodes are silicon and germanium. Silicon diodes have approximately .7 volt drop while germanium has approximately .3 volt drop. This diode drop is very small but has to be considered for the voltage level delivered to the load.

When the supply voltage reverses polarity at the end of the positive half cycle, the diode no longer conducts. It now acts as an open circuit and no current is delivered to the load. Consequently, the diode only conducts during the positive half cycles which converts the AC voltage source to a pulsating DC voltage. The voltage supplied to the load is alternating but not changing polarity, therefore, it is a usable DC voltage. This is **half-wave rectification** since only half of the input waveform is usable.

Let's evaluate the value of the DC output voltage to the load if the input supply voltage is 24 volts rms. The rms value of the AC input waveform is the effective value for the complete sine wave. Since the diode blocks part of the waveform, this rms value does not apply to the DC output waveform. We must convert the rms value to a peak value so we can calculate the DC output voltage.

$$INPUT V_{PK} = \frac{V_{rms}}{.707}$$

$$INPUT V_{PK} = \frac{24V}{.707}$$

$$INPUT V_{PK} = 33.946volts$$

This 33.946 volts is the peak value for the input waveform. The voltage drop of the diode now has to be subtracted from this peak value. Let's use a silicon type diode.

$$OUTPUT V_{PK} = INPUT V_{PK} - DD$$

$$OUTPUT V_{PK} = 33.946 - .7 volts$$

$$OUTPUT V_{PK} = 33.246volts$$

The rms value of the AC input waveform is the effective value for the complete sine wave. This value can't be used for the output waveform since it is not a sine wave anymore. The average value for half-wave DC must be used.

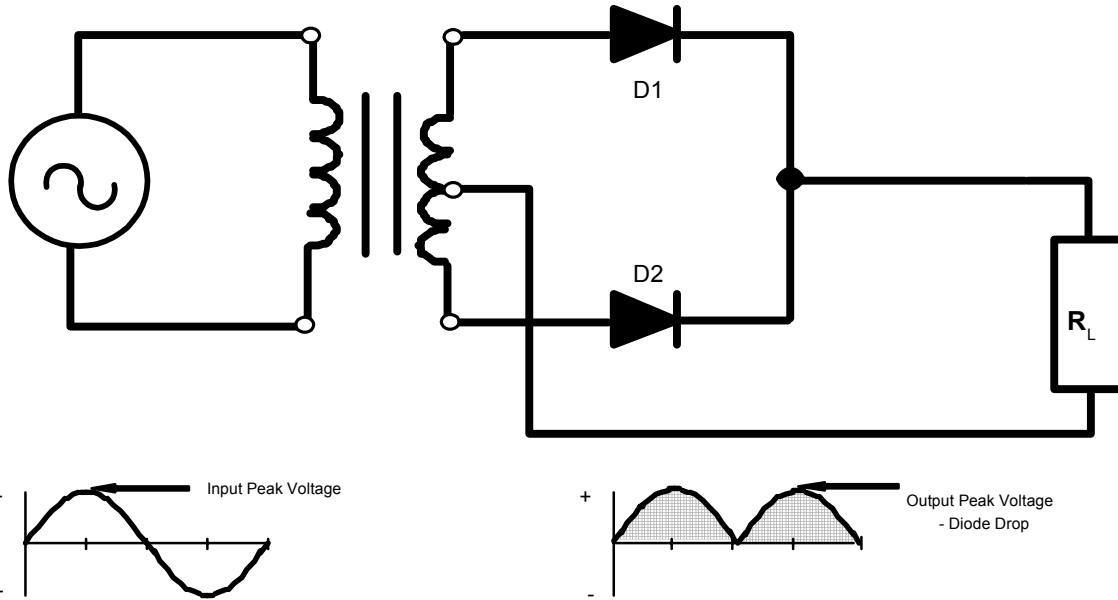
$$V_{AV} = \frac{OUTPUT V_{PK}}{\pi}$$

$$V_{AV} = 33.246volts \times .318$$

$$V_{AV} = 10.583volts$$

This V_{AV} value is the effective or average DC voltage which can be used just as though it were a battery. Notice that we used π in this calculation. Remember π represents 180° in radian mode. This is the average DC voltage usable for this basic half-wave rectifier.

FULL WAVE RECTIFICATION



SI lary winding with the load connected from there to the cathodes of the two diodes. With an AC voltage source applied, the diode (**D1**) will conduct during the positive half-cycle and (**D2**) conducts during the negative half-cycle. There is still only one diode drop to be considered since only one is conducting at any time. Also notice that there is a transformer and the voltage/current/turns relationships have to be considered.

Again the voltage supplied to the load is alternating but not changing polarity. It is a usable DC voltage and now there are two output cycles for one input cycle. This is **full-wave rectification**.

Let's evaluate the value of the DC output voltage to the load if the input supply voltage across half of the secondary winding of the transformer is 24 volts rms. This will give us a good comparison to the half-wave calculations from before. We must again convert the rms value to a peak value so we can calculate the DC output voltage.

$$INPUT V_{PK} = \frac{V_{rms}}{.707}$$

$$INPUT V_{PK} = \frac{24V}{.707}$$

$$INPUT V_{PK} = 33.946volts$$

This 33.946 volts is the peak value for the input waveform applied to the rectifier. The voltage drop of the diode again has to be subtracted from this peak value.

$$OUTPUT V_{PK} = INPUT V_{PK} - DD$$

$$OUTPUT V_{PK} = 33.946 - .7 volts$$

$$OUTPUT V_{PK} = 33.246volts$$

The rms value of the AC input waveform is the effective value for the complete sine wave. This value also can't be used for the output waveform since it is not a sine wave either. The average value for this full-wave DC must be used.

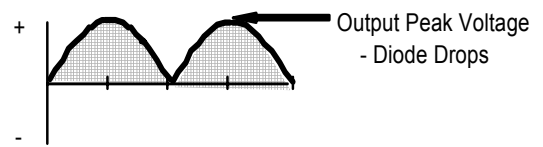
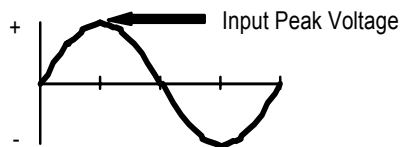
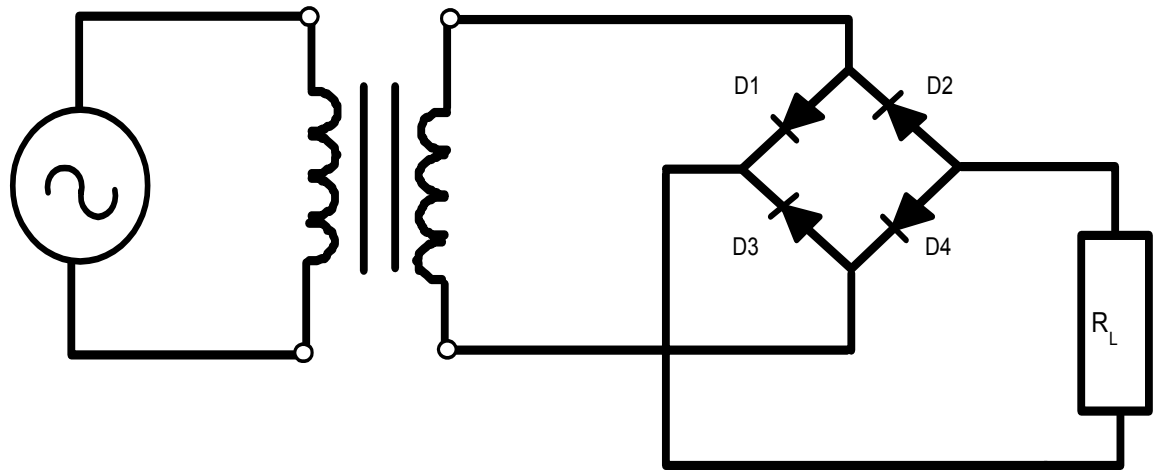
$$V_{AV} = 2\left(\frac{OUTPUT V_{PK}}{\pi}\right)$$

$$V_{AV} = 33.246volts \times .637$$

$$V_{AV} = 21.165volts$$

This V_{AV} value is the effective or average DC voltage which can be used just as though it were a battery. Notice that this relationship is the same as for half-wave rectification, except we have multiplied by 2. This is the average DC voltage usable for this basic full-wave rectifier.

FULL WAVE BRIDGE RECTIFICATION



Shown above

type. With the secondary voltage applied to the bridge, diodes **(D1 and D2)** will conduct during the positive half cycle and **(D2 and D3)** conducts during the negative half-cycle. Now there will be two diode drops to be considered since two diodes are conducting. Also don't forget to consider the voltage/current/turns relationships due to the transformer.

Again the voltage supplied to the load is alternating but not changing polarity. It is a usable DC voltage and there are two output cycles for one input cycle. This is **full-wave bridge rectification**.

Let's evaluate the value of the DC output voltage to the load if the input supply voltage of the secondary winding of the transformer is 24 volts rms. We must again convert the rms value to a peak value so we can calculate the DC output voltage.

$$INPUT V_{PK} = \frac{V_{rms}}{.707}$$

$$INPUT V_{PK} = \frac{24V}{.707}$$

$$INPUT V_{PK} = 33.946volts$$

This 33.946 volts is the peak value for the input waveform applied to the rectifier. The voltage drop of the two diodes has to be subtracted from this peak value.

$$OUTPUT V_{PK} = INPUT V_{PK} - DD$$

$$OUTPUT V_{PK} = 33.946 - 1.4 volts$$

$$OUTPUT V_{PK} = 32.546volts$$

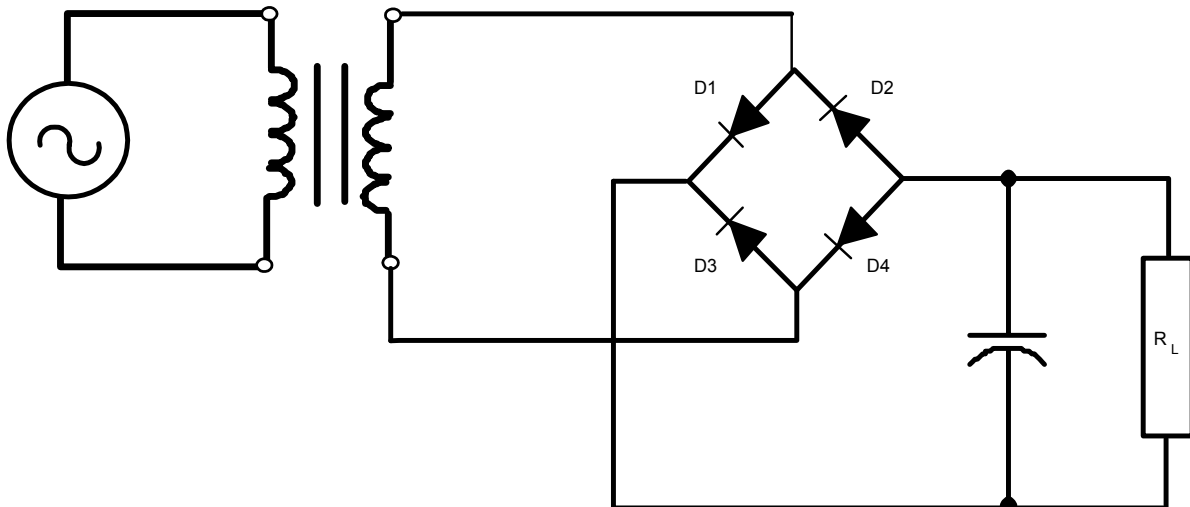
The rms value of the AC input waveform is the effective value for the complete sine wave. This value also can't be used for the output waveform since it is not a sine wave either. The average value for this full-wave DC must be used.

$$V_{AV} = 2\left(\frac{OUTPUT V_{PK}}{\pi}\right)$$

$$V_{AV} = 32.546volts \times .637$$

$$V_{AV} = 20.732volts$$

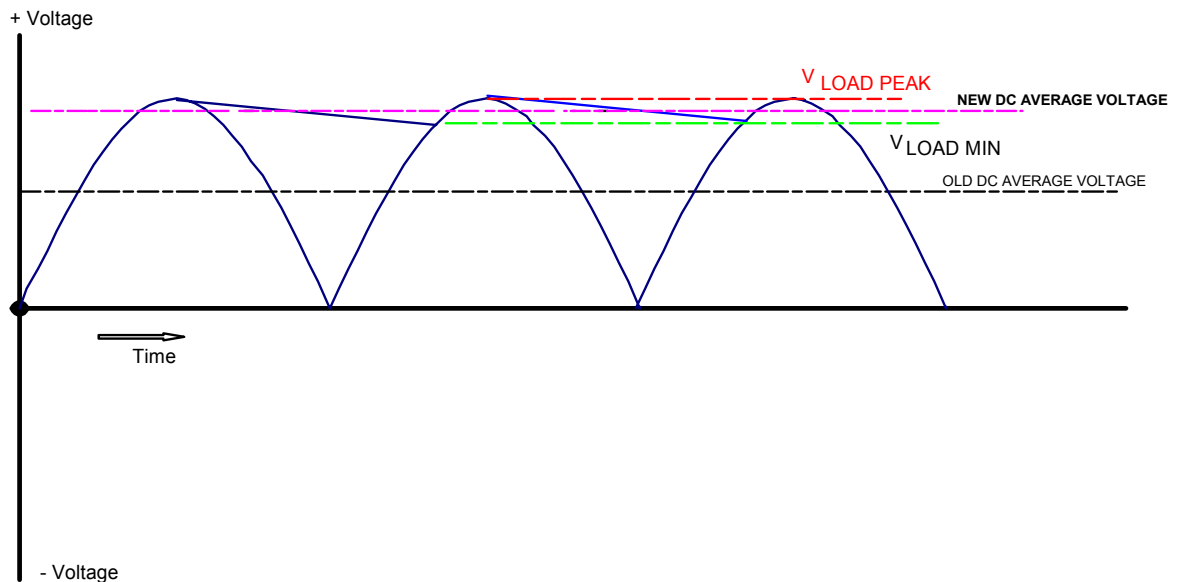
POWER SUPPLY FILTERING WITH A CAPACITOR



T] of

application. Because the load voltage is DC, we can use an electrolytic capacitor, which are polarity sensitive. Electrolytic capacitors are very popular in this application because of their availability and low cost.

The capacitor will quickly charge during a portion of each half-cycle and then slowly discharge, causing the full-wave rectified waveform to take the shape of the one shown below. As can be seen, the load voltage never drops below $V_{LOAD\ MIN}$. The result is a more continuous load current and increased DC or average voltage. The peak to peak ripple value of this new waveform is a product of the size of the capacitor added to the circuit. Since the waveform is not linear, the sizing of the capacitor would be a complicated process.





PROGRAMMABLE LOGIC CONTROLLERS

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What is a PLC?

A programmable logic controller is a solid-state industrialized computer system designed to perform the logic functions previously accomplished by components such as electromechanical relays, drum switches, mechanical times/counters, etc., for the control and operation of manufacturing process equipment and machinery.

Why change from relay logic? Even though the electromechanical relay (control relays, pneumatic timer relays, etc.) has served well for many generations, often, under adverse conditions, the ever-increasing sophistication and complexity of modern processing equipment requires faster acting, more reliable control functions than electromechanical relays and/or timing devices can offer. Relays have to be hardwired to perform a specific function, and when the system requirements change, the relay wiring has to be changed or modified. In many cases complete control panels had to be replaced since it was not economically feasible to rewire the old panels with each system changeover.

It was, in fact, the requirements of the auto industry and other highly specialized, high-speed repetitive manufacturing processes that created a demand for smaller, faster acting, and more reliable control devices. The electrical/electronics industry responded with modular-designed, solid-state electronic devices. These early devices, while offering solid-state reliability, lower power consumption, expandability, and elimination of much of the hard-wiring, also brought with them a new language. The language consisted of AND gates, OR gates, NOT gates, OFF RETURN MEMORY, J-K flip flops, and so on. Most of industry's technical staff resisted these new systems.

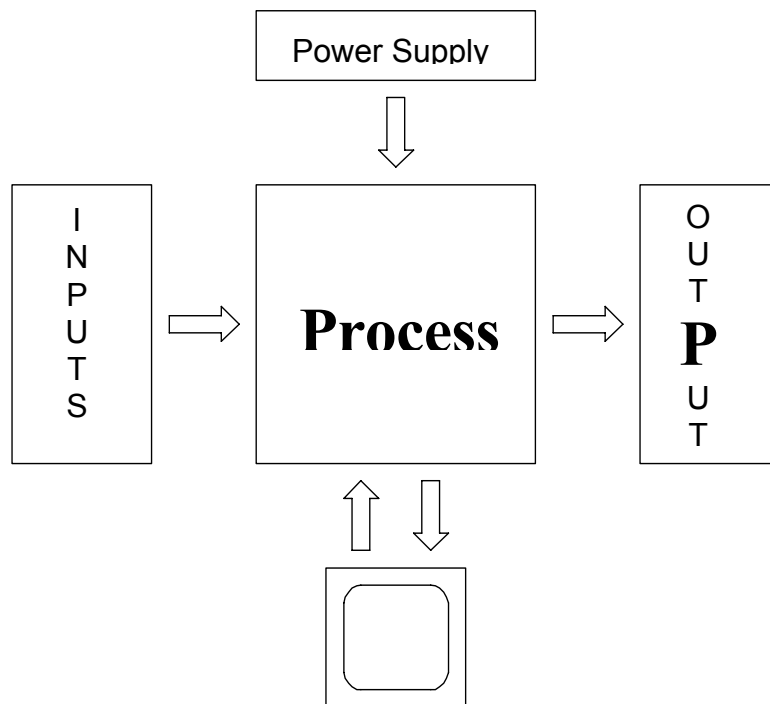
What happened to simple relay logic and ladder diagrams they asked the solid-state device manufactures. The reluctance of the end user to learn a new language and the advent of the microprocessor gave the industry what is now known as the **programmable logic controller** (PLC). Richard (Dick) E. Morley, who was the founder of the Modicon Corporation, invented the first programmable logic controller in 1969.

Internally there are still AND gates, OR gates, and so forth in the processor, but the design engineers have preprogrammed the PLC so that programs can be entered using RELAY LADDER LOGIC. While RELAY LADDER LOGIC may not have the mystique of other computer languages such as FORTRAN and COBOL, it is a high level, real world, graphic language that is understood by most electricians.

The National Electrical Manufacturing Association (NEMA) defines a programmable controller as follows:

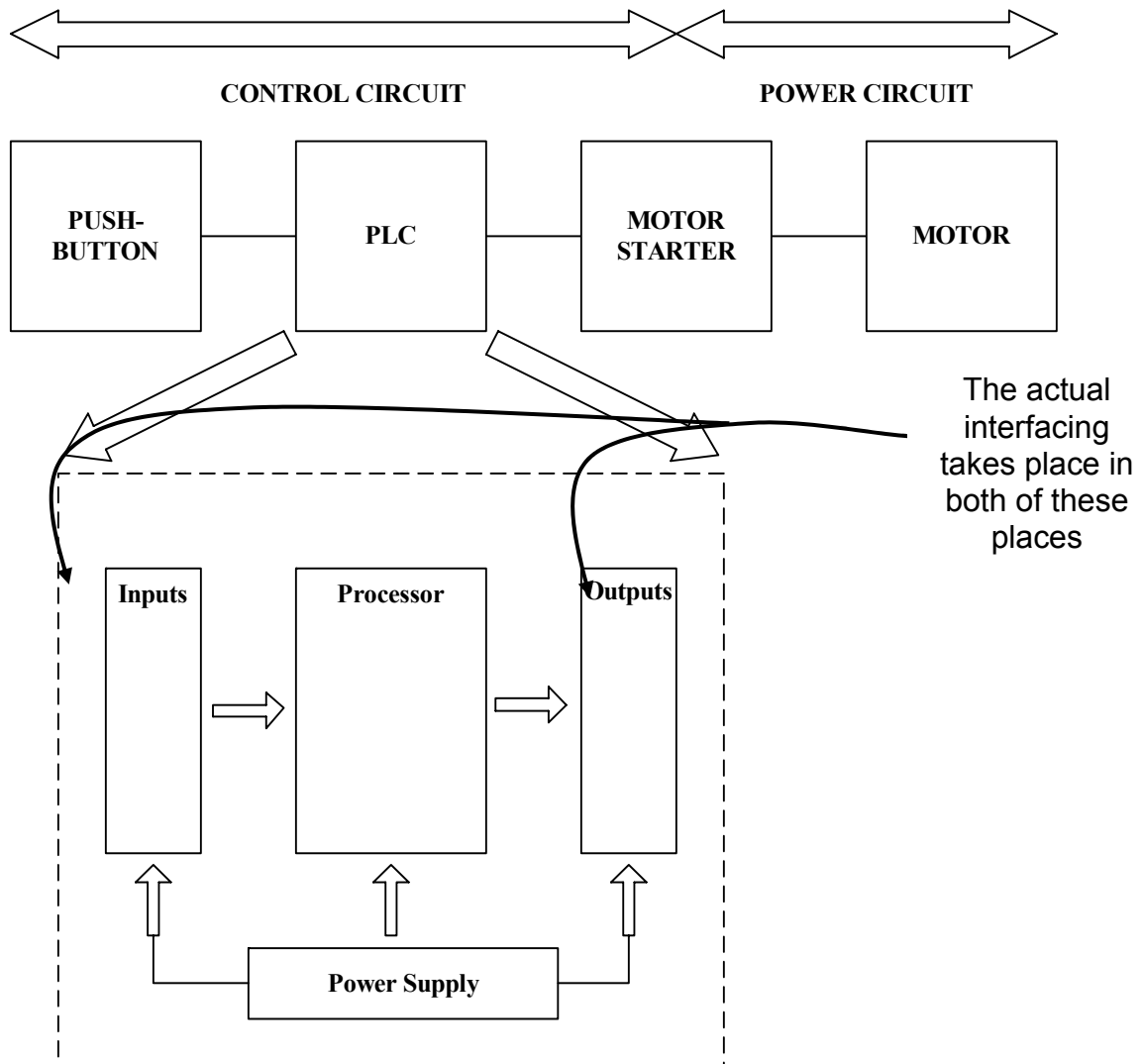
A programmable controller is a digital electronic apparatus with a programmable memory for storing instructions to implement specific functions, such as logic, sequencing, timing, counting, and arithmetic to control machines and processes.

What does a PLC consist of, and how is it different from a computer control system? The PLC consists of a programming device (keyboard), processor unit, power supply, and an input/output **interface** such as the system illustrated below.



Term

NOTE: An interface occurs when two systems come together and interact, or communicate. In the case of the PLC, the communication or interaction is between the inputs (limit switches, push buttons, sensors, etc.), outputs (coils, solenoids, lights, and so forth), and the processor. This interface happens when any input voltage (AC or DC) or current signal is changed to a low-voltage DC signal that the processor uses internally for the decision making process.



PLC's are designed to be operated by plant engineers and maintenance personnel with limited knowledge of computers. The PLC is like the computer, which has an internal memory for its operation and storage of a program, the PLC also has memory for storing the user program, or LOGIC, as well as a memory for controlling the operation of a process machine or driven equipment.

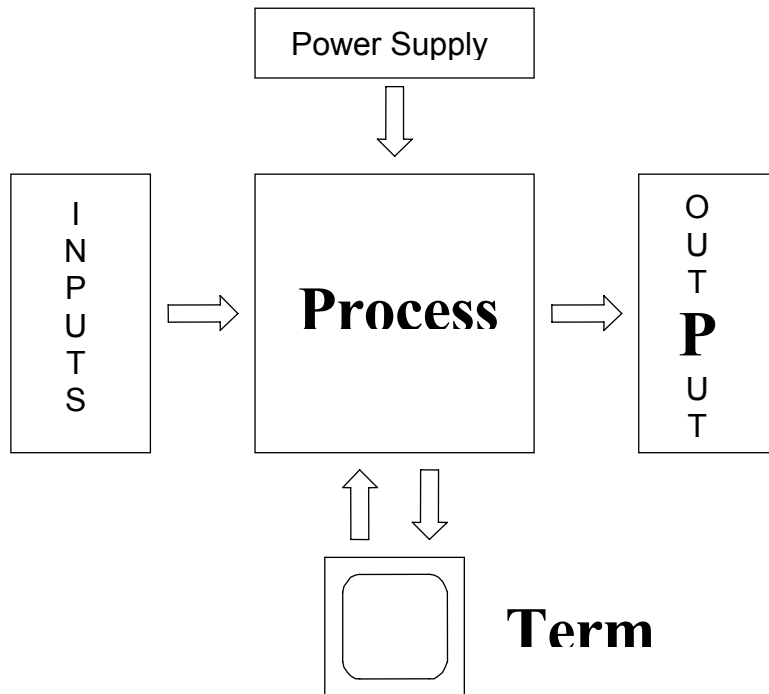
But unlike the computer, the PLC is programmed in RELAY LADDER LOGIC, not one of the computer languages. It should be stated, however, that some PLC's will use a form of Boolean Algebra to enter the RELAY LADDER LOGIC. Some of the newest PLC software packages are now programming with graphical blocks, similar to a flowchart.

The PLC is also designed to operate in the industrial environment with wide ranges of ambient temperature, vibration, and humidity, and is not usually affected by the electrical noise that is inherent in most industrial locations.

Maybe one of the biggest, or at least most significant, differences between the PLC and a computer is that PLC's have been designed for installation and maintenance by plant electricians who are not required to be highly-skilled electronics technicians. Troubleshooting is simplified in most PLC's because they include fault indicators, blown-fuse indicators, input and output status indicators, and written fault information that can be displayed on the programmer.

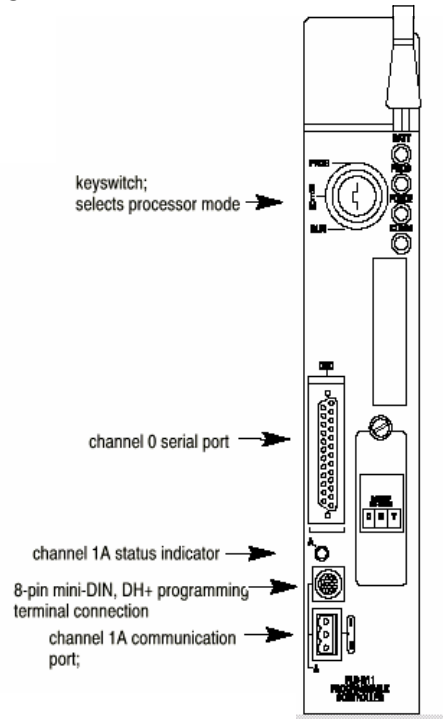
Although the PLC and the computer are different in many ways, the computer is often used for programming and monitoring the PLC. Using computers in conjunction with PLC's will be discussed in later chapters.

A typical PLC can be divided into four components. These components, as shown below, consist of the **processor unit**, **power supply**, the **input/output sections** (interfaces), and the **programming device**.



The **processor unit** houses the processor which is the decision-maker, or “brain” of the system. The brain is a microprocessor-based system that replaces control relays, counters, timers, sequences, and so forth, and is designed so that the user can enter the desired program in RELAY LADDER LOGIC. The processor then makes all the decisions necessary to carry out the user program, based on the status of the inputs and outputs for control of a machine or process. It can also perform arithmetic functions, data manipulation, and communications between the local input/output section, remotely located I/O sections, and/or other networked PLC systems.

Shown below is the family of PLC 5 Enhanced Processors. To the right is a line drawing that shows the: status LEDs, keyswitch, communication ports, battery cover.



NOTE: Some manufacturers refer to the processor as a **CPU** or central processing unit.

The **power supply** is necessary to convert 120 or 240 volts (V) AC voltages to the low voltage DC required for the logic circuits of the processor, and for the internal power required for the I/O modules. The power supply can be a separate unit, one of modular design that plugs into the processor rack (shown below), or one, depending on the manufacturer, that is an integral part of the processor.

Slot mounted power supplies



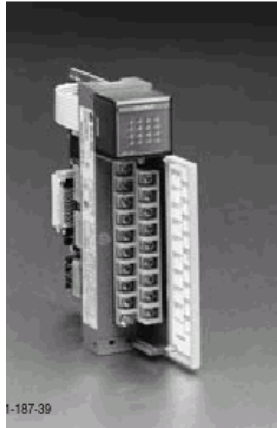
These power supply modules are used in 1771 I/O chassis to provide 5Vdc power directly to the chassis back plane. These power supplies occupy one or two slots and can provide up to 8 amps per supply to the I/O chassis

NOTE: The power supply ***does not*** supply power for the actual input or output devices themselves; it only provides the power needed for the internal circuitry of the input and output modules. DC power for the input and output devices, if required, must be provided from a separate source.

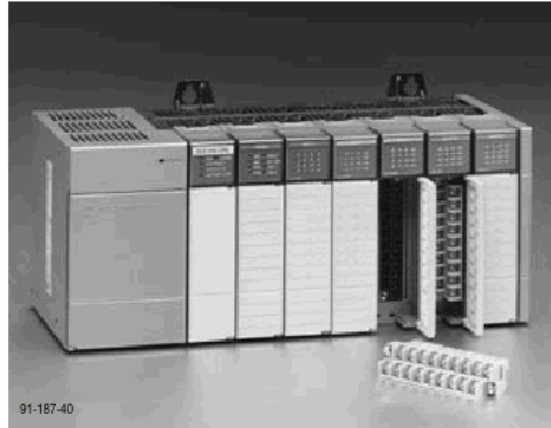
The size or amperage rating of the power supply is based on the size, number, and type of I/O modules that are to be used. Power supplies are normally available with output current ratings of 3-20 amps.

NOTE: Consider future needs and the possibility of expansion when initially sizing the power supply. It is cheaper in the longrun to install a larger power supply initially than to try and add additional capacity at a later date.

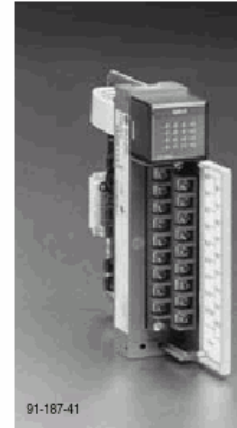
The **input/output section** consists of input modules and output modules. The number of input and output modules necessary is dictated by the requirements of the equipment that is to be controlled by a PLC. Modules are “plugged-in” or added as required.



**A 16 point SLC
SLC
Input Card**



A fully populated SLC Chassis
Power Supply on the left
Processor in the first slot
Then six cards in the I/O section

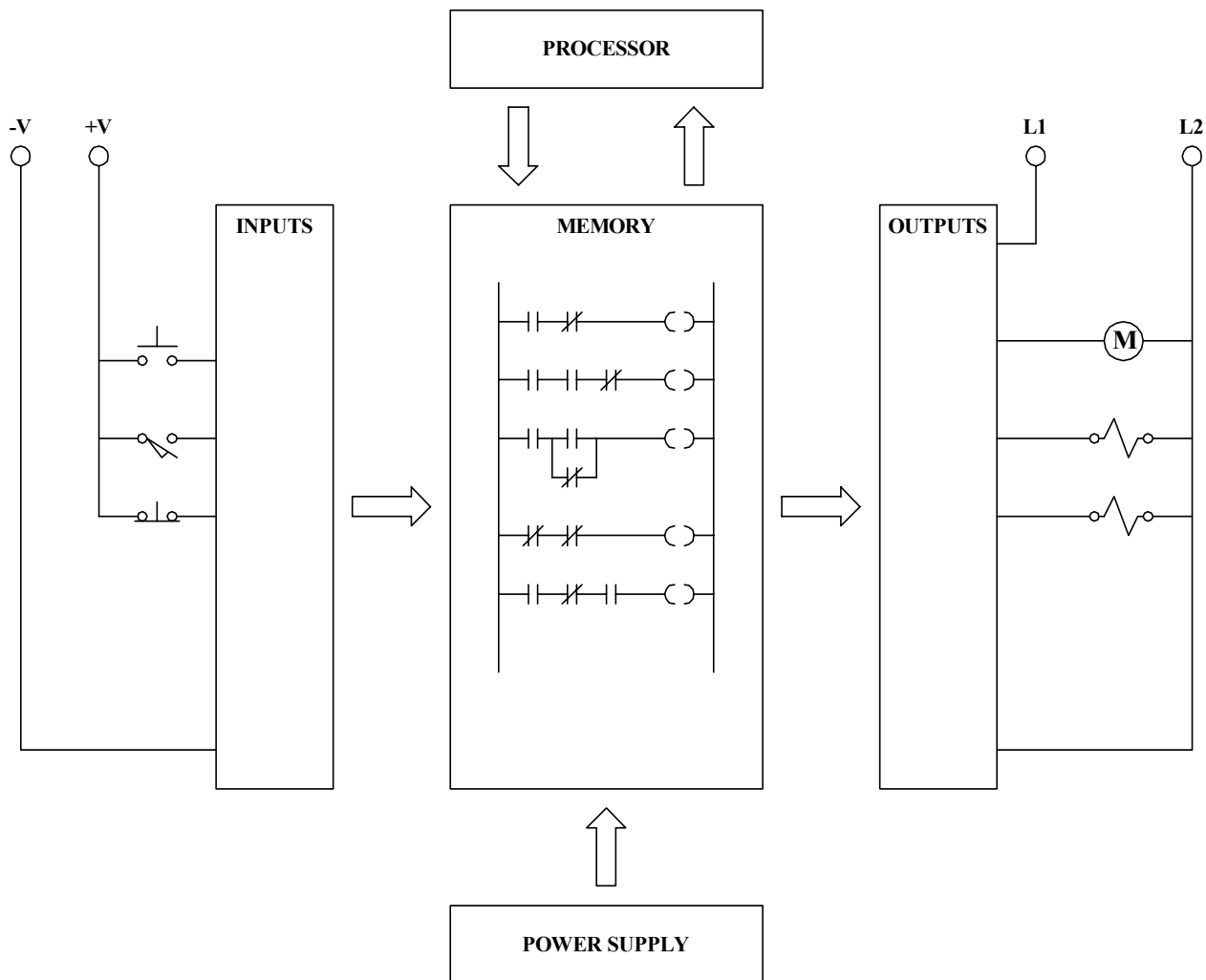


**A 16 point
Output card**

Input and output modules, referred to as the I/O (I for input and O for output) are where the real-world devices are connected. The real-world input (I) devices can be push buttons, limit switches, analog sensors, thumbwheels, selector switches, etc., while the real-world output devices (O) can be hard-wired to motor starter coils, solenoid valves, indicator lights, positioning valves, and the like. The term *real world* is used to separate actual devices that exist and must be physically wired as compared to the internal functions of the PLC system that duplicate the function of relays, timers, counters, and so on, even though none physically exists. This may seem a bit strange and hard to understand at this point, but the distinction between what the processor can do internally-which eliminates the need for all the previously-used control relays, timers, counters, and so forth-will be graphically shown and readily understandable later in the text.

Real-world input and output devices are of two types: discrete and analog. *Discrete* I/O devices are either ON or OFF, open or closed, while analog devices have an infinite number of possible values. Examples of analog input devices are temperature probes, and pressure indicators. The input from an analog input

device (varying voltage or current) is converted by way of an Analog-to-digital converter (ADC). The conversion value is proportional to the analog input signal and is stored in memory for later use or comparison. Limit switches, push buttons, and the like, are examples of *discrete input devices*. The drawing below shows discrete inputs and outputs.



Examples of *discrete output devices* are motor starter coils, solenoids, and indicator lamps. Analog output devices require varying voltage or current levels to control the analog output. The varying value will be accomplished using a Digital-to-Analog Converter (DAC). The analog output normally is isolated from the output logic circuitry by means of optical coupling.

A reference was made earlier in this chapter to the I/O section as an interface. Although not a common reference, it is an accurate one. The I/O section contains the circuitry necessary to convert input voltages of 120-240 V AC or 0-24 V DC, etc., from discrete input devices to low-level DC voltages for the processor. Similarly, the output module changes low-level DC signals from the processor to 120-240 V AC or DC voltages required to operate the discrete output devices. This is a brief overview of the I/O section and its function. How input and output devices are wired to I/O modules and more information about the module circuitry itself is covered in Chapter 2.

The **programming device** is used to enter the desired program or sequence of operation into the PLC memory. The program is entered using RELAY LADDER LOGIC, and it is this program that determines the sequence of operation and ultimate control of the process equipment or driven machinery. The programming device can be any one of the three types: hand-held; dedicated; or personal computer.

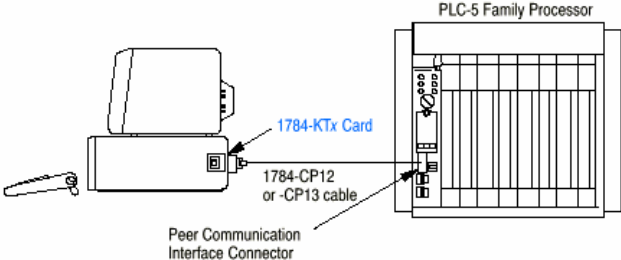
The hand-held programmer used either **LED** (light emitting diode) or **LCD** (liquid crystal display). The hand-held programmers are small, lightweight, and convenient to use in the field. The small size, however, limits the display capabilities, which in turn limits its effectiveness for reviewing the program or using the programmer for troubleshooting.

Several manufacturers offer a dedicated programmer that uses a standard video display terminal (**VDT**) for displaying the program. The use of a standard viewing screen allows more of the program to be viewed at one time and makes troubleshooting and memory access much easier.

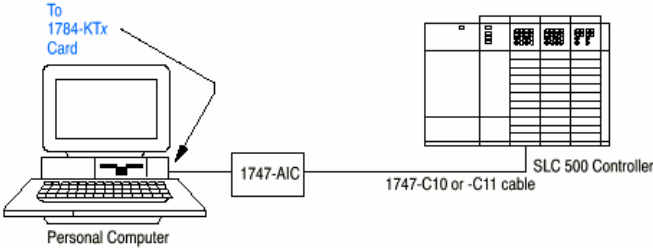
A personal computer (PC) can be used to program most of the PLC's on the market today if it can run DOS and it is IBM compatible. Some PLC's require only software to communicate with a personal computer, while others require special hardware keys and/or communication cards for them to work successfully as programming devices. Once communicators between the personal computer and the PLC have been established, the PC provides all the benefits of the dedicated programmer, plus it provides program storage as well as runs all the various software packages we have come to depend on today such as spreadsheets, word processing, and graphics.

Due to the versatility and lower cost-when compared to dedicated programmers- PCs have become the most popular programming device.

Communicating to a PLC-5 Processor



Communicating to a Single SLC 500 Processor Using a Point-to-Point DH-485 Network



Shown in the figure above are just two of the possible communications configurations possible with a personal computer and a PLC.

SUMMARY

Programmable logic controllers (PLCs) have made it possible to precisely control large process machines and driven equipment with less physical wiring and lower installation costs than is required with standard electromechanical relays, pneumatic timers, drum switches, and so on. The programmability allows for fast and easy changes in the RELAY LADDER LOGIC to meet the changing needs of the process or driven equipment without the need for expensive time-consuming rewiring. By designing the modern programmable logic controller (PLC) to be “technician friendly”, the PLC is easier to program and to be used by maintenance technicians who have little or no electronics background.



NUMBER SYSTEMS

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INTRODUCTION

This chapter introduces the number systems and digital codes that are most often encountered in programmable logic controllers. The most common number systems used for addressing the input and output assignments as well as developing programs are the binary, decimal, hexadecimal and octal systems.

A familiarity with number systems is a necessity when working with PLC's. This is true because the basic function of these devices is to represent, store, and operate on numbers. In general, PLC's work on binary numbers in one form or another to do even the simplest of operations. The work being done in the PLC is normally unseen to the troubleshooter but there will be occasions when they will need to interpret the various codes or quantities being used.

First let's review the basics of number systems:

- ◆ Each system has a base or radix.
- ◆ Each system can be used for counting.
- ◆ Each system can be used to represent quantities or codes.
- ◆ Each system uses a set of symbols.
- ◆ Each system uses positional weighing.
- ◆ Each system can be converted to another.

NUMBER SYSTEM IDENTIFICATION

When working with different number systems, it is often necessary to have some method of identifying which number system the digits are being used in. This is even more evident with numbers using only 0's and 1's. For example, the number 101 is one hundred and one in the decimal system. Yet, in the binary system it represents a quantity of five.

To distinguish one system from another a small subscript number is generally written after the number. The identifying subscript is the base or radix of the number system being used. Several examples are given below.

$$101_2 = 5_{10}$$

$$101_{10} = 1100101_2$$

Remember the base of a number system is set by the number of symbols used in that system. The number systems normally encountered while using PLC's are base 2, base 8, base 10, and base 16. These systems are labeled binary, octal, decimal and hexadecimal respectively. To study the common characteristics of these number systems, let's study the most familiar system, the decimal system.

DECIMAL NUMBER SYSTEM

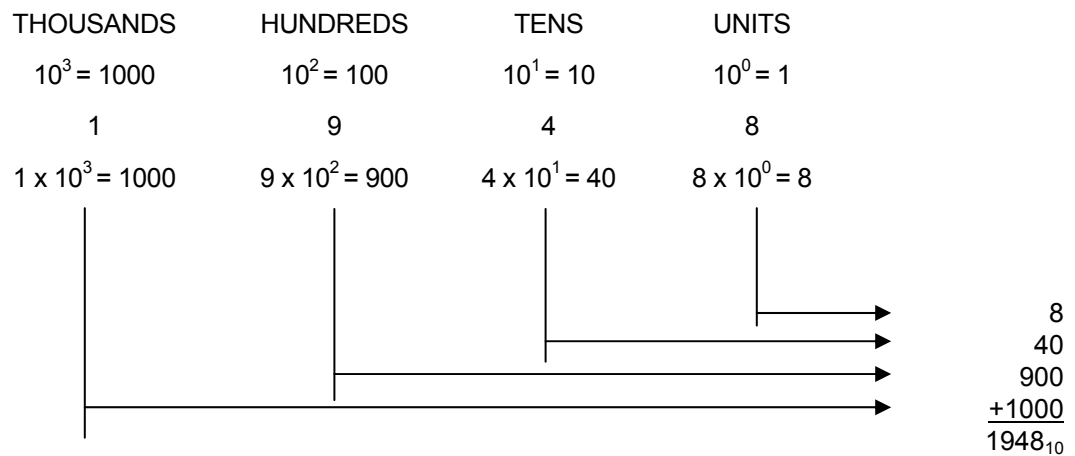
People usually learn to count to ten then by tens and that is the decimal system. The decimal system is a base 10 system. It has 10 symbols or digits. This number system is based on the fact that most people have either ten fingers or toes, so we learned to count in groups of ten. The symbols or digits for the decimal system are 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9. We use these symbols to represent quantities that we have counted.

The decimal system is so familiar to us that we don't even think about what to do if we count beyond the basic group. How do we show a number with a value greater than 9? The method we are so familiar with is the same method used in all number systems, positional weighing. As shown below, each position can be expressed as a power of ten. Starting with 10^0 as the least significant position, each position moving to the left is then increased by a power of one. The first position is called the units place and any digit from 0-9 can be used there. The next position to the left of the units place is the tens place; next is the hundreds place, the thousands place and so on, with each place expanding the capability of the decimal system by a power of 10 as shown below.

PLACE NAME	THOUSANDS	HUNDREDS	TENS	UNITS
BASE/EXPONENT	10^3	10^2	10^1	10^0
DIGITS	0-9	0-9	0-9	0-9

What we don't even think about when we use the decimal system is how we interpret the digits in the different positions into a total value. In any number system, the digit in a position is multiplied by its positional weight, which is the system base to the positions exponent. Then we add all of these products. In other words each position's digit times its positional weight is added to the total number.

For example if we used the number 1948 in the base 10 system as an example, we actually do the following conversion without thinking about it.



The concept of positional weighing is common to almost all number systems. As we can see in the example above the exponent of the base starts with zero for the least significant digit and increases by one for each position to the left. This will be true for each of the number systems we study.

BINARY NUMBER SYSTEM

The basic distinguishing characteristic of a number system is its base. The base indicates the number of symbols or digits used in that system. The binary system has a base of 2 since only the symbols or digits 1 and 0 are used in counting or representing quantities.

The binary system is simple but inconvenient to use because we are not familiar with it. Once you understand the system it is easy to work with. You can see the benefits of the system when it comes to constructing the hardware used in digital systems.

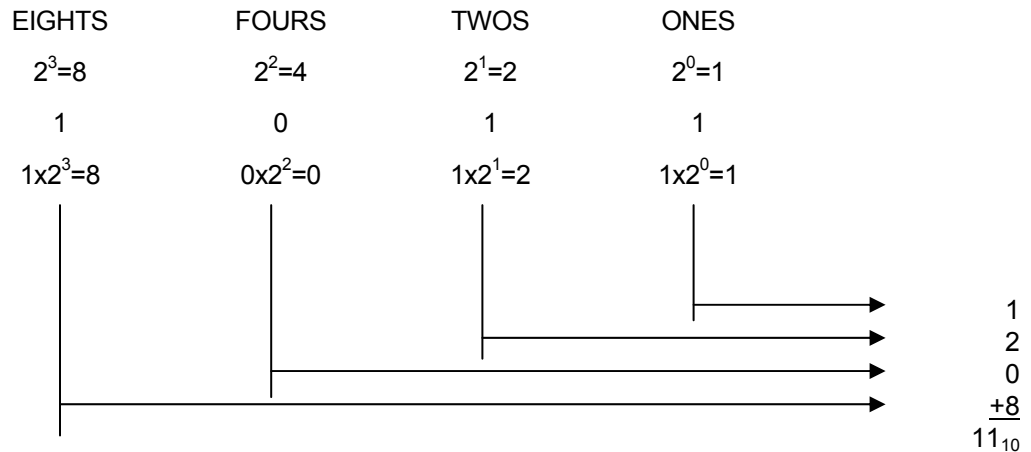
In a digital system using the binary code only two states need to be represented, on or off, a 1 or a 0. If we used the decimal code we would have to construct a circuit that could generate ten distinct states. A circuit that has only two states is simpler and cheaper to construct and much more reliable.

If we apply the concepts that we know are the same in all number systems, we can consider the table below for a binary number.

PLACE NAME	EIGHTS	FOURS	TWOS	ONES
BASE/EXPONENT	2^3	2^2	2^1	2^0
DIGITS	0-1	0-1	0-1	0-1

What we will have to think about when we use the binary system is how we interpret the digits in the different positions into a total value. As in any number system, the digit in a position is multiplied by its positional weight. Then we add all of these products. In other words each position's digit times its positional weight is added to the total number.

For example if we used the number 1011 in the base 2 system as an example, we can do the following conversion.



The quantity represented by the binary number 1011 was determined by multiplying its positional weight by each digit and obtaining a sum. We have just converted from one number system, binary, to another, decimal, by using the positional weight method. When we analyze the size of the number, we find that the binary system did not represent as large of number with four positions as the decimal system did. This is the binary system's main drawback. Even though the binary system is cumbersome for large numbers a digital machine must use some form of number system using 0's and 1's.

HEXADECIMAL NUMBER SYSTEM

The hexadecimal number system was designed to overcome the shortcomings of the binary system. The hex system uses 16 different symbols. Therefore it is a base 16 number system. The symbols used are 0-9 and A-F, with 0 being the least and F being the most significant. The letters are used because it is necessary to represent 16_{10} different values with a single symbol for each value as shown below.

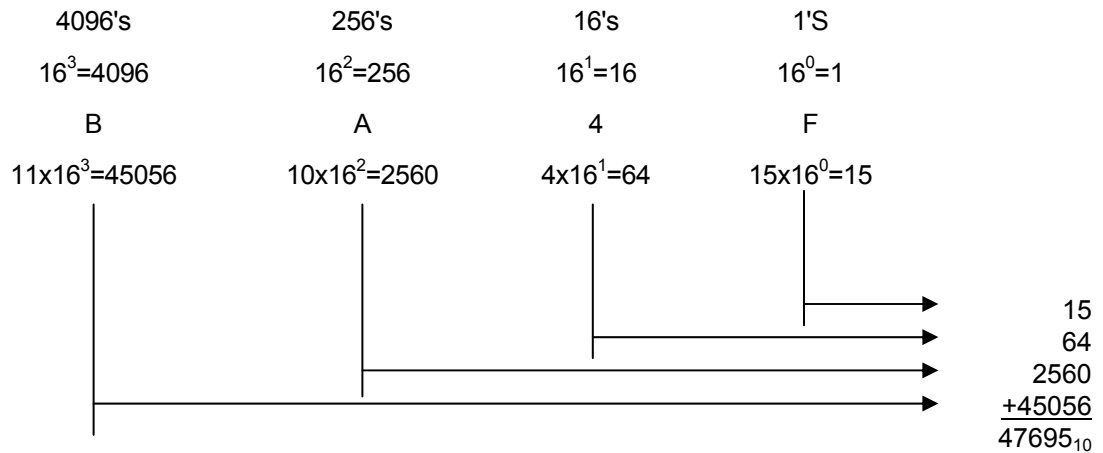
Decimal	Binary	Hex
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F

When comparing the three number systems side by side in the above table we can see that the hexadecimal system uses fewer characters to represent larger numbers. As with the other number systems the hexadecimal system can be represented by its decimal equivalent using the positional weight method.

The table below shows the hexadecimal positional weight method.

PLACE NAME	4096'S	256'S	16'S	ONES
BASE/EXPONENT	16^3	16^2	16^1	16^0
DIGITS	0-F	0-F	0-F	0-F

In any number system, the digit in a position is multiplied by its positional weight. Then we add all of these products. In other words each position's digit times its positional weight is added to the total number. The one thing we have to do in the hexadecimal system is use the decimal value of each hexadecimal digit as shown in the example below. If we used the number BA4F in the base 16 system as an example, we do the following conversion.



We see that the hexadecimal number BA4F is equivalent to the decimal number 47,695. This illustrates the hexadecimal number system's ability to represent very large numbers with smaller groups of digits.

OCTAL NUMBER SYSTEM

The last number system that we cover is the octal system. Allen-Bradley uses the octal numbering system for I/O addressing in the PLC-2 and the PLC-5 families. We need to understand the octal system in order to simplify the maintenance and troubleshooting of these systems.

Octal means eight, so we can expect this system to have a base 8. This means that this system will only use the digits 0-7 as shown in the table below.

PLACE NAME	512'S	64'S	8'S	1'S
BASE/EXPONENT	8^3	8^2	8^1	8^0
DIGITS	0-7	0-7	0-7	0-7

Again, as in any number system, the digit in a position is multiplied by its positional weight. Then we add all of these products. In other words each position's digit times its positional weight is added to the total number. For example if we used the number 6742 in the base 8 system as an example, we can do the following conversion.

512'S	64'S	8'S	1'S	
$8^3=512$	$8^2=64$	$8^1=8$	$8^0=1$	
6	7	4	2	
$6 \times 8^3 = 3072$	$7 \times 8^2 = 448$	$4 \times 8^1 = 32$	$2 \times 8^0 = 2$	
				$ \begin{array}{r} 2 \\ 32 \\ 448 \\ +3072 \\ \hline 3554_{10} \end{array} $

By using the positional weight times the digits and then adding the sum of the products, we find that the number 6742_8 represents the same quantity as the number 3554_{10} . We have converted an octal number to a decimal number.

If we look at the number systems that we have covered in the table below, we recognize the relationships between them. We see the use of positional weighing and realize that we can convert any of the systems to decimal.

Decimal	Binary	Octal	Hex
0	0000	0	0
1	0001	1	1
2	0010	2	2
3	0011	3	3
4	0100	4	4
5	0101	5	5
6	0110	6	6
7	0111	7	7
8	1000	10	8
9	1001	11	9
10	1010	12	A
11	1011	13	B
12	1100	14	C
13	1101	15	D
14	1110	16	E
15	1111	17	F

There is a need to convert between the number systems. It is very common to have to convert from decimal to octal or octal to hexadecimal. We have seen the method of conversion from binary, hexadecimal, and octal to decimal is the positional weight method. Now we need to learn some more techniques.

NUMBER SYSTEM CONVERSIONS

First, we will deal with the most direct conversions and the most common. If we have a quantity represented in the binary format, all we need to do to convert it to hexadecimal or octal is group the digits. In the table below, the octal numbers are shown below the binary equivalent.

BINARY	111	110	101	100	011	010	001	000
OCTAL	7	6	5	4	3	2	1	0

The table shows us that a group of three binary digits represent each of the octal digits up to the number 7_8 . How will we convert larger octal numbers? Time for some mathematical shenanigans. Because the base 8 of the octal system is the third power of 2, which is the base of the binary numbers, the conversion is simple. Three binary numbers are used to represent each octal digit. Convert each octal digit one at a time to its binary equivalent, as shown in the examples below.

EXAMPLE 1			EXAMPLE 2					
2	3	←octal→	7	6	1	7	5	2
↓	↓	↓	↓	↓	↓	↓	↓	↓
010	011	←binary→	111	110	001	111	101	010

By converting one digit at a time, we have converted 23_8 to 010011_2 and 761752_8 to 111110001111101010_2 . Grouping the binary digits into groups of three and converting them directly to octal also works as shown in the examples below.

EXAMPLE 1					EXAMPLE 2			
100	011	101	011	←binary→	101	111	000	001
↓	↓	↓	↓	↓	↓	↓	↓	↓
4	3	5	3	←octal→	5	7	0	1

This converted the number 100011101011_2 to 4353_8 and the number 101111000001_2 to 5701_8 . The simplicity of converting from octal to binary and vice versa has many advantages in digital systems. It is easier to print out, read and record octal numbers than the long strings of binary numbers.

Now we have a quantity represented in the binary format, and we want to convert it to hexadecimal. All we need to do to convert it to hexadecimal is group the binary digits. In the table below, the hexadecimal numbers are shown above the binary equivalent.

BINARY	1111	1110	1101	1100	1011	1010	1001	1000
HEX	F	E	D	C	B	A	9	8

The table shows us that a group of four binary digits represent each of the hexadecimal digits F_{16} to 8_{16} . The grouping method will also work from 0_{16} up to the number 7_{16} . How will we convert larger hexadecimal numbers? The mathematical shenanigans we looked at before again comes into play. Because the base 16 of the hexadecimal system is the fourth power of 2, which is the base of the binary numbers, the conversion is simple. Four binary numbers are used to represent each hexadecimal digit. Convert each hexadecimal digit one at a time to its binary equivalent, as shown in the example below.

HEX→	<table border="1"> <tr> <td>7</td> <td>F</td> <td>D</td> <td>A</td> <td>5</td> <td>C</td> </tr> </table>						7	F	D	A	5	C
7	F	D	A	5	C							
↓	↓	↓	↓	↓	↓	↓						
BINARY→	<table border="1"> <tr> <td>0111</td> <td>1111</td> <td>1101</td> <td>1010</td> <td>0101</td> <td>1100</td> </tr> </table>						0111	1111	1101	1010	0101	1100
0111	1111	1101	1010	0101	1100							

By converting one digit at a time, we have converted $7FDA5C_{16}$ to $01111111101101001011100_2$. Grouping the binary digits into groups of four and converting them directly to hexadecimal also works as shown in the table below.

BINARY→	<table border="1"> <tr> <td>1011</td> <td>1111</td> <td>1000</td> <td>1001</td> </tr> </table>				1011	1111	1000	1001
1011	1111	1000	1001					
↓	↓	↓	↓	↓				
HEX→	<table border="1"> <tr> <td>B</td> <td>F</td> <td>8</td> <td>9</td> </tr> </table>				B	F	8	9
B	F	8	9					

This converted the number 1011111110001001_2 to $BF89_{16}$. The simplicity of converting from hexadecimal to binary and vice versa has the same advantages as octal conversions did when working with digital systems. It is easier to print out, read and record the hexadecimal numbers than the long strings of binary numbers.

The grouping method also works very well for converting from hex to octal or vice versa if the binary system is used as an intermediary. Examine the examples shown below.

EXAMPLE 1				EXAMPLE 2			
OCTAL→	3 4 7			HEX→	F A		
↓	↓	↓	↓	↓	↓	↓	↓
BINARY→	011	100	111	BINARY→	1111	1010	
REGROUPED				REGROUPED			
	0	1110	0111		11	111	010
↓	↓	↓	↓	↓	↓	↓	↓
HEX→	0 E 7			OCTAL→	3 7 2		

The last conversions we will consider will be those from decimal to the other number systems. Each conversion uses the same method, the divide by base, to convert a decimal number into its system. Start with a decimal to binary conversion. To convert 227_{10} to its binary equivalent, we must divide it by the base of the binary system and record the remainder. Continue to divide the decimal number until there is only a remainder as shown below.

227	÷	2	=	113	Remainder	1	(LSB)
113	÷	2	=	56	1		
56	÷	2	=	28	0		
28	÷	2	=	14	0		
14	÷	2	=	7	0		
7	÷	2	=	3	1		
3	÷	2	=	1	1		
1	÷	2	=	0	1	(MSB)	

The remainder from the first division is recorded as the least significant bit and the last remainder is the most significant bit of the binary number. Therefore:

$$227_{10} = 11100011_2$$

If we convert the same decimal number to either hex or octal the easiest method is first to convert to binary then use the grouping method to do the final conversion to either hex or octal.

BINARY CODED DECIMAL

The last concept in numbers that we have to deal with is not a counting system but a **CODE**. Binary coded decimal was introduced as a convenient means for us to handle numbers that had to be input to digital machines and to interpret numbers output from the machines. The best solution to this need was a direct conversion code from decimal to digital. In decimal, we have the digits 0-9, in binary coded decimal; a 4-bit binary number represents each of these decimal digits. The table below shows this.

Decimal	Binary	BCD
0	0000	0000
1	0001	0001
2	0010	0010
3	0011	0011
4	0100	0100
5	0101	0101
6	0110	0110
7	0111	0111
8	1000	1000
9	1001	1001

The BCD representation of a decimal number is obtained simply by replacing each decimal digit by its four-bit BCD equivalent. The BCD representation of the decimal number 7493_{10} is shown below.

7	4	9	3
0111	0100	1001	0011

Typical PLC applications of BCD codes include data entry via thumbwheel switches, data display via 7-segment displays, input from optical encoders, and many other uses.

Typically the conversion of decimal to BCD or vice versa takes place in the thumbwheel switch or 7-segment display. The PLC is provided the BCD data and converted internally to binary code through some instruction. Input or output of BCD takes four lines for each decimal digit.

To distinguish a BCD coded number, the letters BCD are used as the subscript. For example: 239_{10} in BCD is $0010\ 0011\ 1001_{\text{BCD}}$.

One advantage of the BCD code is that because so many types of electronic equipment use it as their input or output format, it has become so accepted that it is almost a standard. Another benefit of BCD is that the ten BCD code combinations are easy to remember. Once you begin to work with them they may be almost as recognizable to you as decimal numbers

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