Kirchoff’s Laws

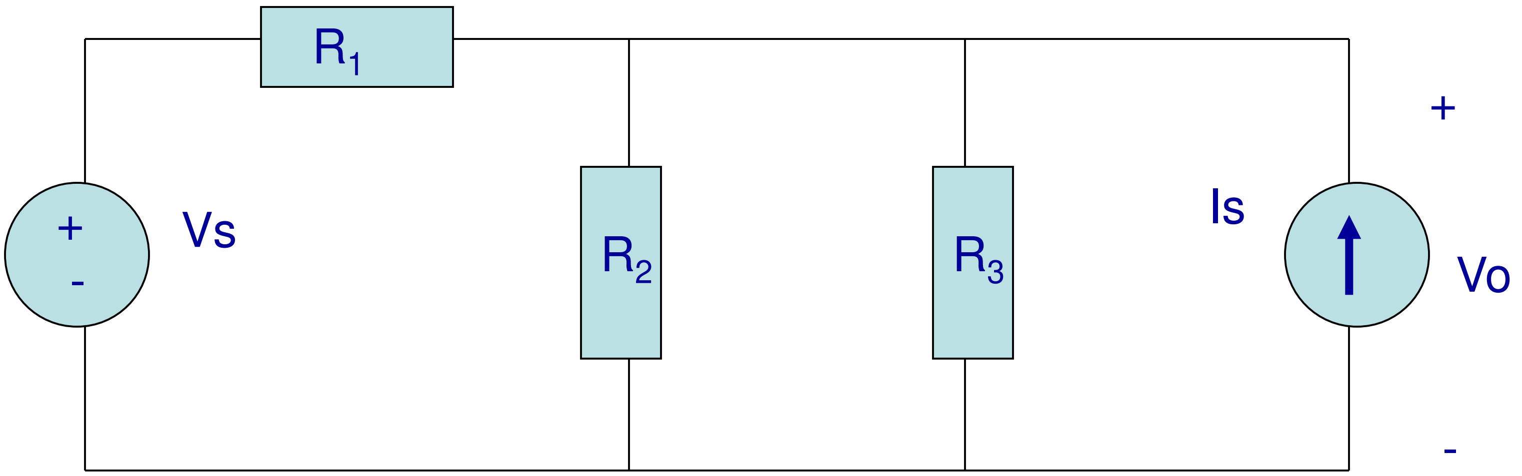
Chapter 3

Circuit Definitions

- Node – any point where 2 or more circuit elements are connected together
  - Wires usually have negligible resistance
  - Each node has one voltage (w.r.t. ground)
- Branch – a circuit element between two nodes
- Loop – a collection of branches that form a closed path returning to the same node without going through any other nodes or branches twice

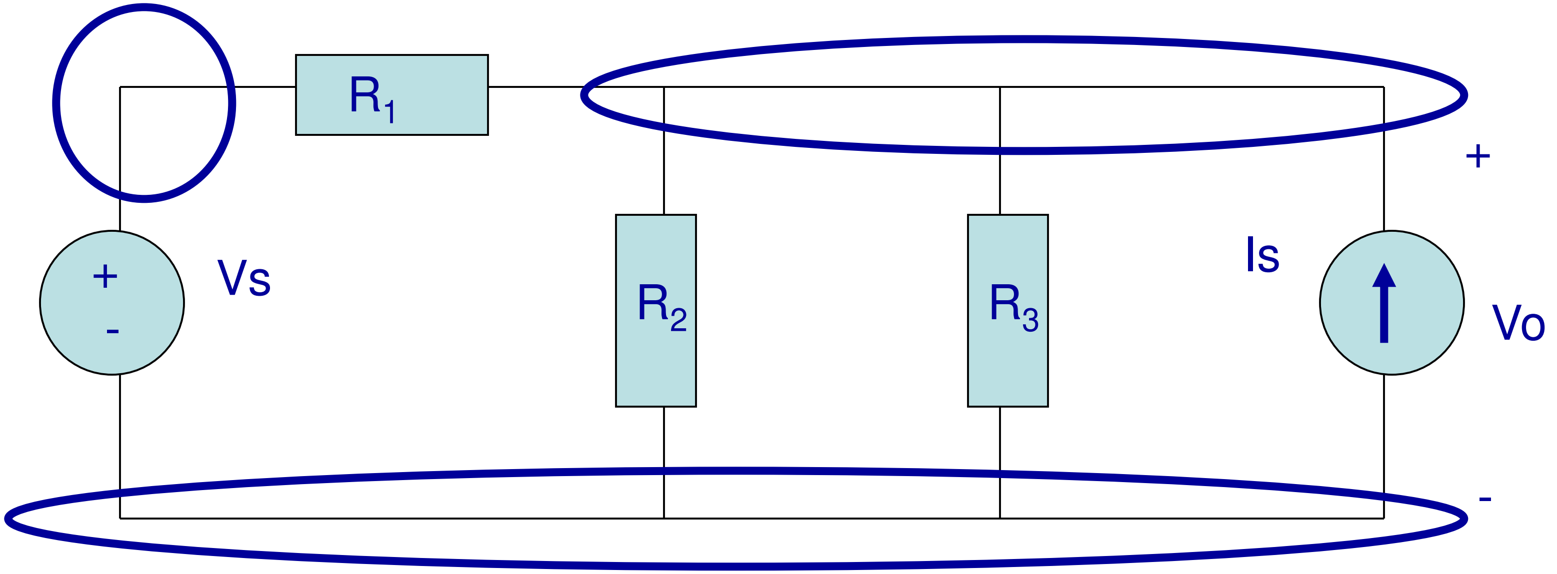
Example

- How many nodes, branches & loops?



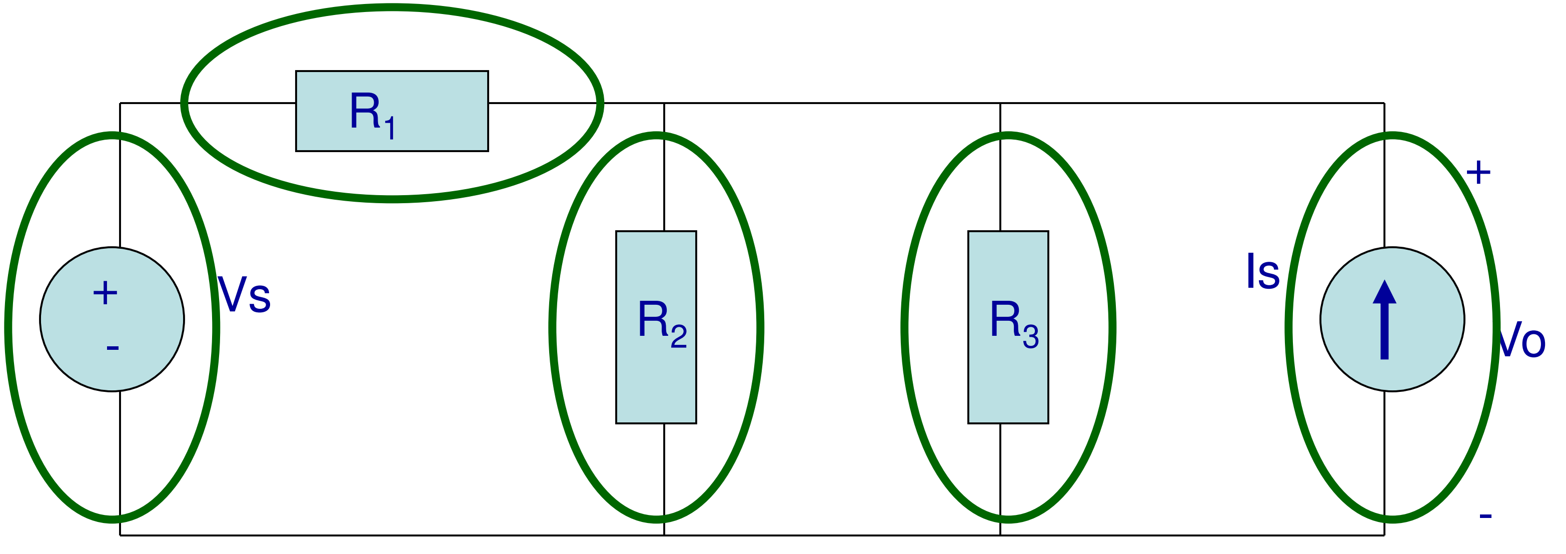
Example

- Three nodes



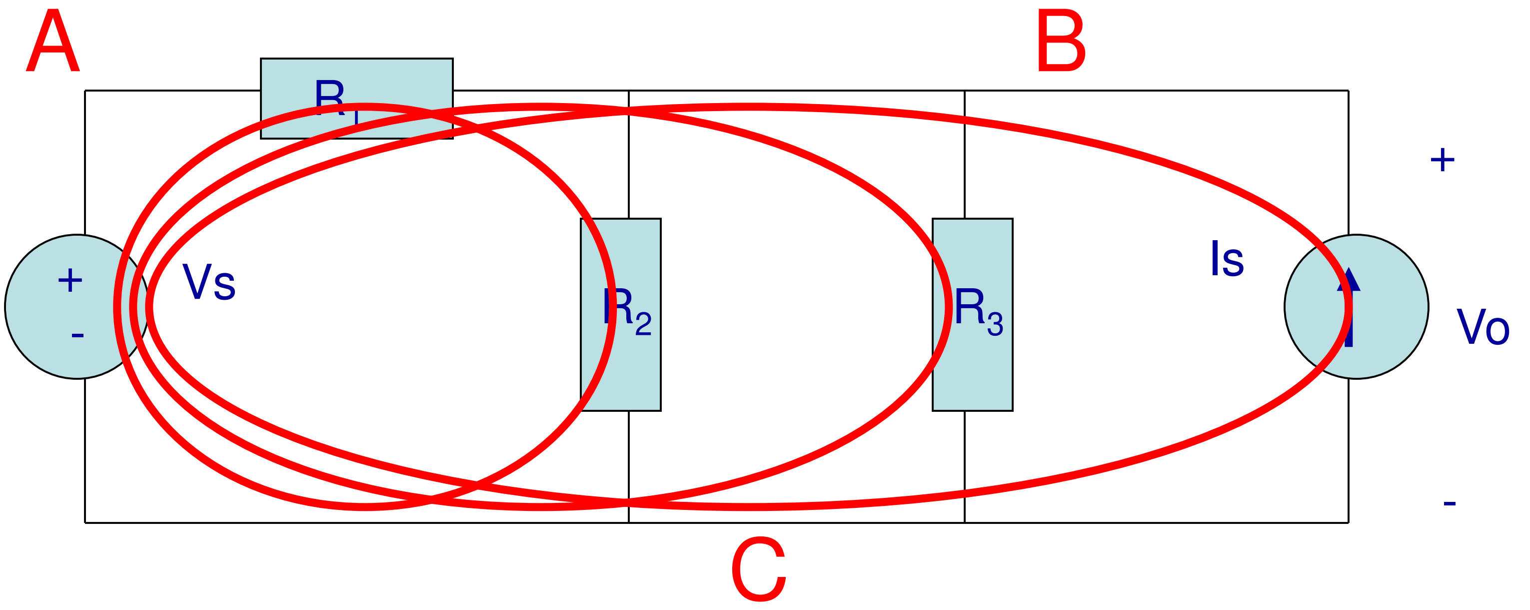
Example

- 5 Branches



Example

- Three Loops, if starting at node A

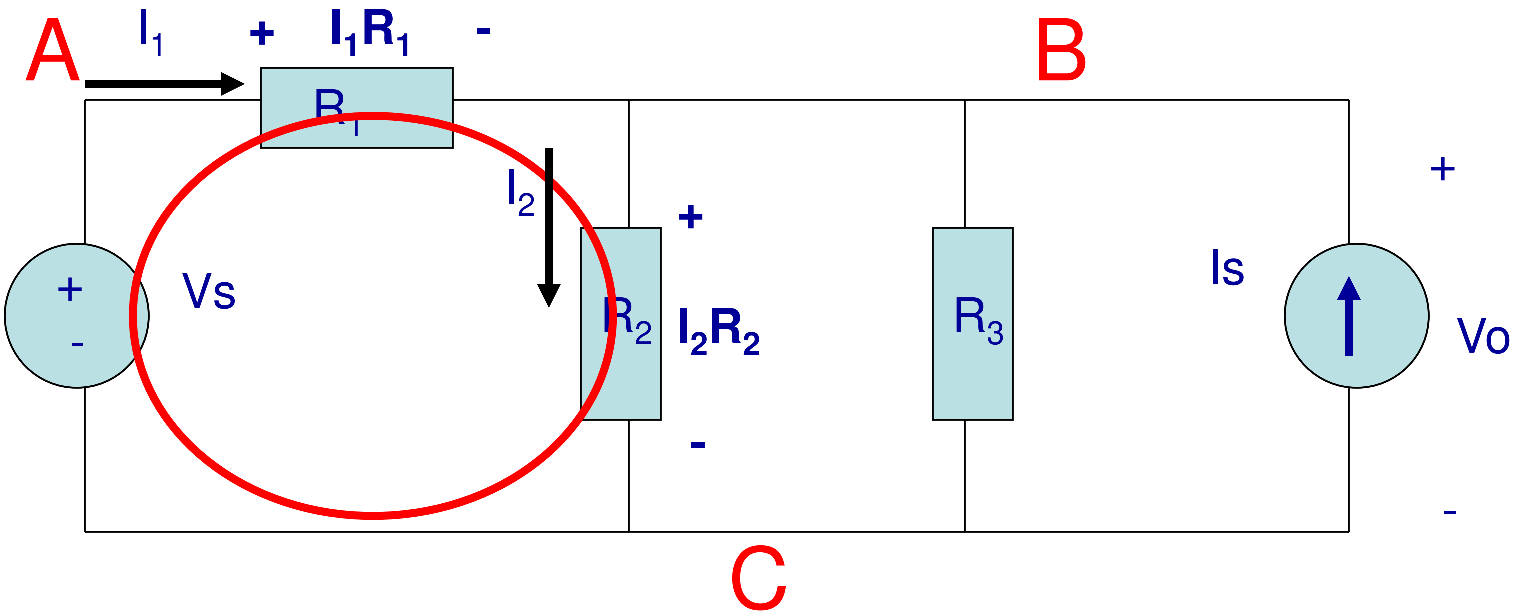


Kirchoff's Voltage Law (KVL)

- The algebraic sum of voltages around each loop is zero
  - Beginning with one node, add voltages across each branch in the loop (if you encounter a + sign first) and subtract voltages (if you encounter a – sign first)
- Σ voltage drops - Σ voltage rises = 0
- Or Σ voltage drops = Σ voltage rises

Example

- Kirchoff's Voltage Law around 1st Loop

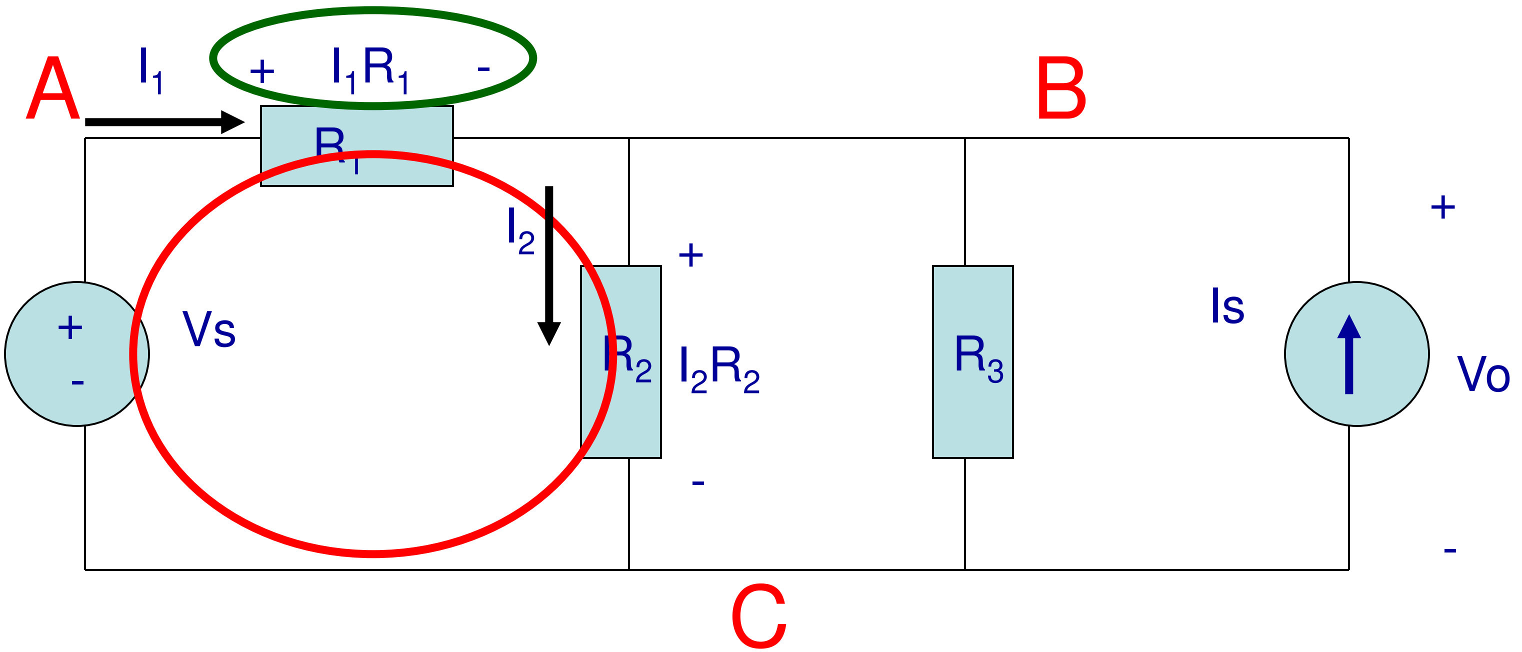


Assign current variables and directions

Use Ohm's law to assign voltages and polarities consistent with passive devices (current enters at the + side)

Example

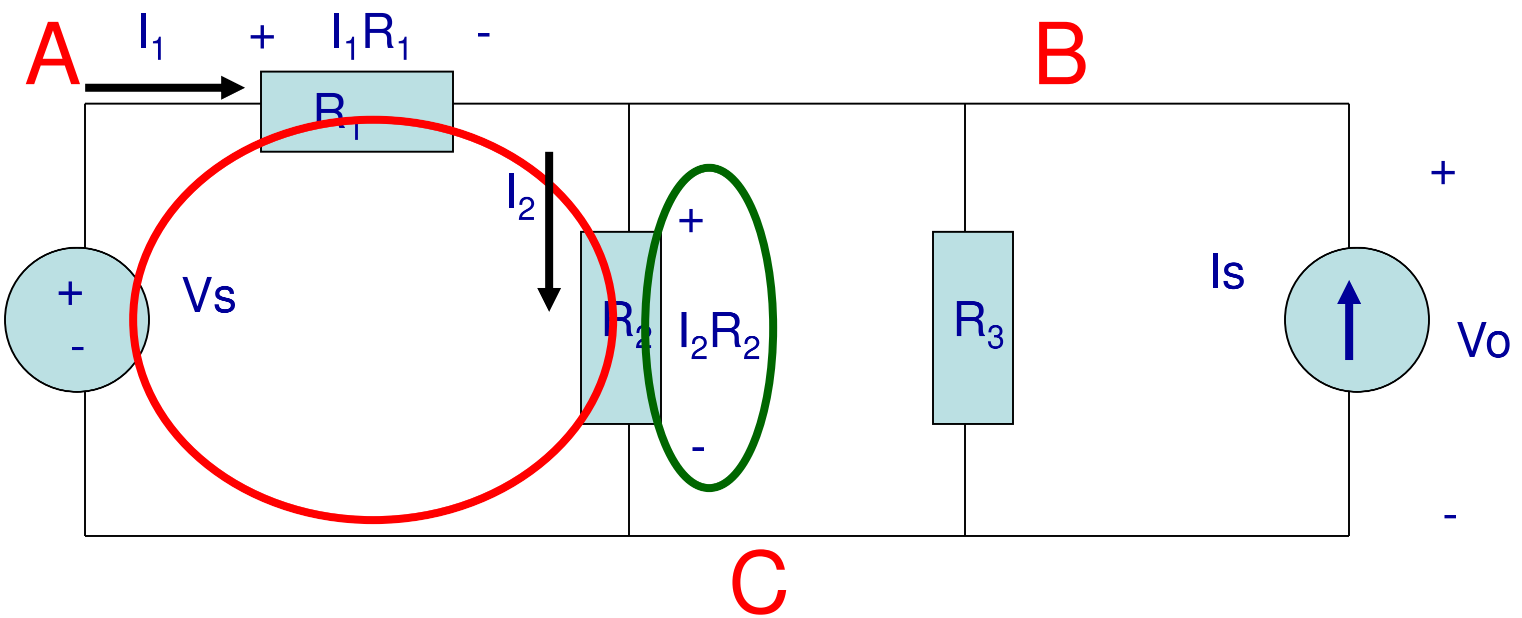
- Kirchoff's Voltage Law around 1st Loop



Starting at node A, add the 1st voltage drop: + I_1R_1

Example

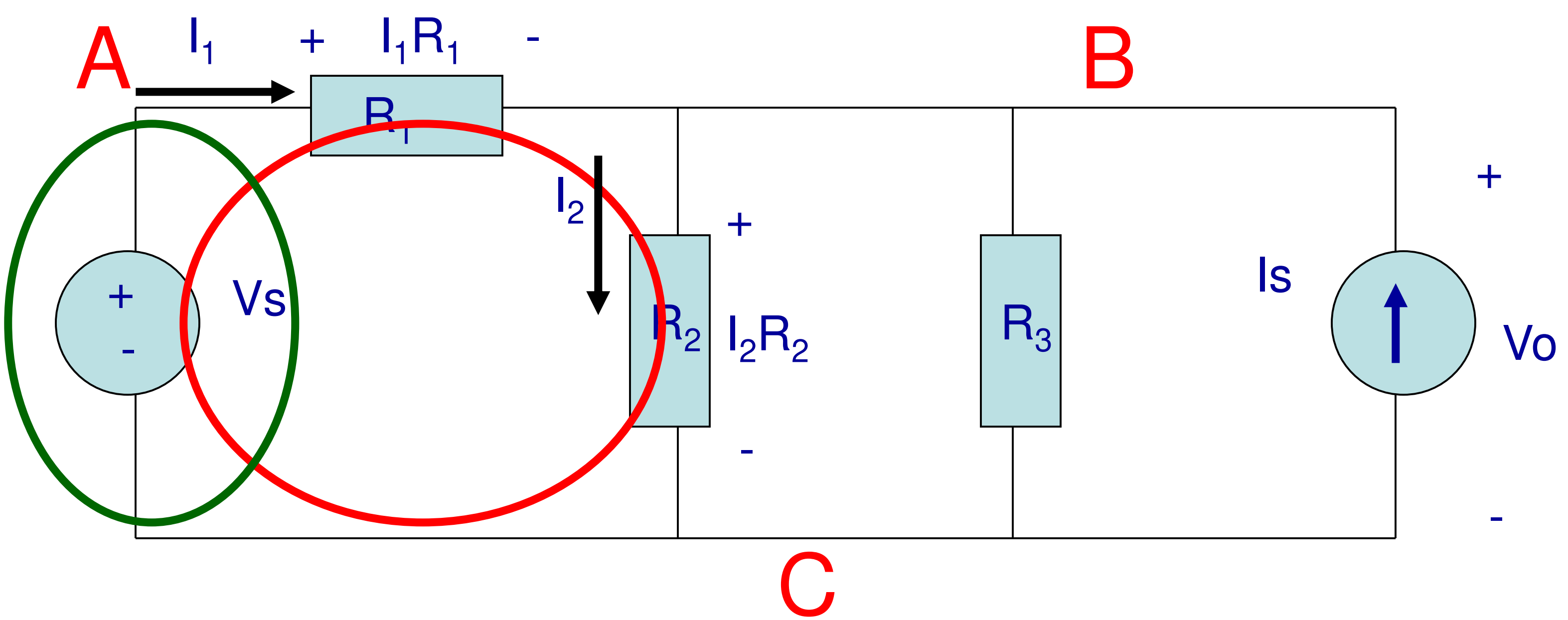
- Kirchoff's Voltage Law around 1st Loop



Add the voltage drop from B to C through R_2: $+ I_1R_1 + I_2R_2$

Example

- Kirchoff's Voltage Law around 1st Loop

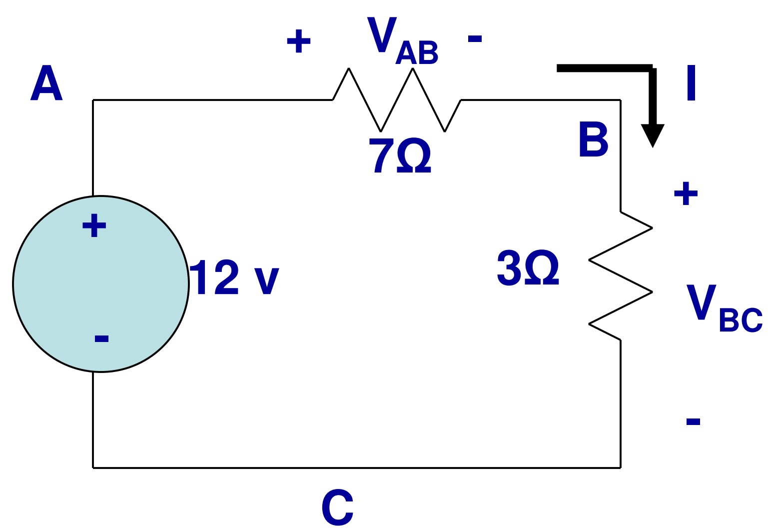


Subtract the voltage rise from C to A through Vs: $+ I_1R_1 + I_2R_2 - Vs = 0$

Notice that the sign of each term matches the polarity encountered 1st

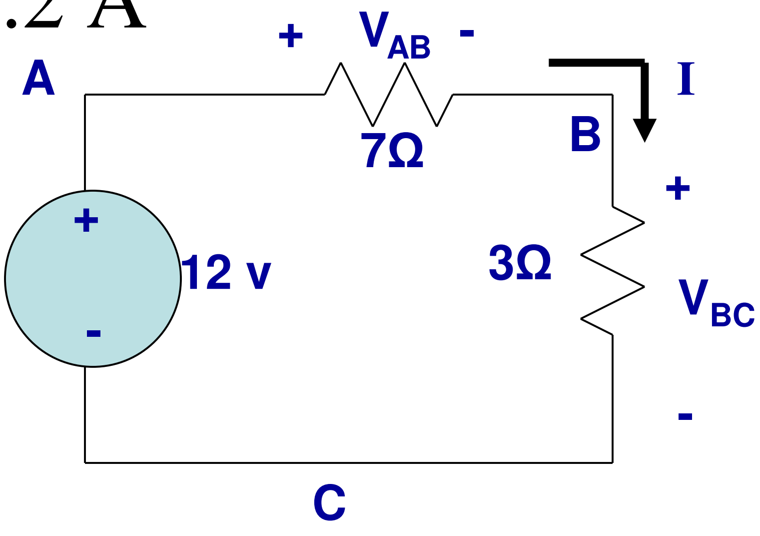
Circuit Analysis

- When given a circuit with sources and resistors having fixed values, you can use Kirchoff’s two laws and Ohm’s law to determine all branch voltages and currents



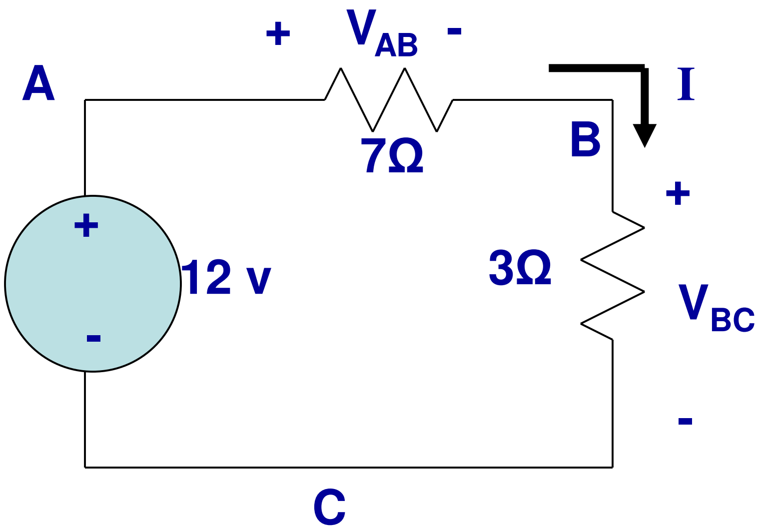
Circuit Analysis

- By Ohm's law: $V_{AB} = I \cdot 7\Omega$ and $V_{BC} = I \cdot 3\Omega$
- By KVL: $V_{AB} + V_{BC} - 12\ v = 0$
- Substituting: $I \cdot 7\Omega + I \cdot 3\Omega - 12\ v = 0$
- Solving: $I = 1.2\ A$



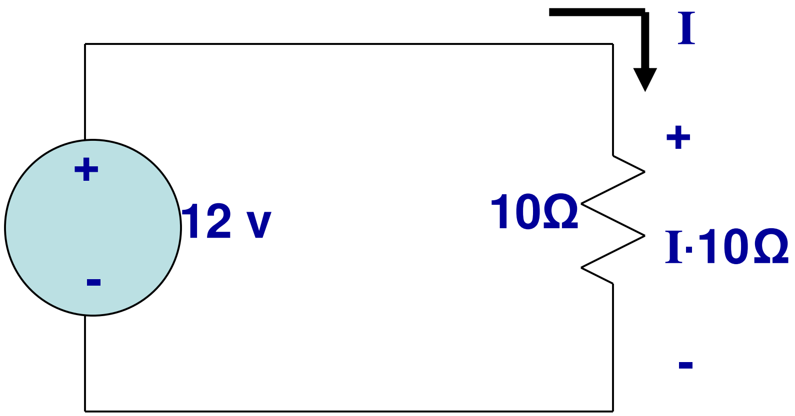
Circuit Analysis

- Since $V_{AB} = I \cdot 7\Omega$ and $V_{BC} = I \cdot 3\Omega$
- And $I = 1.2\ A$
- So $V_{AB} = 8.4\ v$ and $V_{BC} = 3.6\ v$



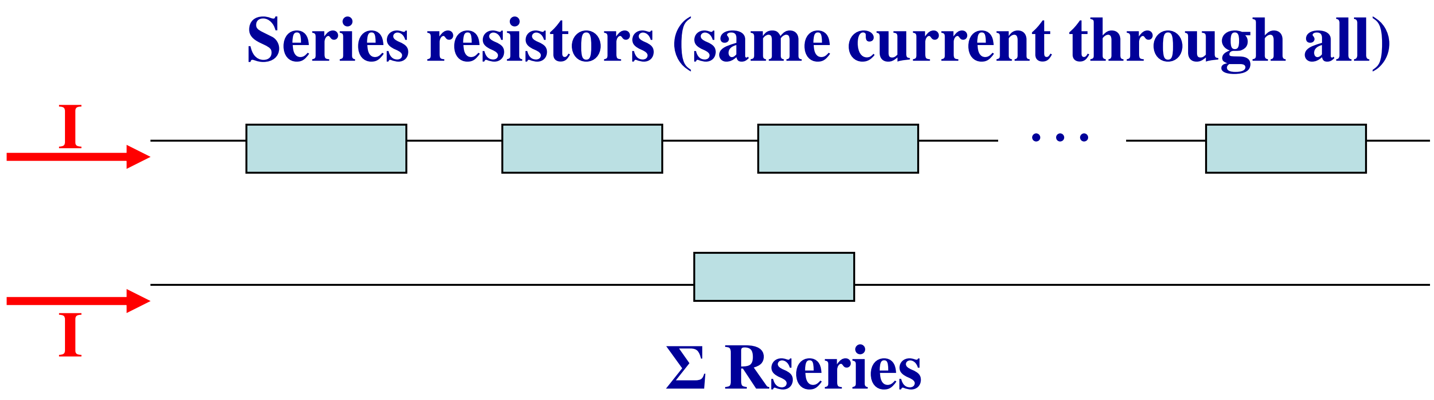
Series Resistors

- KVL: $+I \cdot 10\Omega - 12\text{ v} = 0$, So $I = 1.2$ A
- From the viewpoint of the source, the 7 and 3 ohm resistors in series are equivalent to the 10 ohms



Series Resistors

- To the rest of the circuit, series resistors can be replaced by an equivalent resistance equal to the sum of all resistors

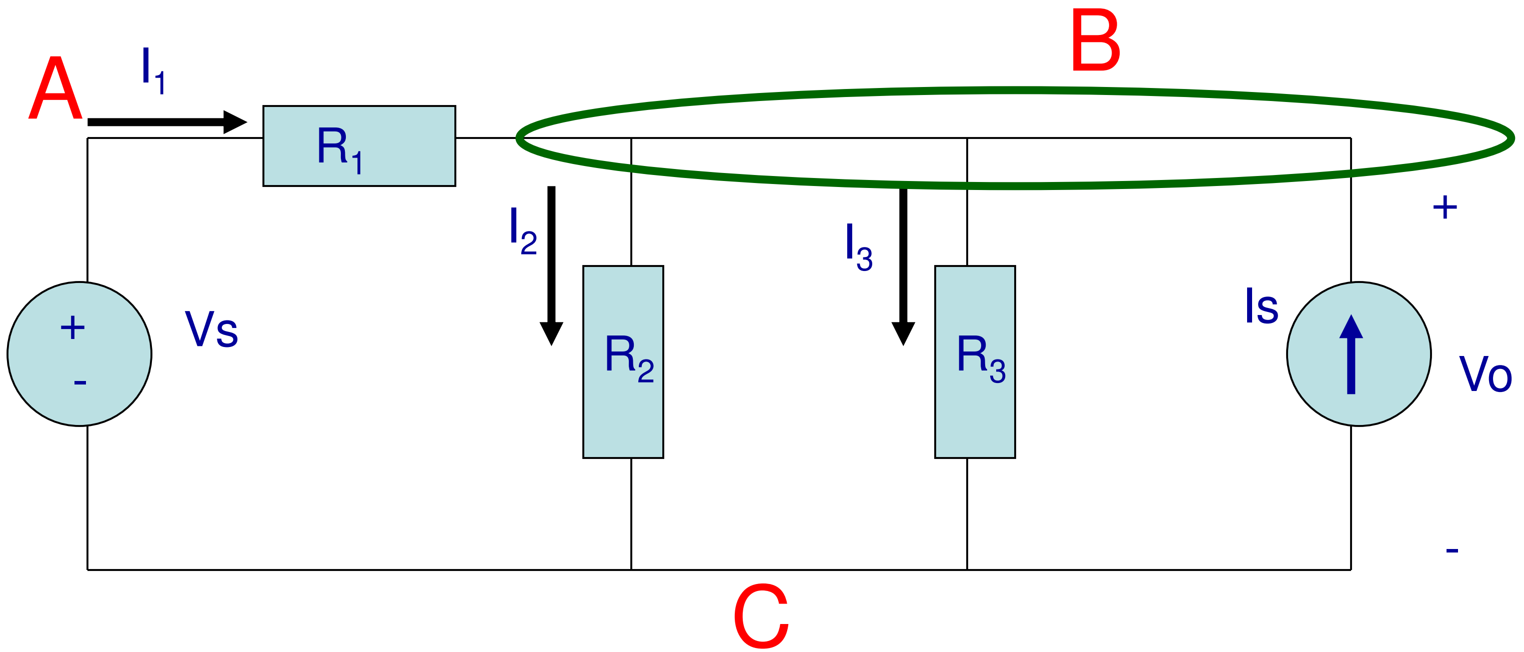


Kirchoff's Current Law (KCL)

- The algebraic sum of currents entering a node is zero
  - Add each branch current entering the node and subtract each branch current leaving the node
- Σ currents in - Σ currents out = 0
- Or Σ currents in = Σ currents out

Example

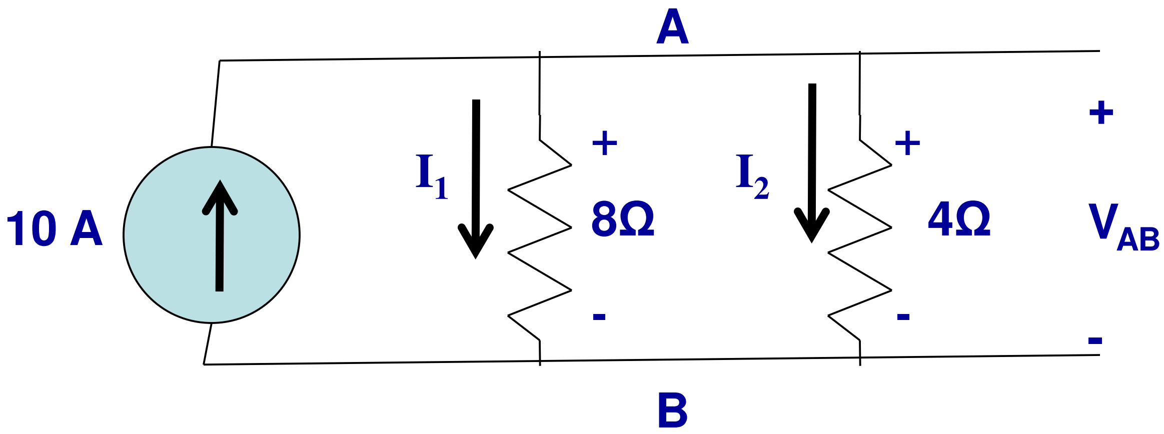
- Kirchoff's Current Law at B



Assign current variables and directions

Add currents in, subtract currents out: $I_1 - I_2 - I_3 + Is = 0$

Circuit Analysis



By KVL: $- I_1 \cdot 8\Omega + I_2 \cdot 4\Omega = 0$

Solving: $I_2 = 2 \cdot I_1$

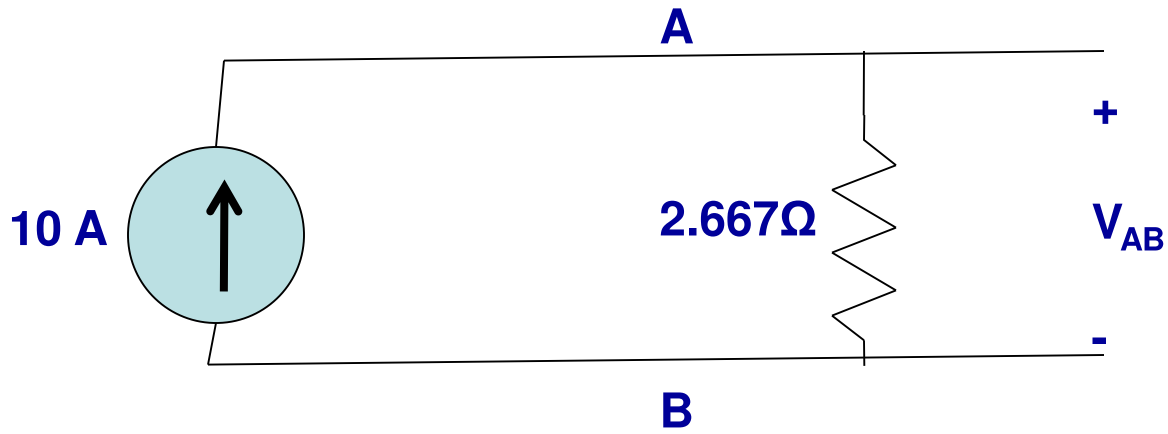
By KCL: $10A = I_1 + I_2$

Substituting: $10A = I_1 + 2 \cdot I_1 = 3 \cdot I_1$

So $I_1 = 3.33$ A and $I_2 = 6.67$ A

And $V_{AB} = 26.33$ volts

Circuit Analysis



By Ohm's Law: $V_{AB} = 10\ A \cdot 2.667\ \Omega$

So $V_{AB} = 26.67$ volts

Replacing two parallel resistors (8 and 4 Ω) by one equivalent one produces the same result from the viewpoint of the rest of the circuit.

Parallel Resistors

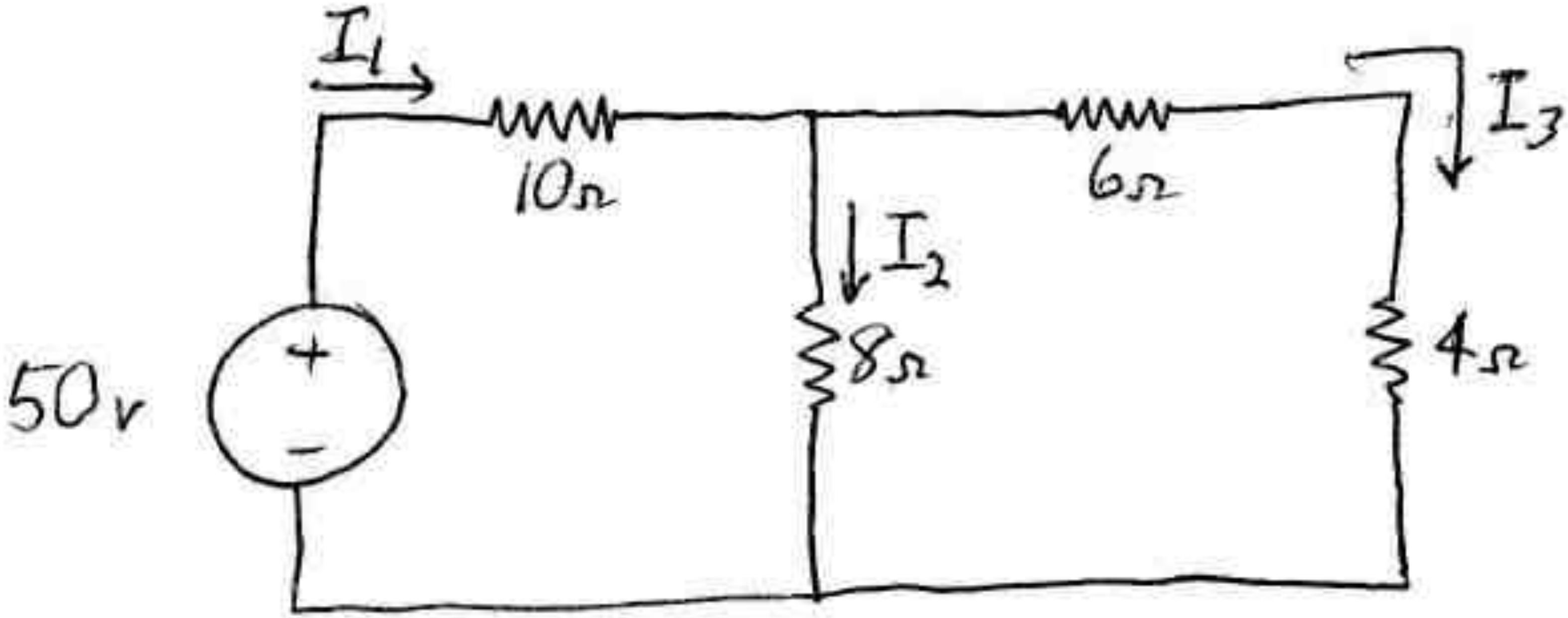
- The equivalent resistance for any number of resistors in parallel (i.e. they have the same voltage across each resistor):

$$Req = \frac{1}{1/R_1 + 1/R_2 + \cdots + 1/R_N}$$

- For two parallel resistors:

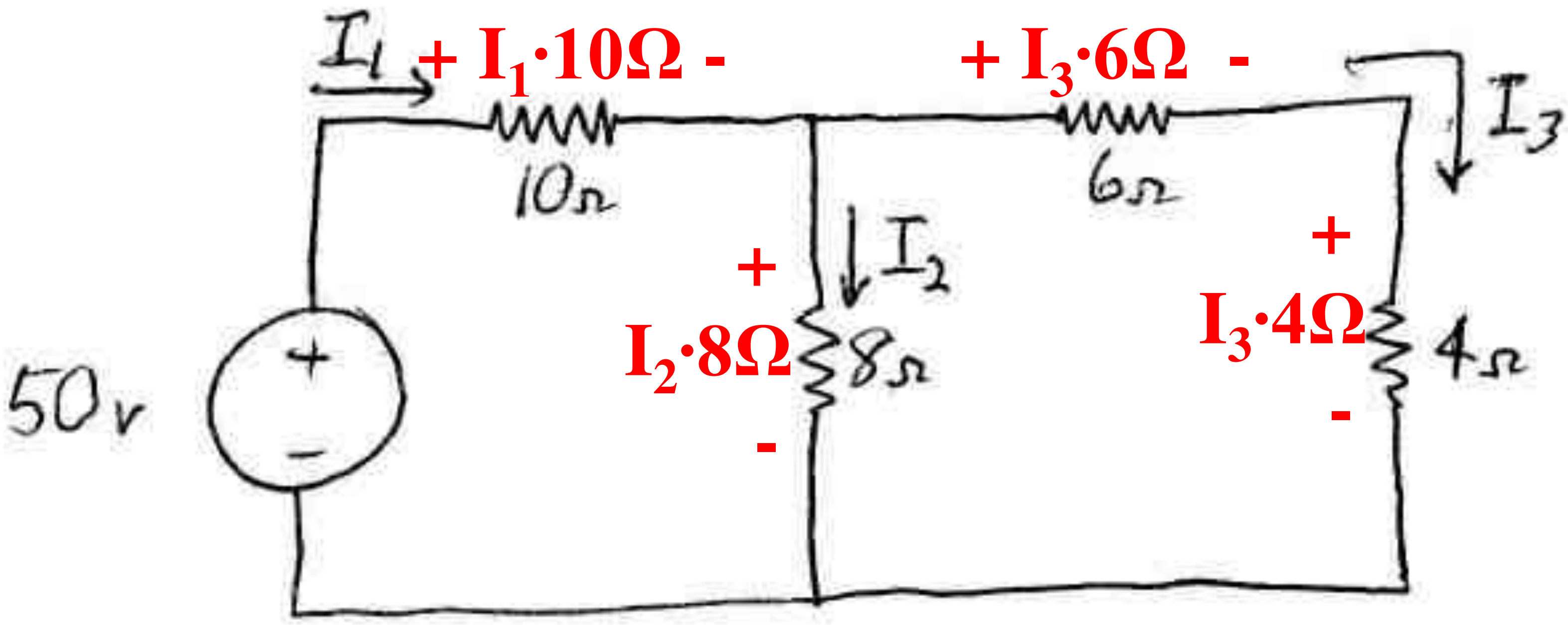
$$Req = R_1 \cdot R_2 / (R_1 + R_2)$$

Example Circuit



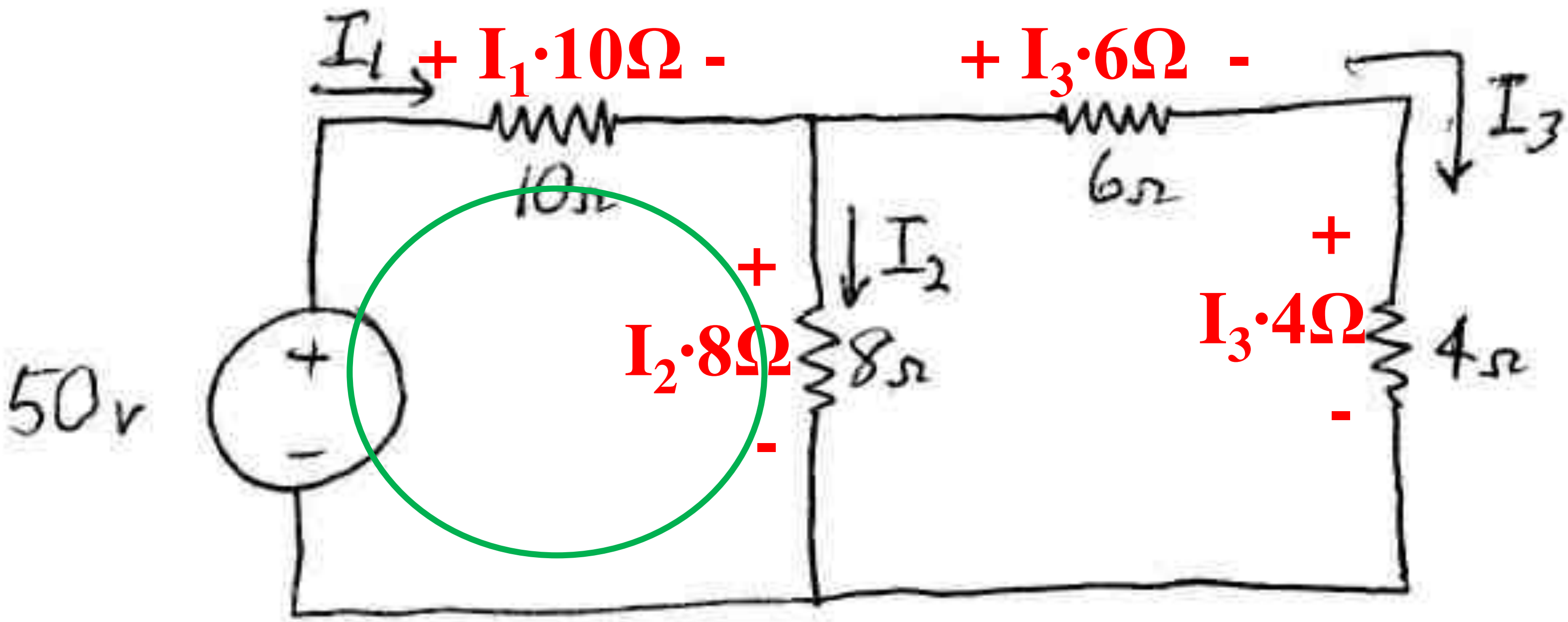
Solve for the currents through each resistor
And the voltages across each resistor

Example Circuit



Using Ohm's law, add polarities and expressions for each resistor voltage

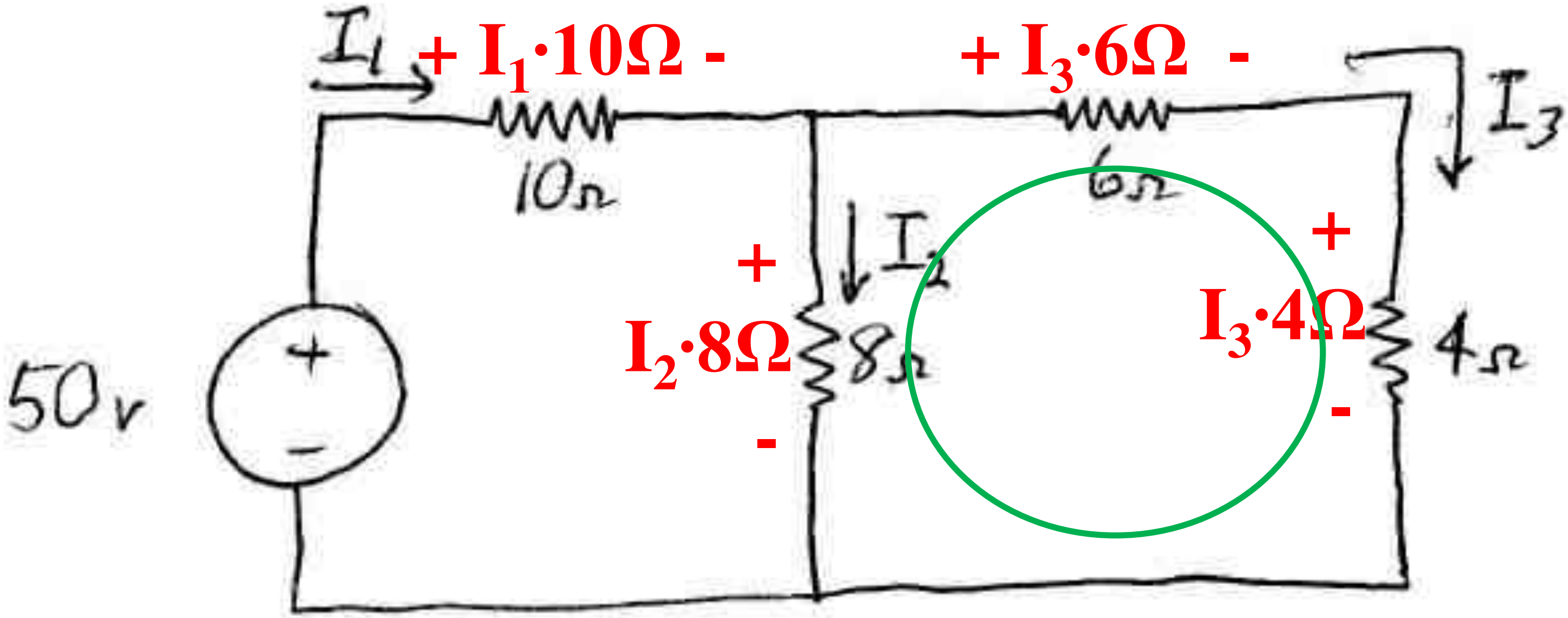
Example Circuit



Write 1st Kirchoff's voltage law equation

$$-50\text{ v} + I_1 \cdot 10\Omega + I_2 \cdot 8\Omega = 0$$

Example Circuit

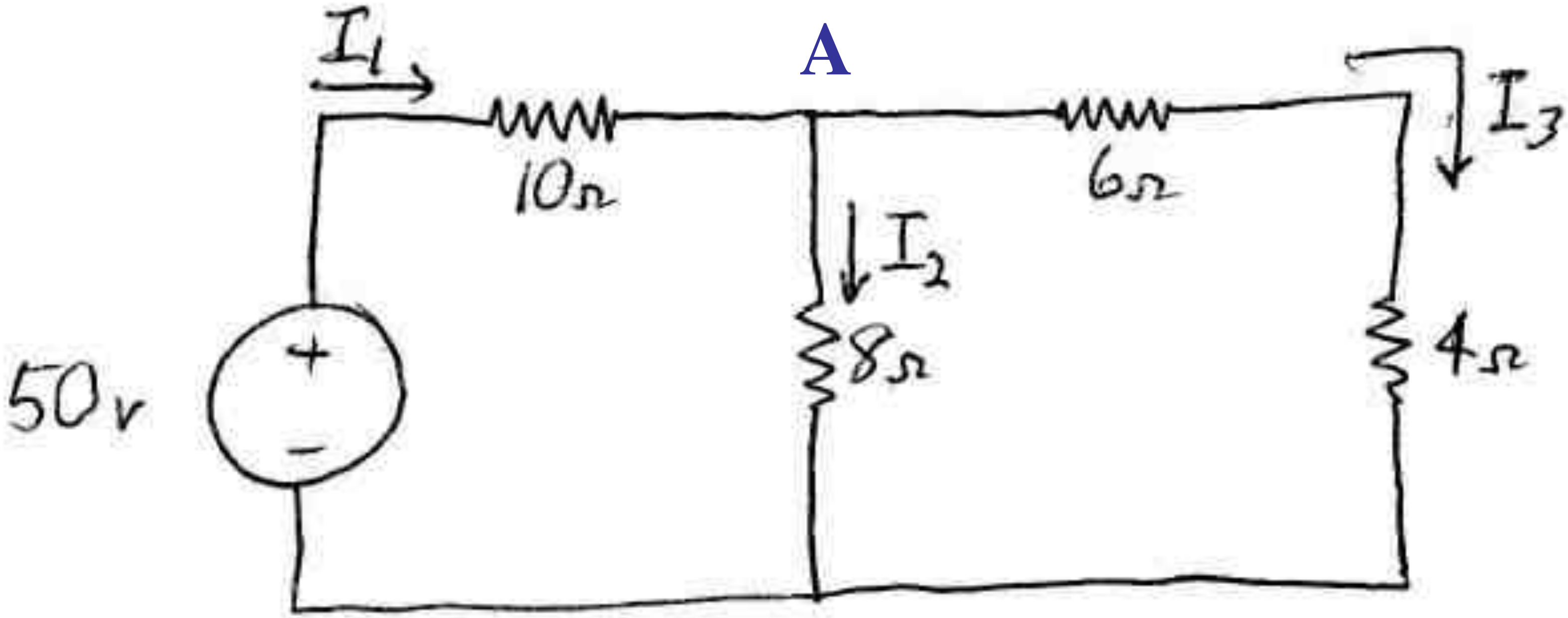


Write 2nd Kirchoff's voltage law equation

$$-I_2 \cdot 8\Omega + I_3 \cdot 6\Omega + I_3 \cdot 4\Omega = 0$$

$$\text{or } I_2 = I_3 \cdot (6+4)/8 = 1.25 \cdot I_3$$

Example Circuit



Write Kirchoff's current law equation at A

$$+I_1 - I_2 - I_3 = 0$$

Example Circuit

- We now have 3 equations in 3 unknowns, so we can solve for the currents through each resistor, that are used to find the voltage across each resistor
- Since $I_1 - I_2 - I_3 = 0$, $I_1 = I_2 + I_3$
- Substituting into the 1st KVL equation

$$-50 \text{ v} + (I_2 + I_3)\cdot 10\Omega + I_2\cdot 8\Omega = 0$$

$$\text{or } I_2\cdot 18\ \Omega + I_3\cdot 10\ \Omega = 50 \text{ volts}$$

Example Circuit

- But from the 2nd KVL equation, $I_2 = 1.25 \cdot I_3$
- Substituting into 1st KVL equation:

$(1.25 \cdot I_3) \cdot 18\ \Omega + I_3 \cdot 10\ \Omega = 50$ volts

Or: $I_3 \cdot 22.5\ \Omega + I_3 \cdot 10\ \Omega = 50$ volts

Or: $I_3 \cdot 32.5\ \Omega = 50$ volts

Or: $I_3 = 50$ volts$/32.5\ \Omega$

Or: $I_3 = 1.538$ amps

Example Circuit

- Since $I_3 = 1.538$ amps

  $I_2 = 1.25 \cdot I_3 = 1.923$ amps
- Since $I_1 = I_2 + I_3$, $I_1 = 3.461$ amps
- The voltages across the resistors:

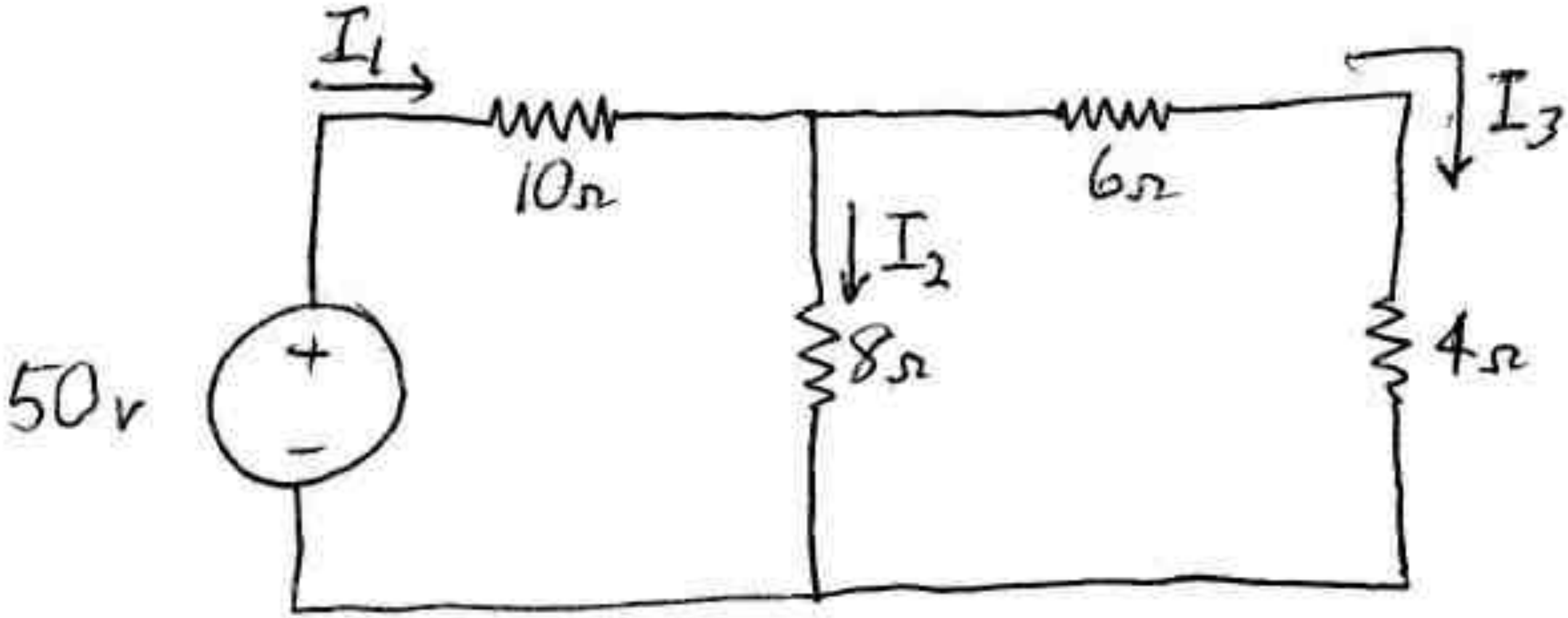
  $I_1 \cdot 10\Omega = 34.61$ volts

  $I_2 \cdot 8\Omega = 15.38$ volts

  $I_3 \cdot 6\Omega = 9.23$ volts

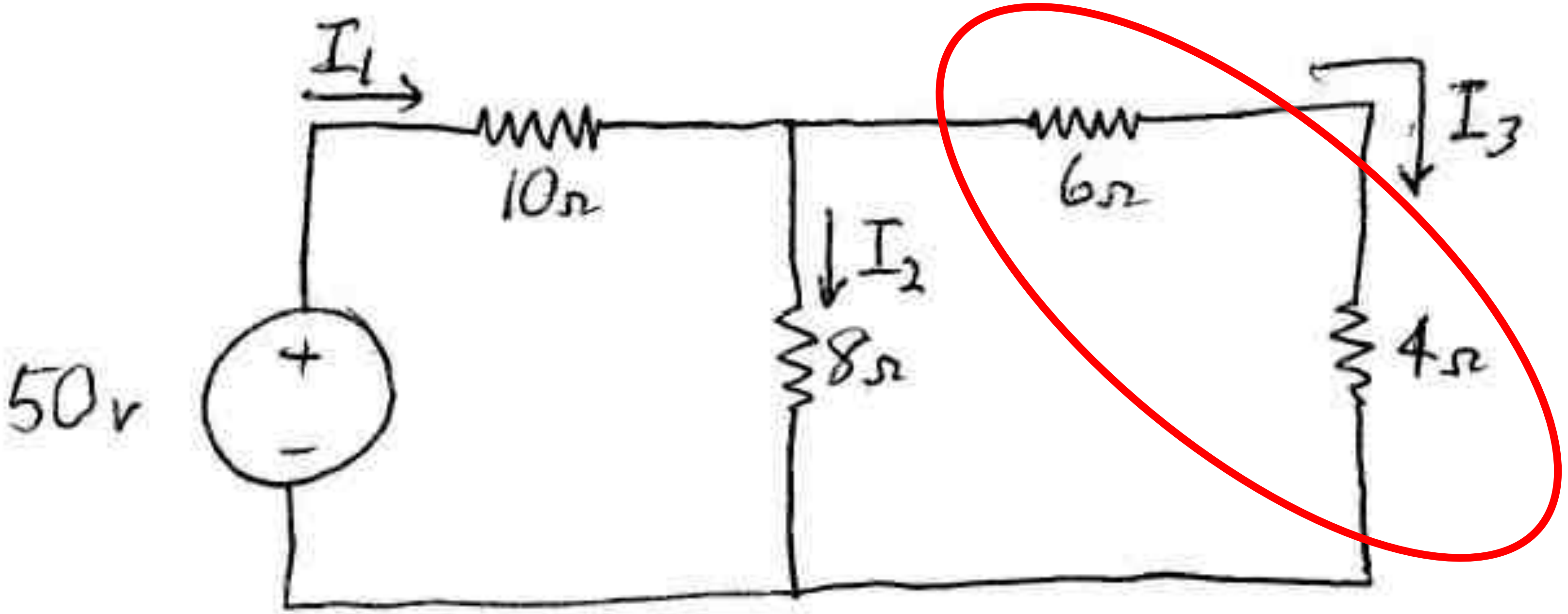
  $I_3 \cdot 4\Omega = 6.15$ volts

Example Circuit



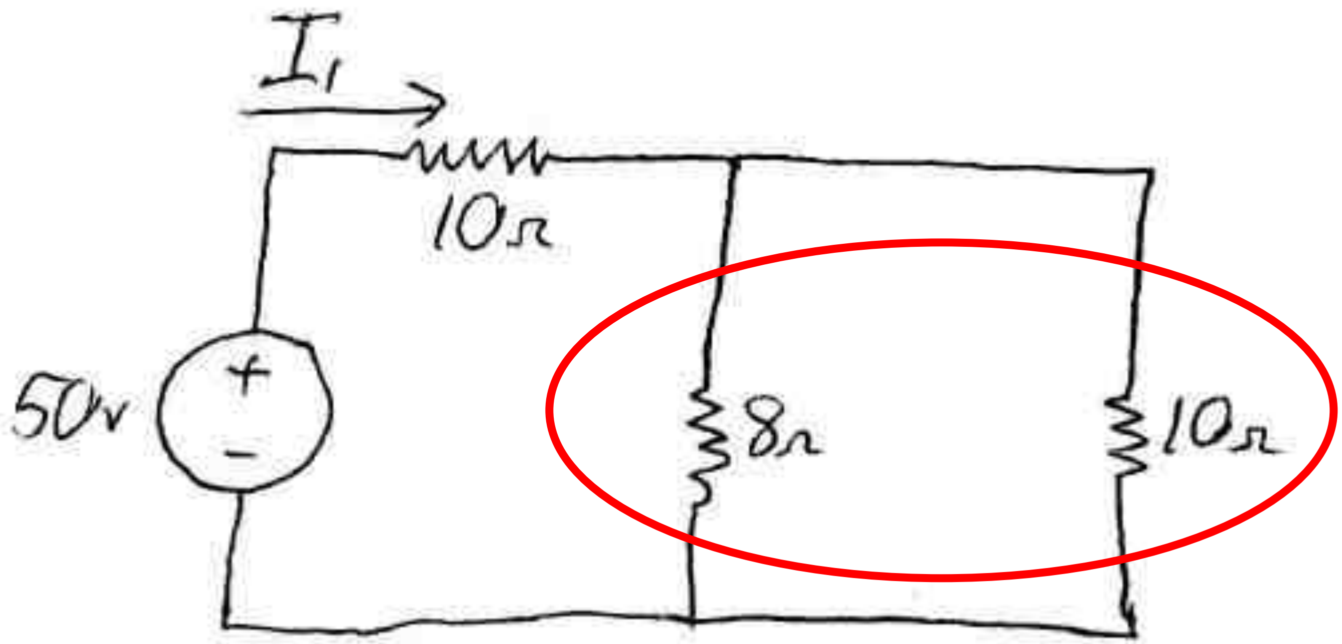
Solve for the currents through each resistor And the voltages across each resistor using Series and parallel simplification.

Example Circuit



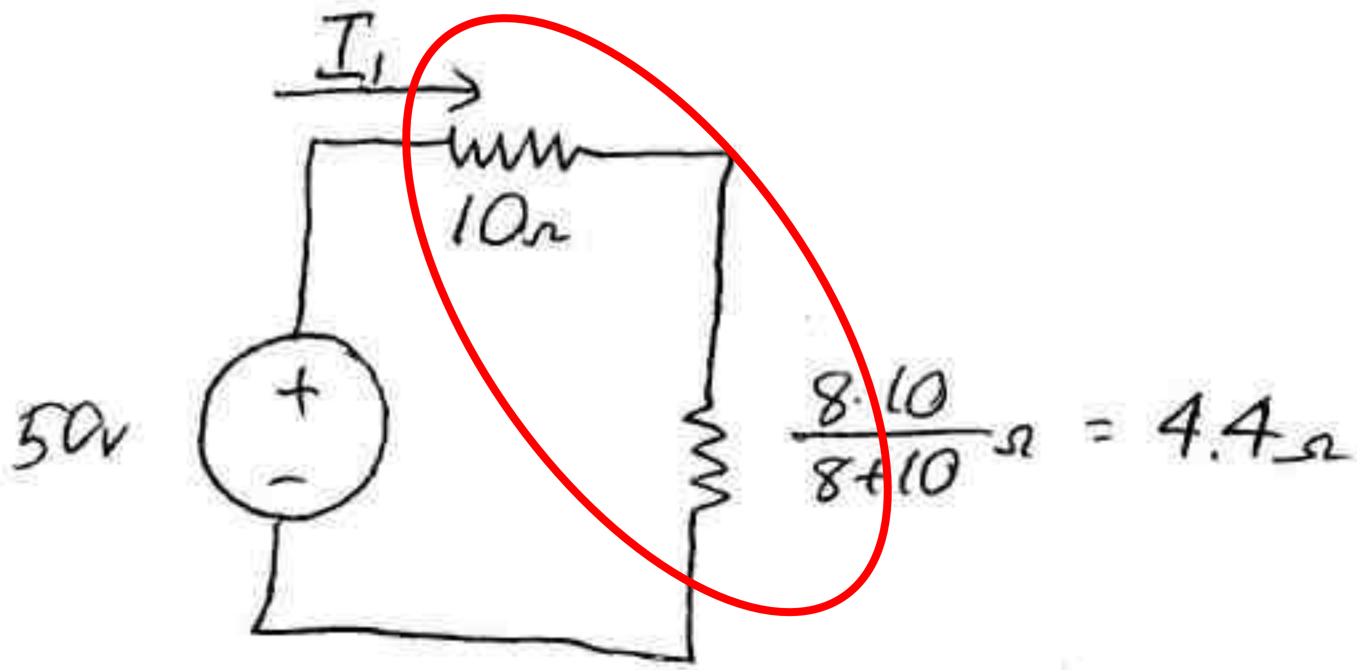
The 6 and 4 ohm resistors are in series, so are combined into 6+4 = 10Ω

Example Circuit



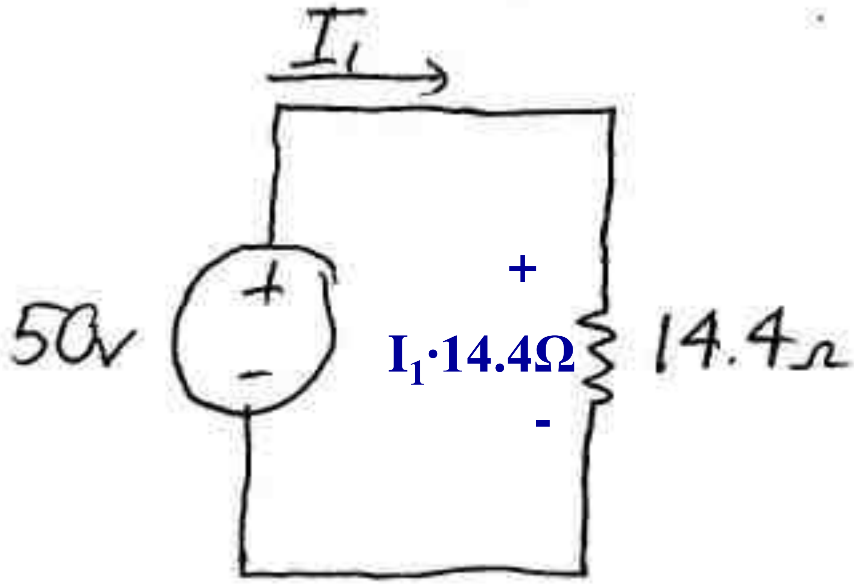
The 8 and 10 ohm resistors are in parallel, so are combined into 8·10/(8+10) =14.4 Ω

Example Circuit



The 10 and 4.4 ohm resistors are in series, so are combined into 10+4 = 14.4Ω

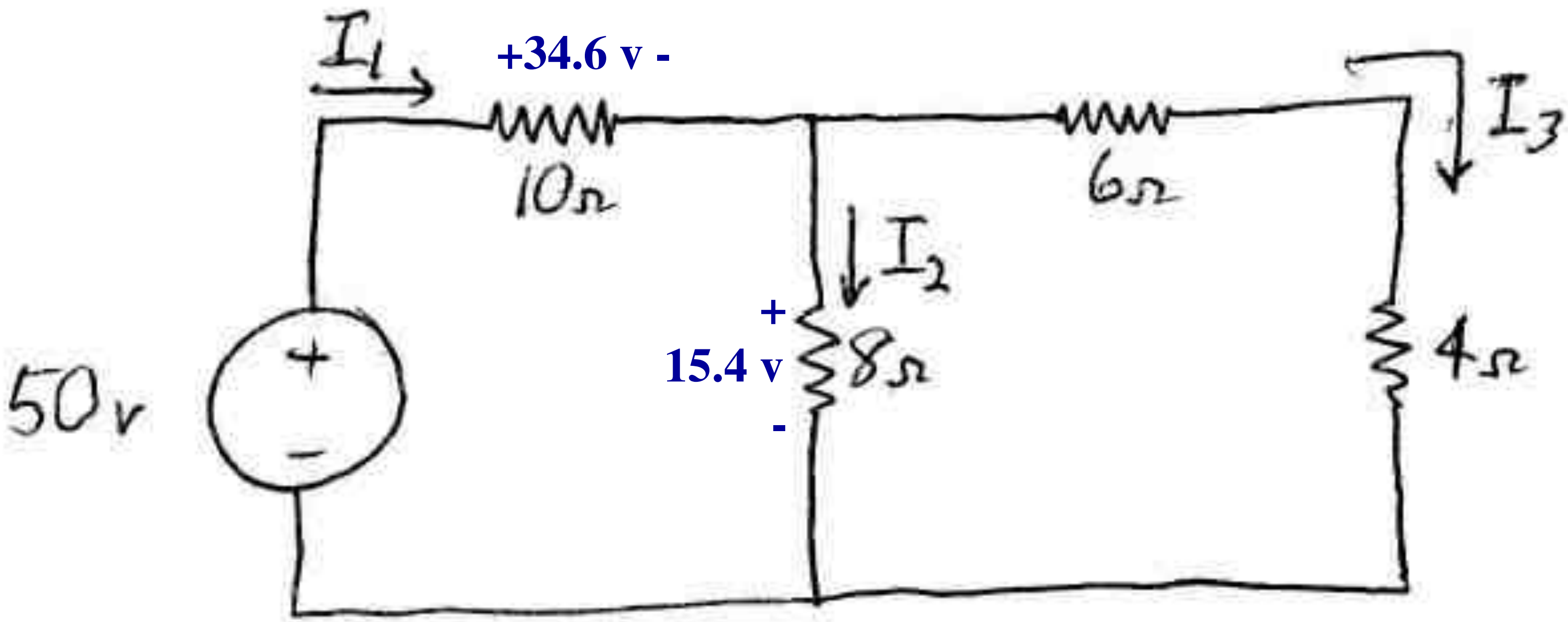
Example Circuit



Writing KVL, $I_1 \cdot 14.4\Omega - 50\text{ v} = 0$

Or $I_1 = 50\text{ v} / 14.4\Omega = 3.46\text{ A}$

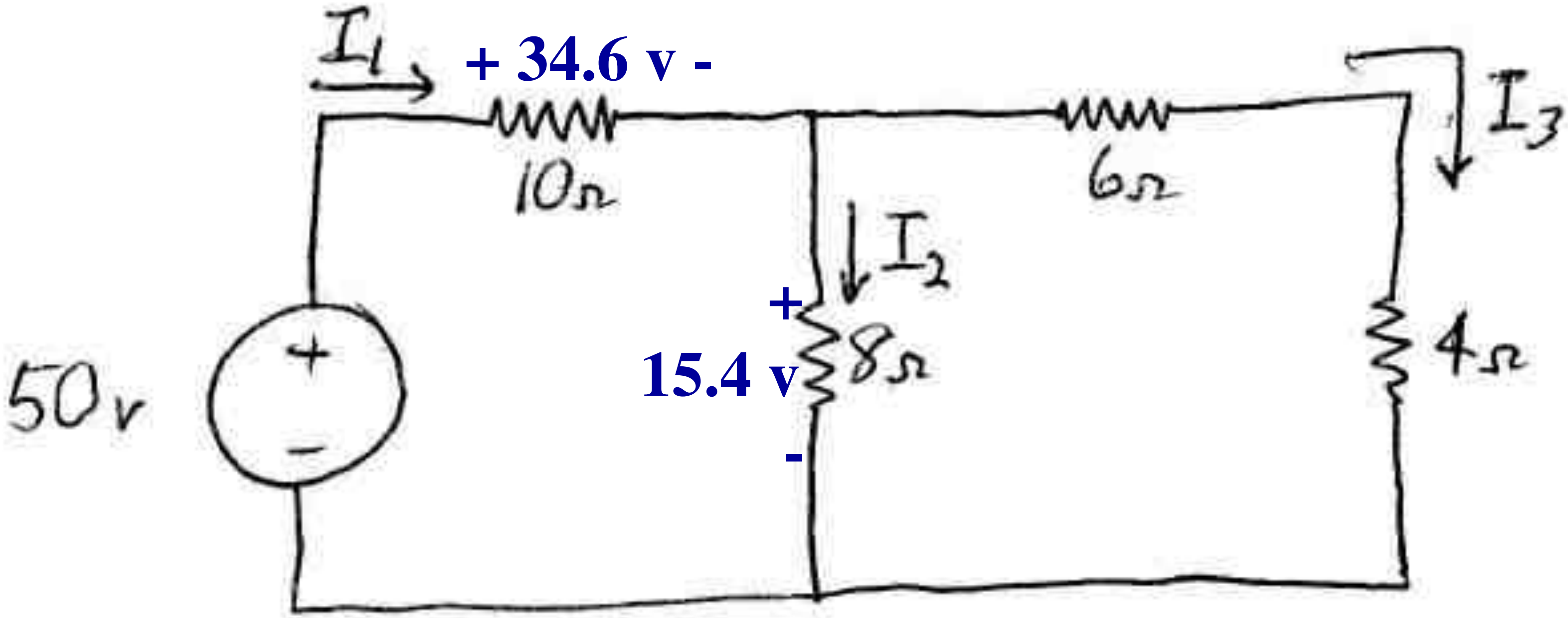
Example Circuit



If I_1 = 3.46 A, then $I_1 \cdot 10\ \Omega$ = 34.6 v

So the voltage across the 8 Ω = 15.4 v

Example Circuit



If $I_2 \cdot 8\ \Omega = 15.4$ v, then $I_2 = 15.4/8 = 1.93$ A

By KCL, $I_1 - I_2 - I_3 = 0$, so $I_3 = I_1 - I_2 = 1.53$ A

Objectives

- At the end of this topic, you should be able to:
  - apply the superposition theorem for circuit analysis
  - apply Thevenin's theorem to simplify the circuit for analysis
  - apply Norton's theorem to simplify the circuit for analysis
  - understand maximum power transfer and perform circuit conversion

Network Theorems

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Network Theorems

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Superposition Theorem

- The Superposition theorem states that if a linear system is driven by more than one independent power source, the total response is the sum of the individual responses. The following example will show the step of finding branches current using superpostion theorem

Refer to the Figure 1, determine the branches current using superposition theorem.

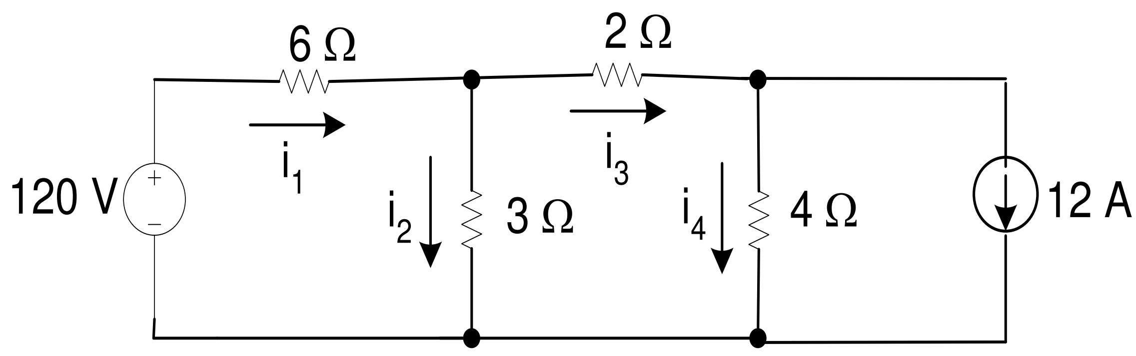


Figure 1

- Solution

- The application of the superposition theorem is shown in Figure 1, where it is used to calculate the branch current. We begin by calculating the branch current caused by the voltage source of 120 V. By substituting the ideal current with open circuit, we deactivate the current source, as shown in Figure 2.

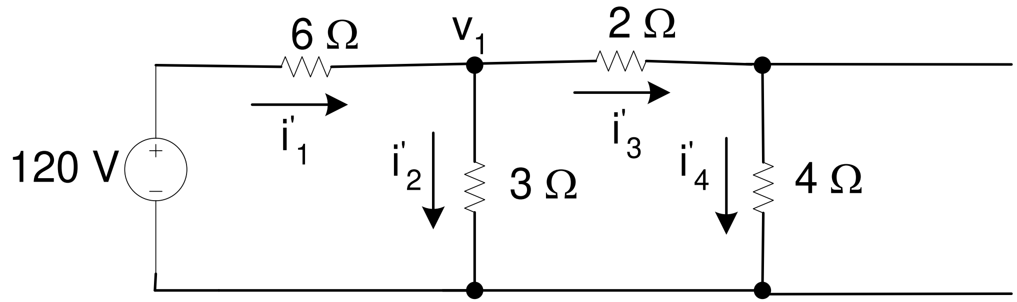


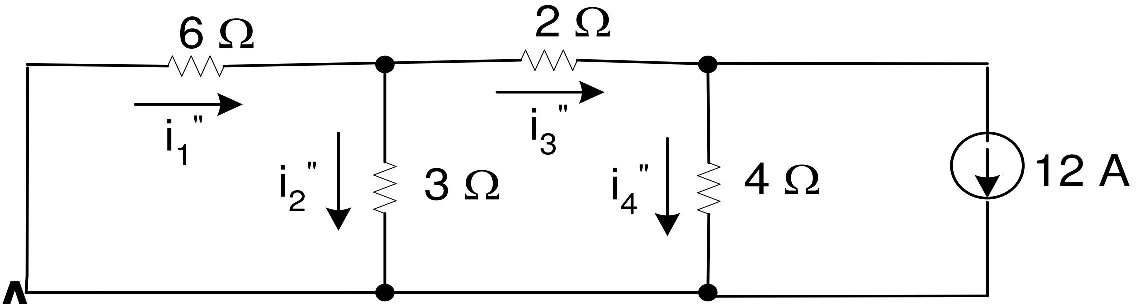
Figure 2

- To calculate the branch current, the node voltage across the 3Ω resistor must be known. Therefore

$$\frac{v_1 - 120}{6} + \frac{v_1}{3} + \frac{v_1}{2+4} = 0$$

where $v_1 = 30$ V

The equations for the current in each branch,



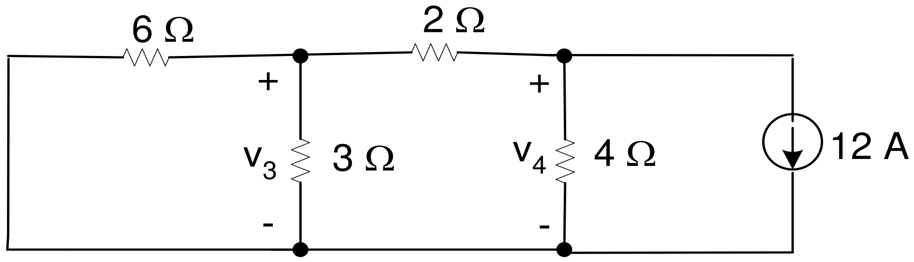
- $i'_1 = \dfrac{120 - 30}{6} = 15\text{ A}$

  $i'_2 = \dfrac{30}{3} = 10\text{ A}$

  $i'_3 = i'_4 = \dfrac{30}{6} = 5\text{ A}$

In order to calculate the current cause by the current source, we deactivate the ideal voltage source with a short circuit, as shown

- To determine the branch current, solve the node voltages across the 3Ω dan 4Ω resistors as shown in Figure 4



$$\frac{v_3}{3} + \frac{v_3}{6} + \frac{v_3 - v_4}{2} = 0$$

$$\frac{v_4 - v_3}{2} + \frac{v_4}{4} + 12 = 0$$

- The two node voltages are

- By solving these equations, we obtain
  - $v_3 = -12$ V
  - $v_4 = -24$ V

Now we can find the branches current,

$$i_1'' = \frac{-v_3}{6} = \frac{12}{6} = 2A$$

$$i_2'' = \frac{v_3}{3} = \frac{-12}{3} = -4A$$

$$i_3'' = \frac{v_3 - v_4}{2} = \frac{-12 + 24}{2} = 6A$$

$$i_4'' = \frac{v_4}{4} = \frac{-24}{4} = -6A$$

To find the actual current of the circuit, add the currents due to both the current and voltage source,

$$i_1 = i'_1 + i''_1 = 15 + 2 = 17\,A$$

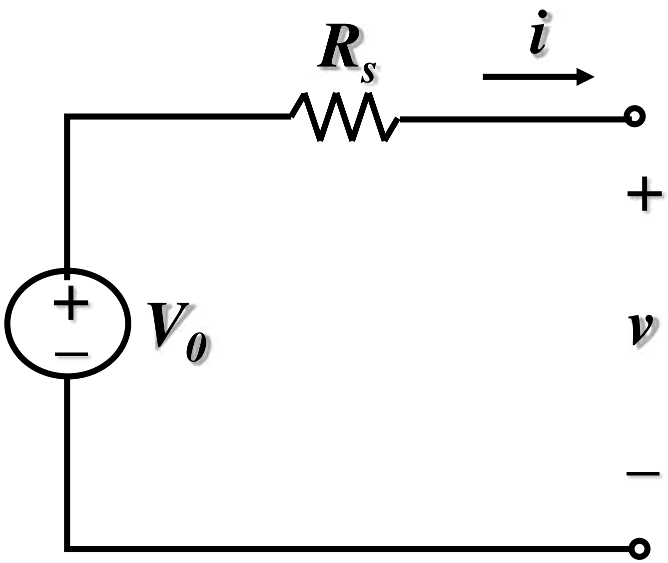
$$i_2 = i'_2 + i''_2 = 10 - 4 = 6\,A$$

$$i_3 = i'_3 + i''_3 = 5 + 6 = 11\,A$$

$$i_4 = i'_4 + i''_4 = 5 - 6 = -1\,A$$

Thevenin and Norton Equivalent Circuits

M. Leon Thévenin (1857-1926), published his famous theorem in 1883.



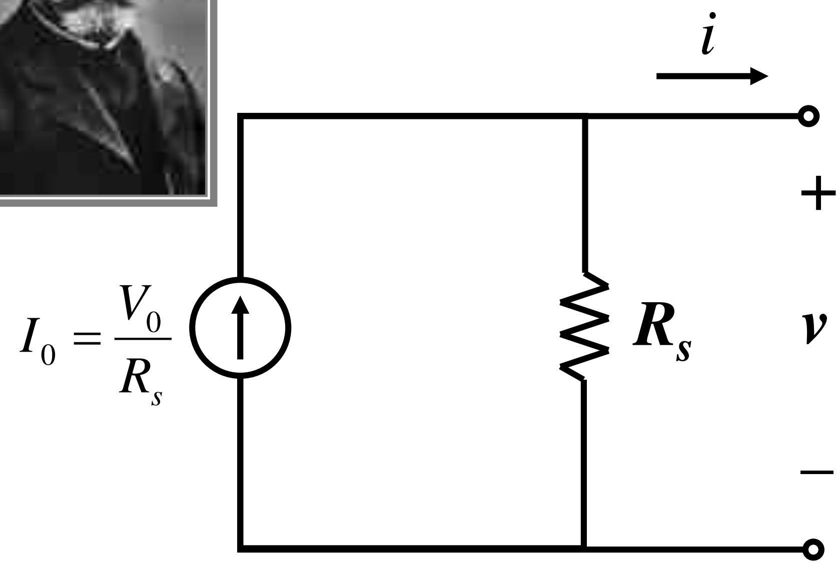


Fig.2.17 (a) Thevenin equivalent circuit ; (b) Norton equivalent circuit

$$v = V_0 - R_s\, i$$

$$i = I_0 - \frac{v}{R_s}$$

The equivalence of these two circuits is a special case of the *Thevenin and Norton Theorem*

Thevenin & Norton Equivalent Circuits

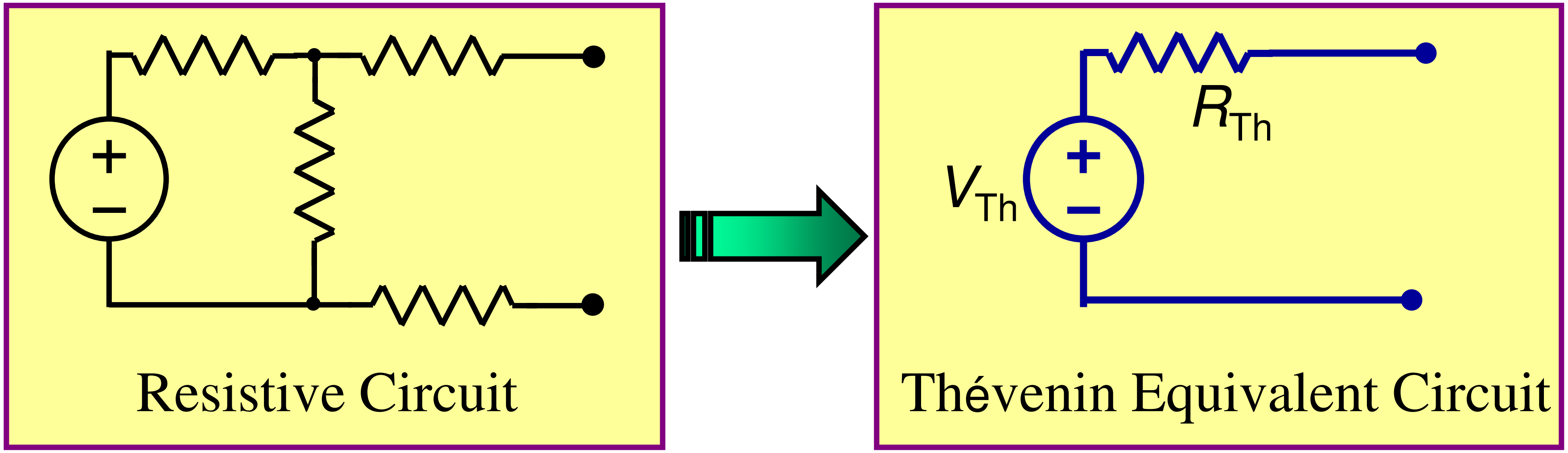
- *Thevenin's Theorem states that it is possible to simplify any linear circuit, no matter how complex, to an equivalent circuit with just a single voltage source and series resistance connected to a load.*

  A series combination of Thevenin equivalent voltage source V_0 and Thevenin equivalent resistance R_s

- Norton's Theorem states that it is possible to simplify any linear circuit, no matter how complex, to an equivalent circuit with just a single current source and parallel resistance connected to a load. Norton form:

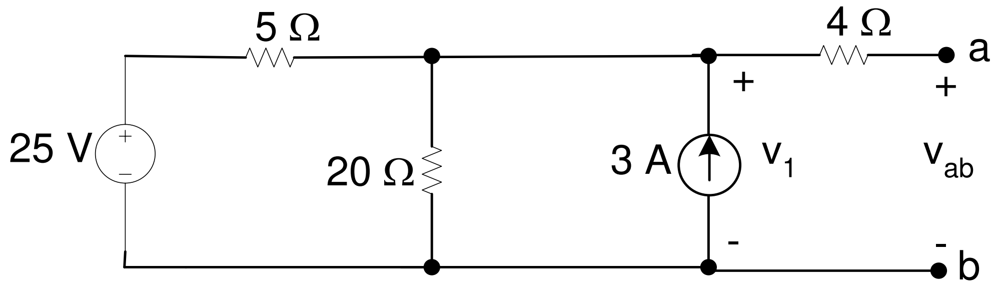
  A parallel combination of Norton equivalent current source I_0 and Norton equivalent resistance R_s

Thévenin's Theorem: A **resistive circuit** can be represented by **one voltage source** and **one resistor**:



- Example

Refer to the Figure 6, find the Thevenin equivalent circuit.



- Solution

- In order to find the Thevenin equivalent circuit for the circuit shown in Figure 6, calculate the open circuit voltage, vab. Note that when the a, b terminals are open, there is no current flow to 4Ω resistor. Therefore, the voltage vab is the same as the voltage across the 3A current source, labeled v_1.
- To find the voltage v_1, solve the equations for the singular node voltage. By choosing the bottom right node as the reference node,

$$\frac{v_1 - 25}{5} + \frac{v_1}{20} - 3 = 0$$

- By solving the equation, v1 = 32 V. Therefore, the Thevenin voltage Vth for the circuit is 32 V.
- The next step is to short circuit the terminals and find the short circuit current for the circuit shown in Figure 7. Note that the current is in the same direction as the falling voltage at the terminal.

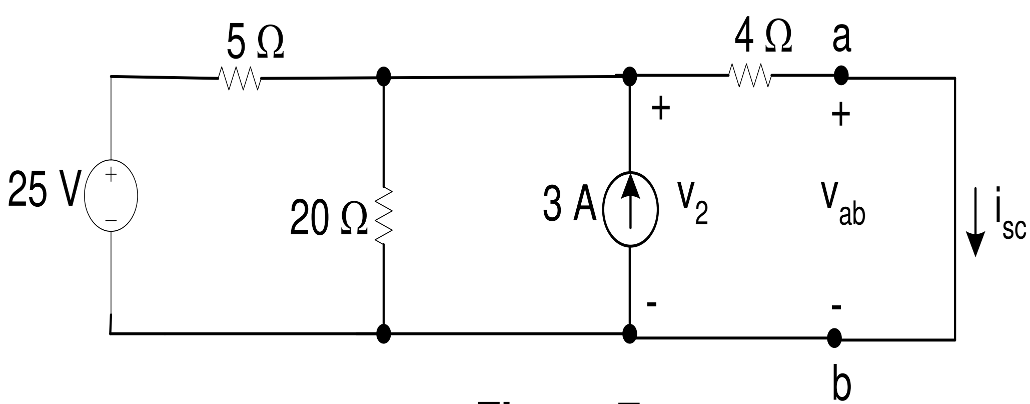


Figure 7

Current i_{sc} can be found if v_2 is known. By using the bottom right node as the reference node, the equationfor v_2 becomes

By solving the above equation, v_2 = 16 V. Therefore, the short circuit current i_{sc} is

$$\frac{v_2 - 25}{5} + \frac{v_2}{20} - 3 + \frac{v_2}{4} = 0$$

$$i_{sc} = \frac{16}{4} = 4A$$

The Thevenin resistance R_{Th} is

$$R_{Th} = \frac{V_{Th}}{i_{sc}} = \frac{32}{4} = 8\Omega$$

Figure 8 shows the Thevenin equivalent circuit for the Figure 6.

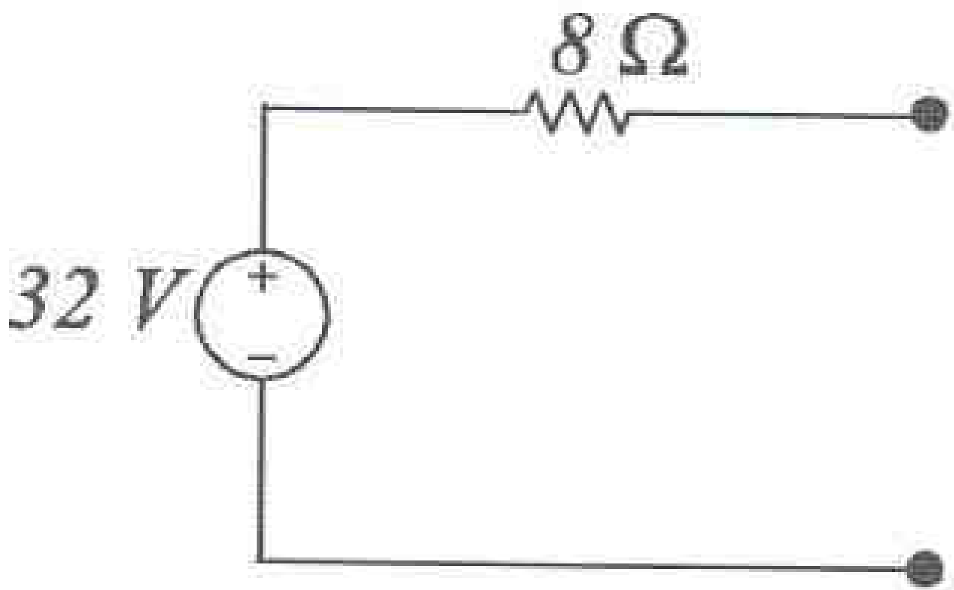


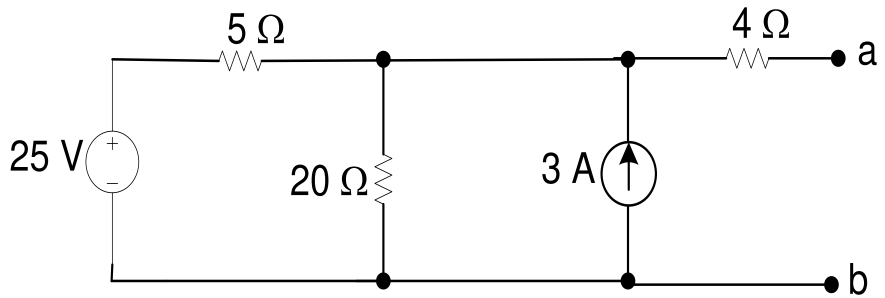
Figure 8

Norton’s Theorem

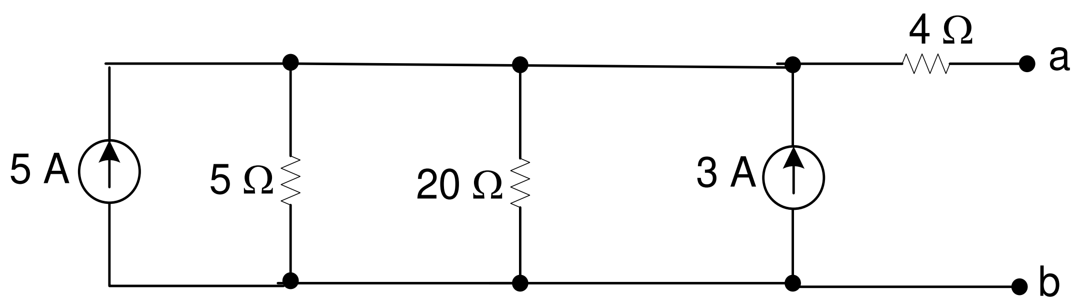
- The Norton equivalent circuit contains an independent current source which is parallel to the Norton equivalent resistance. It can be derived from the Thevenin equivalent circuit by using source transformation. Therefore, the Norton current is equivalent to the short circuit current at the terminal being studied, and Norton resistance is equivalent to Thevenin resistance.

- Example 3

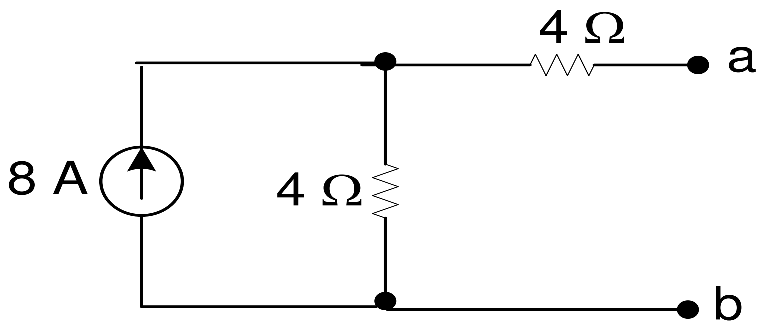
Derive the Thevenin and Norton equivalent circuits of Figure 6.



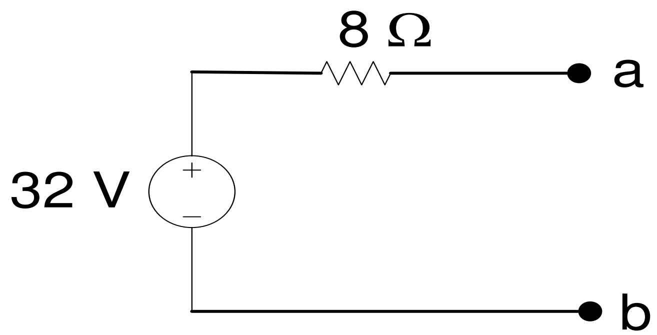
- Solution
- Step 1: Source transformation (The 25V voltage source is converted to a 5 A current source.)



Step 2: Combination of parallel source and parallel resistance



Step 3: Source transformation (combined serial resistance to produce the Thevenin equivalent circuit.)



- Step 4: Source transformation (To produce the Norton equivalent circuit. The current source is 4A ($I = V/R = 32\ V/8\ \Omega$))

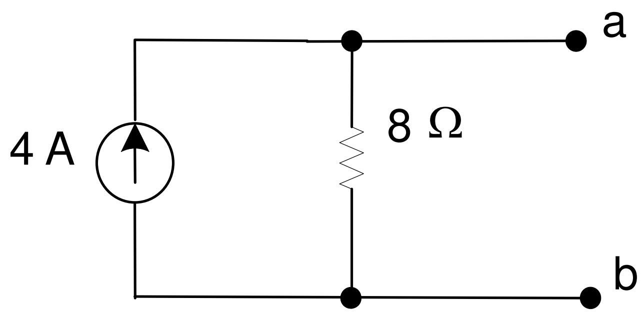


Figure 9 Steps in deriving Thevenin and Norton equivalent circuits.

Maximum Power Transfer

- Maximum power transfer can be illustrated by Figure 10. Assume that a resistance network contains independent and dependent sources, and terminals a and b to which the resistance RL is connected. Then determine the value of RL that allows the delivery of maximum power to the load resistor.

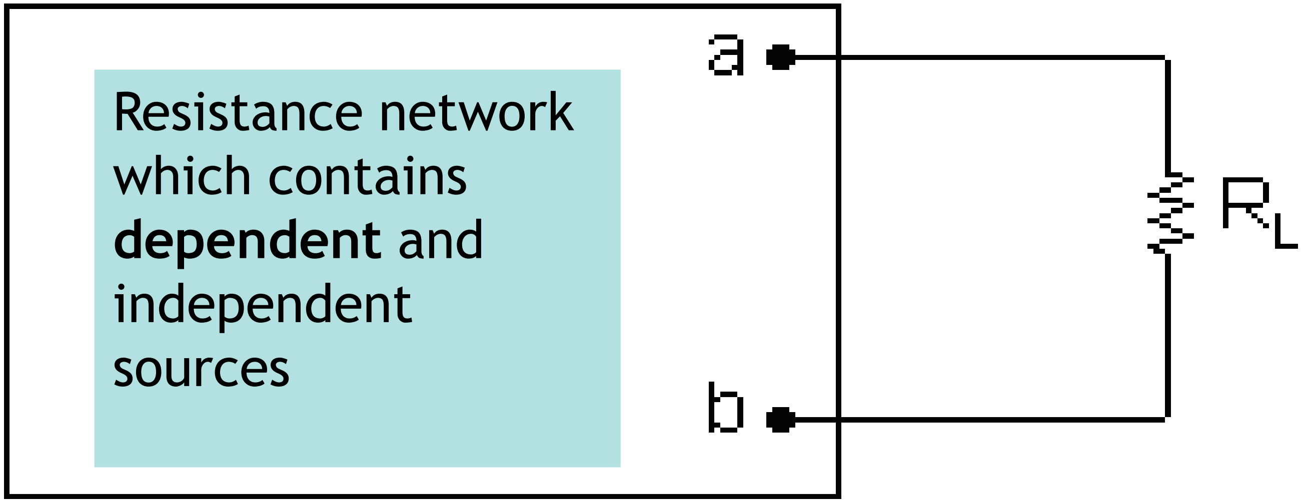

Resistance network which contains **dependent** and independent sources
a
b
R_L

Figure 10

- Maximum power transfer happens when the load resistance R_L is equal to the Thevenin equivalent resistance, R_{Th}. To find the maximum power delivered to R_L,

$$p_{max} = \frac{V_{Th}^2 R_L}{(2R_L)^2} = \frac{V_{Th}^2}{4R_L}$$

Circuit Transformation

- The configuration of circuit connection can be changed to make the calculation easier. There are TWO type of transformations which are Delta (Δ) to star connection (Y) and vice versa.

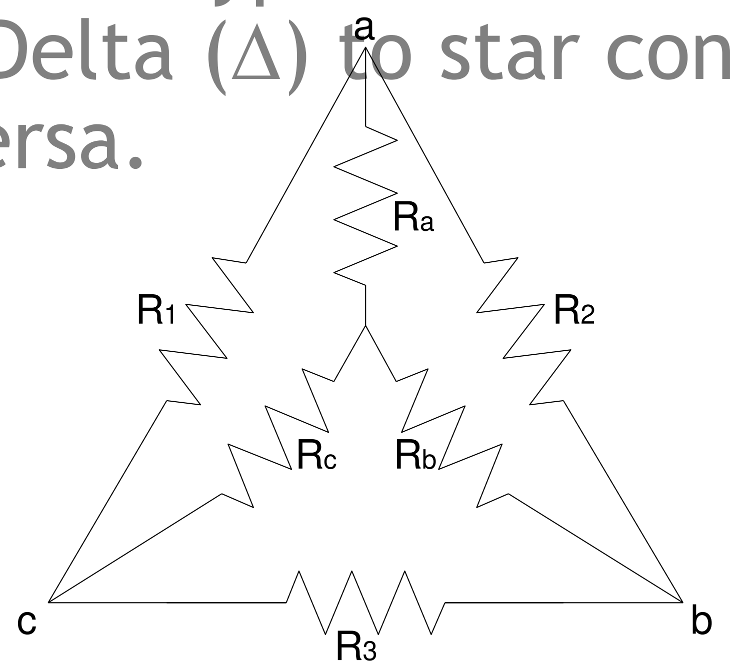


Figure 12 Delta and Star Circuit Connection

- Delta (Δ) to star (Y) transformation:

$$R_a = \frac{R_1 R_2}{R_1 + R_2 + R_3}$$

$$R_b = \frac{R_2 R_3}{R_1 + R_2 + R_3}$$

$$R_c = \frac{R_1 R_3}{R_1 + R_2 + R_3}$$

- Star (Y) to Delta (Δ) transformation:

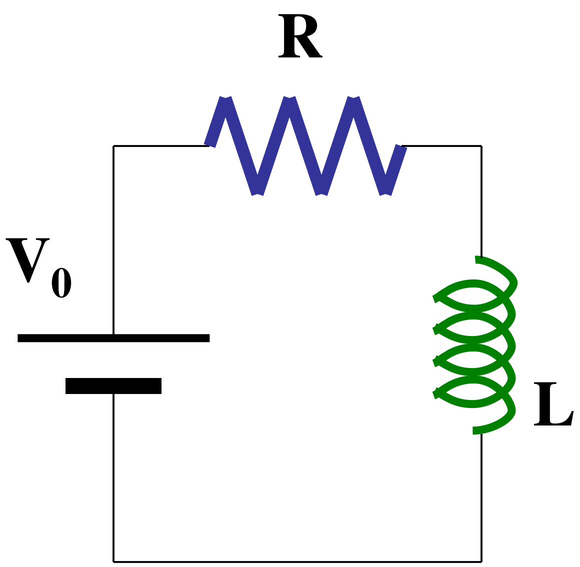
$$R_1 = \frac{R_a R_b + R_b R_c + R_c R_a}{R_b}$$

$$R_2 = \frac{R_a R_b + R_b R_c + R_c R_a}{R_c}$$

$$R_3 = \frac{R_a R_b + R_b R_c + R_c R_a}{R_a}$$

- *Thank You*

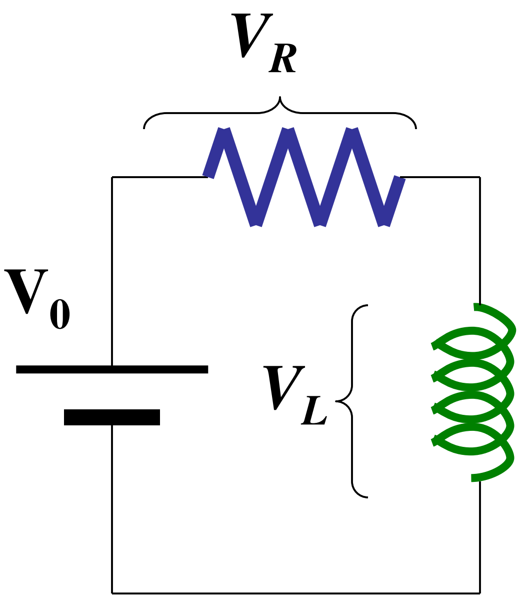
Inductors - how do they work?



$$V_L = L\frac{dI}{dt}$$

Start with no current in the circuit. When the battery is connected, the inductor is resistant to the flow of current. Gradually the current increases to the fixed value V_0/R, meaning that the voltage across the inductor goes to zero. In reality the inductor has a finite resistance since it is a long wire so it will then be more like a pair of series resistances.

Inductors - time constant L/R



Again the behavior of an inductor is seen by analysis with Kirchoff's laws. Suppose we start with no current.

$$V_0 = V_R + V_L = IR + L\frac{dI}{dt}$$

then $I = \frac{V_0}{R}\left[1 - \exp\left[-\frac{Rt}{L}\right]\right]$ **and**

$$V_L = V_0 \exp\left[-\frac{Rt}{L}\right] \quad V_R = V_0\left(1 - \exp\left[-\frac{Rt}{L}\right]\right)$$

There is a fundamental time scale set by L/R, which has units of seconds (=Henry/Ohm)

RLC circuits with sinusoidal sources

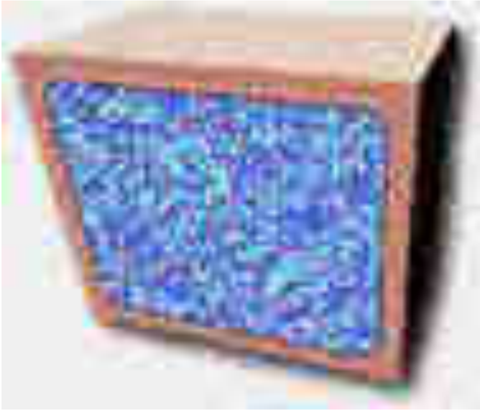
The AC analysis of circuits with inductors is also easy, with the effective resistance (impedance) of an inductor equal to *i*⍰L. From a phasor point of view this means that the inductor leads the resistor by 90 degrees.

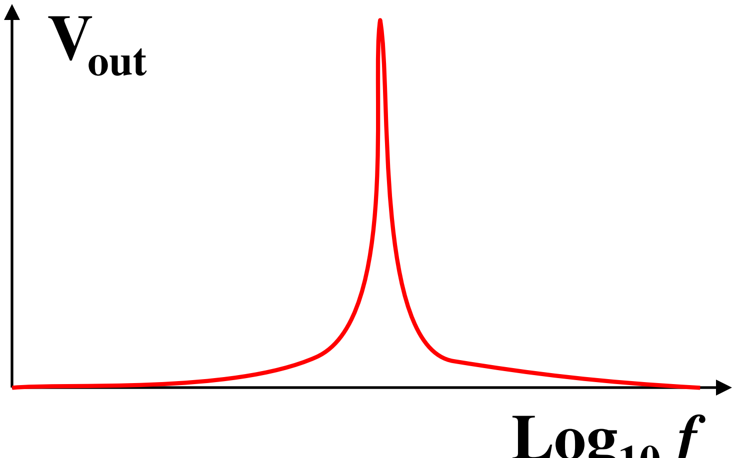
High pass and low pass filters can be made from inductors as well. However the inductors are usually bulkier and relatively expensive compared to capacitors (and more difficult to make in an integrated circuit) so are not used as commonly.

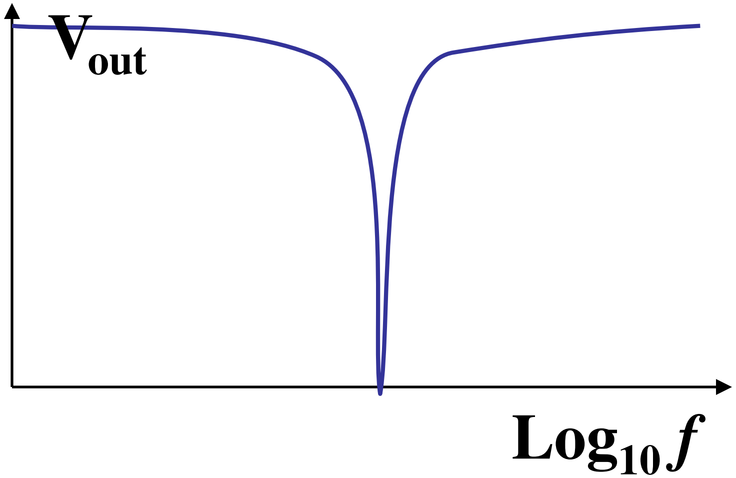
Another limitation is that they are far from ideal. The impedance is usually R_L+*i*⍰L, which means that in order to find the breakpoint you use f = L/(2⍰(R_L+R)).

Notch and Bandpass

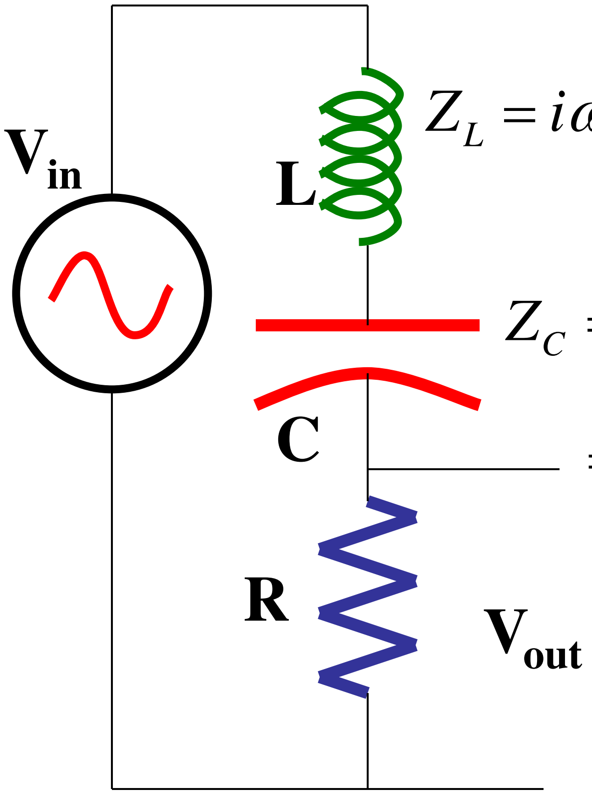
A filter can also serve to select or eliminate a narrow band of frequencies. Examples are radio (select) and parental control "channel eliminator" circuits.







Mathematical analysis of a series LRC circuit - bandpass filter



$$Z_L = i\omega L$$

$$Z_C = \frac{1}{i\omega C} = \frac{-i}{\omega C}$$

First find the total impedance of the circuit

$$Z = R + i\left(\omega L - \frac{1}{\omega C}\right)$$

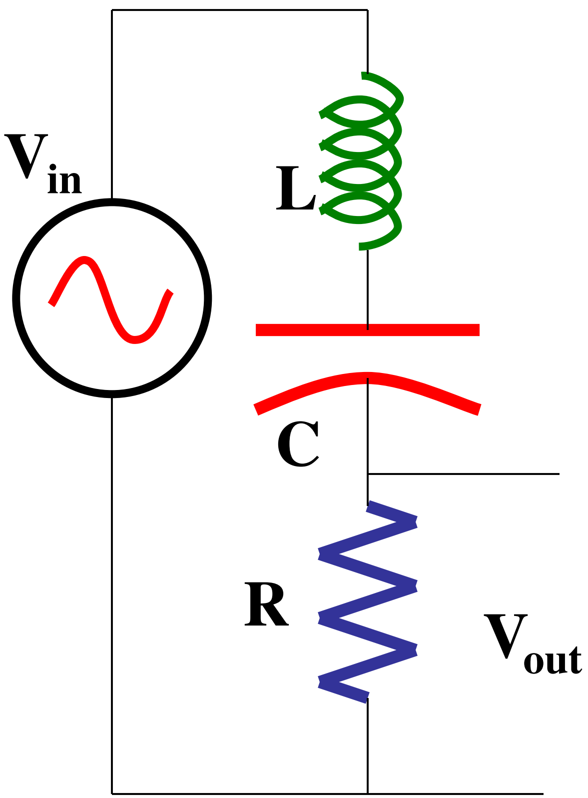
Using a voltage divider

$$\frac{V_{out}}{V_{in}} = \frac{R}{R + i\left(\omega L - \frac{1}{\omega C}\right)}$$

The phase shift goes from 90°to -90°.

$$\phi = -\tan^{-1}\frac{R}{\left(\omega L - \frac{1}{\omega C}\right)}$$

Mathematical analysis of a series LRC circuit - bandpass filter (2)

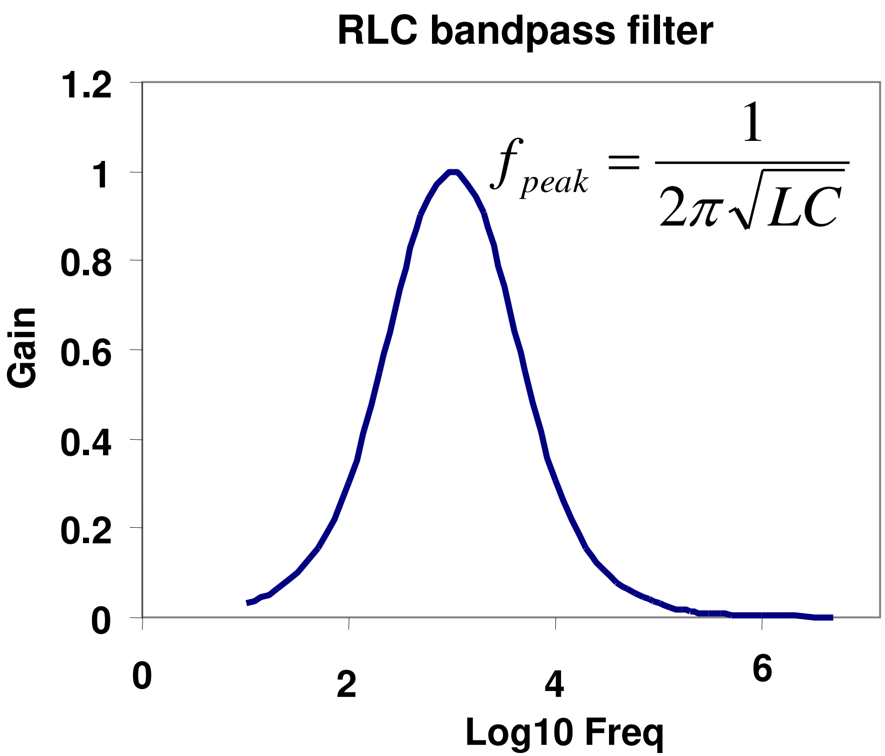


The magnitude of the gain, A_v, is

$$A_v = \left|\frac{V_{out}}{V_{in}}\right| = \frac{R}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}$$

Note that for high frequencies ωL is dominant and the gain is R/ ωL or small. At low frequencies the gain is ω RC because the impedance of the capacitor is dominant. At ω^2 = 1/LC the gain is one (assuming ideal components).

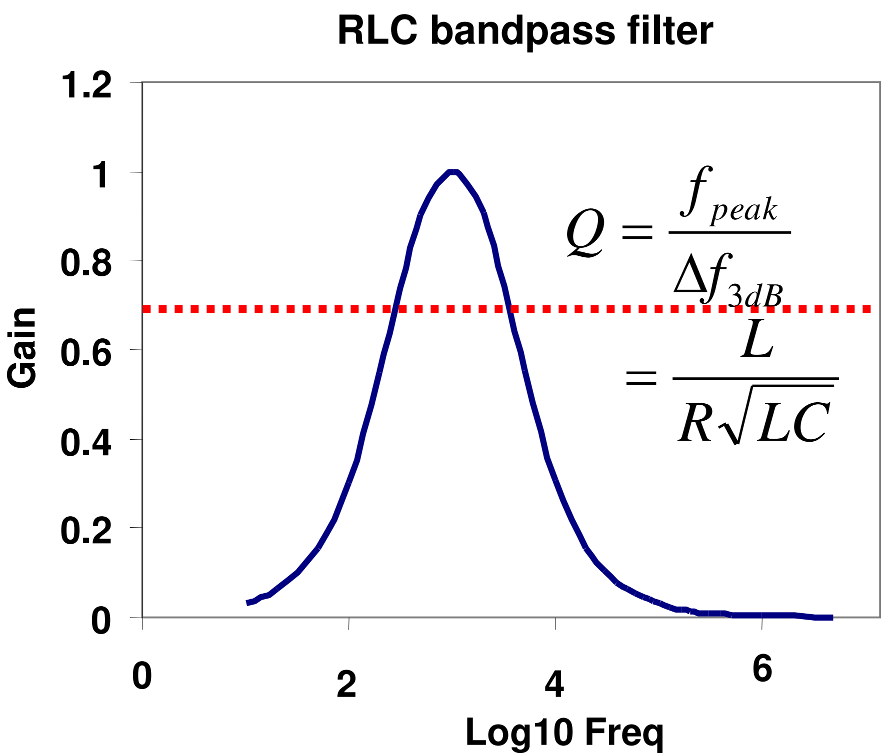
Graphing for a series LRC circuit



$$f_{peak} = \frac{1}{2\pi\sqrt{LC}}$$

Although the gain falls off at 20 dB/decade at high and low frequencies (this means that it is proportional to ⍰) it is more typical to plot it as shown on a semi-log graph, since this emphasizes the peak.

Q factor for a Series LRC circuit



$$Q = \frac{f_{peak}}{\Delta f_{3dB}} = \frac{L}{R\sqrt{LC}}$$

The quality factor or Q is defined as the energy stored divided by the energy loss/cycle. For an electronic bandpass it is the peak frequency divided by the width of the peak or bandwidth (defined by the frequencies where the gain is 3 dB lower than the maximum).

Solve $$\frac{1}{\sqrt{2}} = \frac{R}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}$$

$$\Delta f_{3dB} = \frac{R}{L}$$

Course outcome

C403.4: Identify and select various electrical machines based on their characteristics and applications

Introduction

- The Dc machines are of two types namely DC generators and DC motors.
- A DC generators converts mechanical energy into electrical energy whereas a DC motor converts the electrical energy into mechanical energy.
- In order to understand the operating principle of a DC motor, it is necessary to understand how does a current carrying conductor experience a force, when kept in a magnetic field.

- **Force on current carrying conductor:**

➢ If a straight conductor is placed in the magnetic field produced by a permanent magnet, the current flowing through a conductor in anti clockwise direction.

➢ Due to the presence of two magnetic fields simultaneously, an interaction between them will take place as shown in fig.(1).

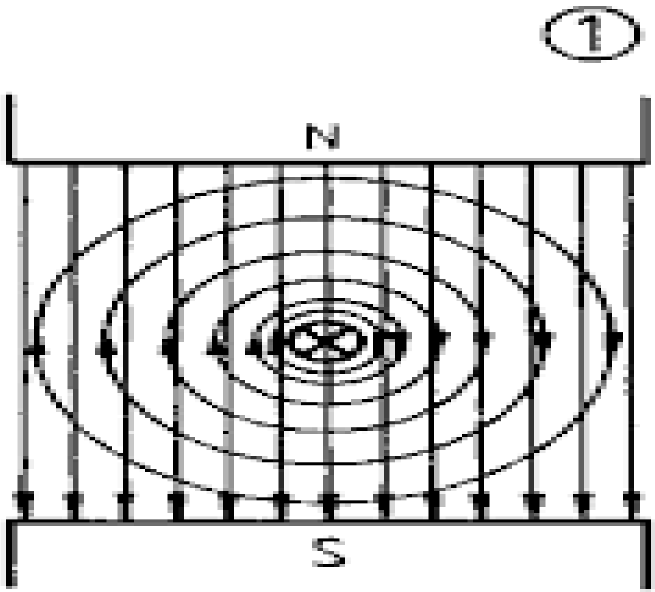


Fig.1(a): Interaction of the fields

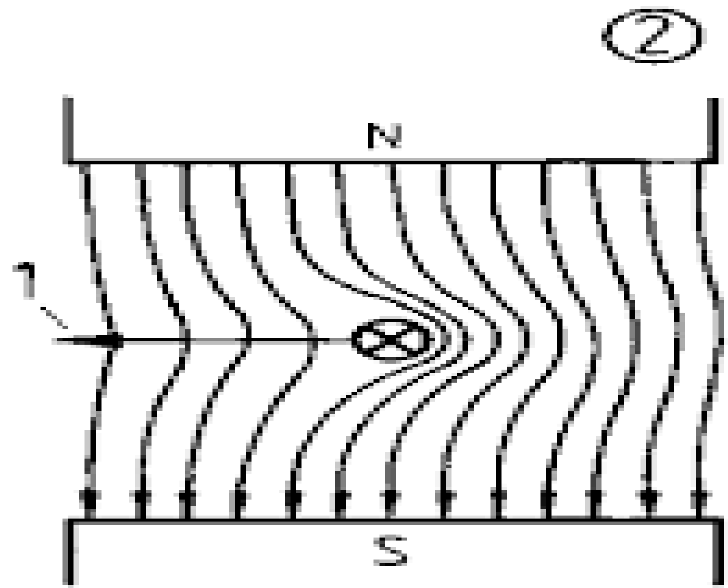


Fig.1(b):Resultant field

- As shown in fig.(1), the flux lines produced by the magnet and the conductor are in opposite direction to each other at left side and hence cancel each other. Therefore the no of flux lines at left side will reduced.
- At the right side, the individual fields are in the same direction, hence will add or strengthen each other. Therefore the no. of flux lines at right side will increase.

- **Magnitude of Force:**

➢ The magnitude of the force experienced by the current carrying conductor placed in the magnetic field is given by,

$$F = BIl \text{ Newton}$$

Where B = Flux density produced by Magnet

I = current flowing through conductor

l = Length of the conductor

- **Direction of force:**

- The direction of rotation of a motor depends on the direction of force exerted on the the armature winding and the direction of force experienced by a current carrying conductor is given by Fleming's left hand rule.
- Statement of Fleming's left hand rule:

  It states that if the first three fingers of the left hand are held mutually at right angles to each other and if index finger indicates the direction of the magnetic field, and if middle finger indicates the direction of current flowing through the conductor, then thumb indicates the direction of force exerted on the conductor. This is shown in fig (2).

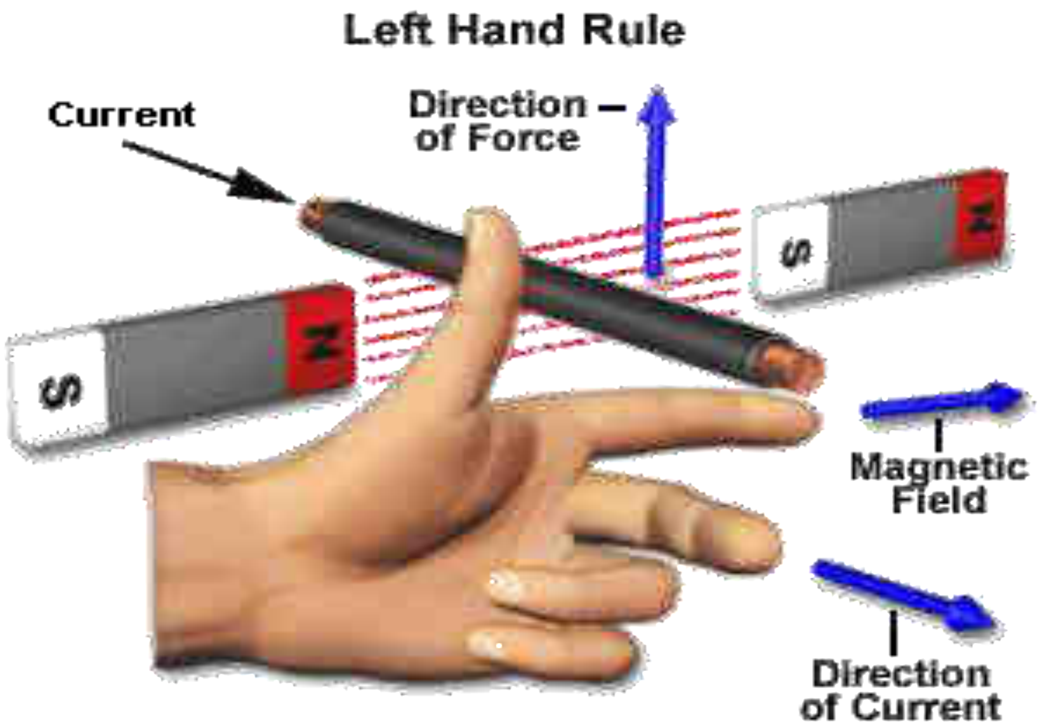


Fig.(2):Fleming's left hand rule thumb

Windings in DC Machine

- In any dc machines, there are two windings:

1. Field winding 2. Armature winding

- Out of these, the field winding is stationary which does not move at all and armature winding is mounted on a shaft. So it can rotate freely.
- Connection of windings for operation as motor:

➢ To operate the dc machine as a motor, the field winding and armature winding is connected across a dc power supply.

DC Motor

- Principle of operation:

➢ When current carrying conductor is placed in a magnetic field, it experienced a force.

➢ In case of DC motor, the magnetic field us developed by the field current i.e. current flowing in field winding and armature winding plays the role of current carrying conductor

➢ So armature winding experienced a force and start rotating.

Construction of DC Motor

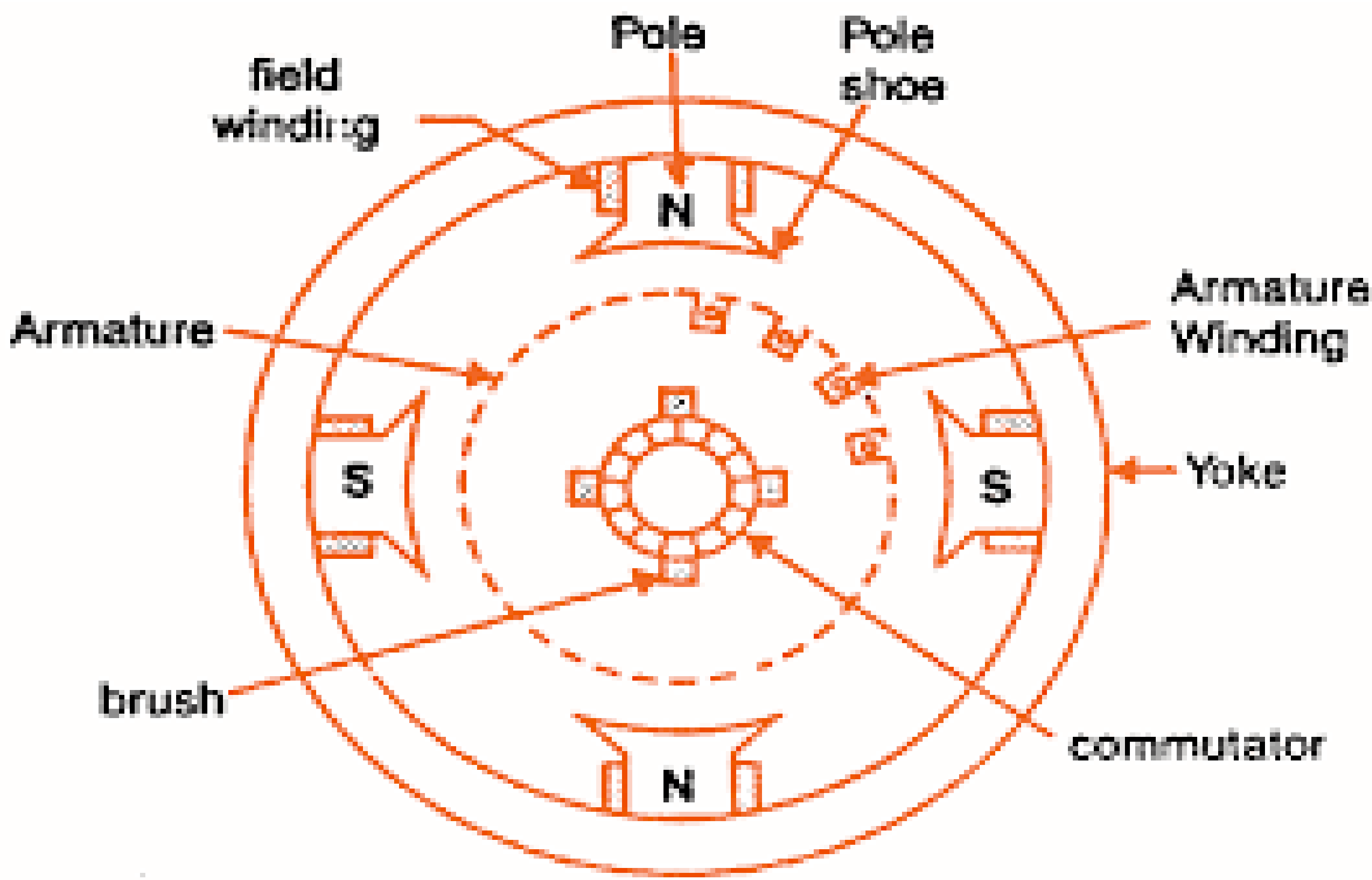


Fig.(1): construction of DC motor

- **Important parts of DC motor:**

1. Yoke
2. Field winding
3. poles
4. Armature
5. Commutator, brushes & gear
6. Brushes

1. Yoke:

- It acts as the outer support of a DC motor.
- It provides mechanical support for the poles.

2. Poles:

- pole of a dc motor is an electromagnet.
- The field winding is wound over the poles.
- Poles produces magnetic flux when the filed winding is excited.

3. Field winding:

- The coils wound around the pole are called field coils and they are connected in series with each other to form field winding.
- When current passing through the field winding, magnetic flux produced in the air gap between pole and armature.

4. Armature:

- Armature is a cylindrical drum mounted on shaft in which number of slots are provided.
- Armature conductors are placed in these slots.
- Theses armature conductors are interconnected to form the armature winding.

5. Commutator:

- A commutator is a cylindrical drum mounted on the shaft alonwith the armature core.
- It collects the current from the armature conductors and passed it to the external load via brushes.

6. Brushes:

- Commutator is rotating. So it is not possible to connect the load directly to it.
- Hence current is conducted from the armature to the external load by the carbon brushes which are held against the surface of commutator by springs.

Back EMF

- When the armature winding of a dc motor starts rotating in the magnetic flux produced by the field winding, it cuts the lines of magnetic flux.
- Hence according to the faraday's laws of electromagnetic induction, there will be an induced emf in the armature winding.
- As per the Lenz's law, this induced emf acts in opposite direction to the armature supply voltage. Hence this emf is called as the back emf and denoted by E_b.

$$E_b = \frac{NP\varphi Z}{60\ A}$$

- **Significance of back emf:**

➢ The presence of back e.m.f. makes the d.c. motor a self -regulating machine i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load.

1. When the motor is running on no load, small torque is required to overcome the friction and windage losses. Therefore, the armature current I_a is small and the back e.m.f. is nearly equal to the applied voltage.

2. If the motor is suddenly loaded, the first effect is to cause the armature to slow down. Therefore, the speed at which the armature conductors move through the field is reduced and hence the back e.m.f. Eb falls. The decreased back e.m.f. allows a larger current to flow through the armature and larger current means increased driving torque. Thus, the driving torque increases as the motor slows down. The motor will stop slowing down when the armature current is just sufficient to produce the increased torque required by the load.

3. If the load on the motor is decreased, the driving torque is momentarily in excess of the requirement so that armature is accelerated. As the armature speed increases, the back e.m.f. Eb also increases and causes the armature current Ia to decrease. The motor will stop accelerating when the armature current is just sufficient to produce the reduced torque required by the load. It follows, therefore, that back e.m.f. in a d.c. motor regulates the flow of armature current i.e., it automatically changes the armature current to meet the Load requirement.

Voltage Equation of a DC Motor

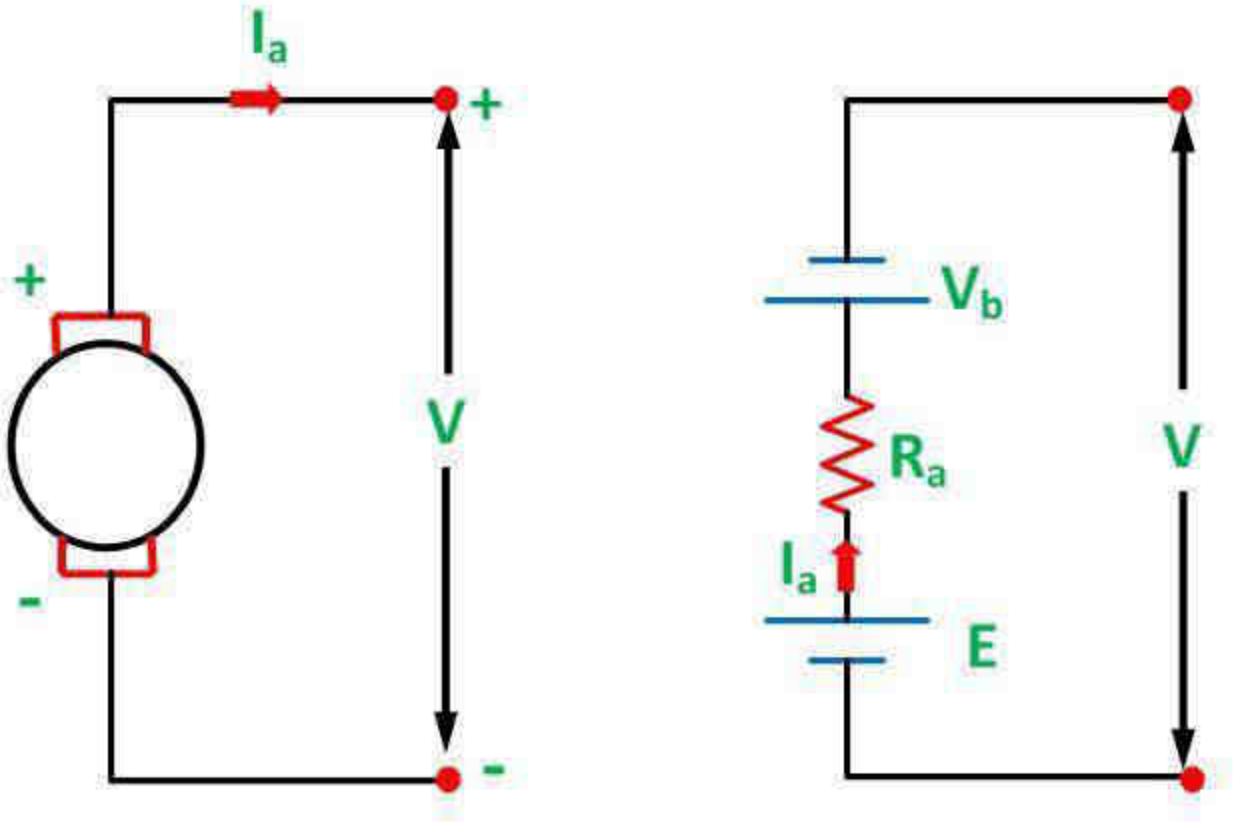


Fig.(1):Equivalent circuit of DC motor

- As shown in fig.(1), the armature supply voltage V has to overcome the opposition posed by the back emf E_b and some other voltage drops such as brush drop and the voltage drop across R_a.
- From fig.(1), we can write that,

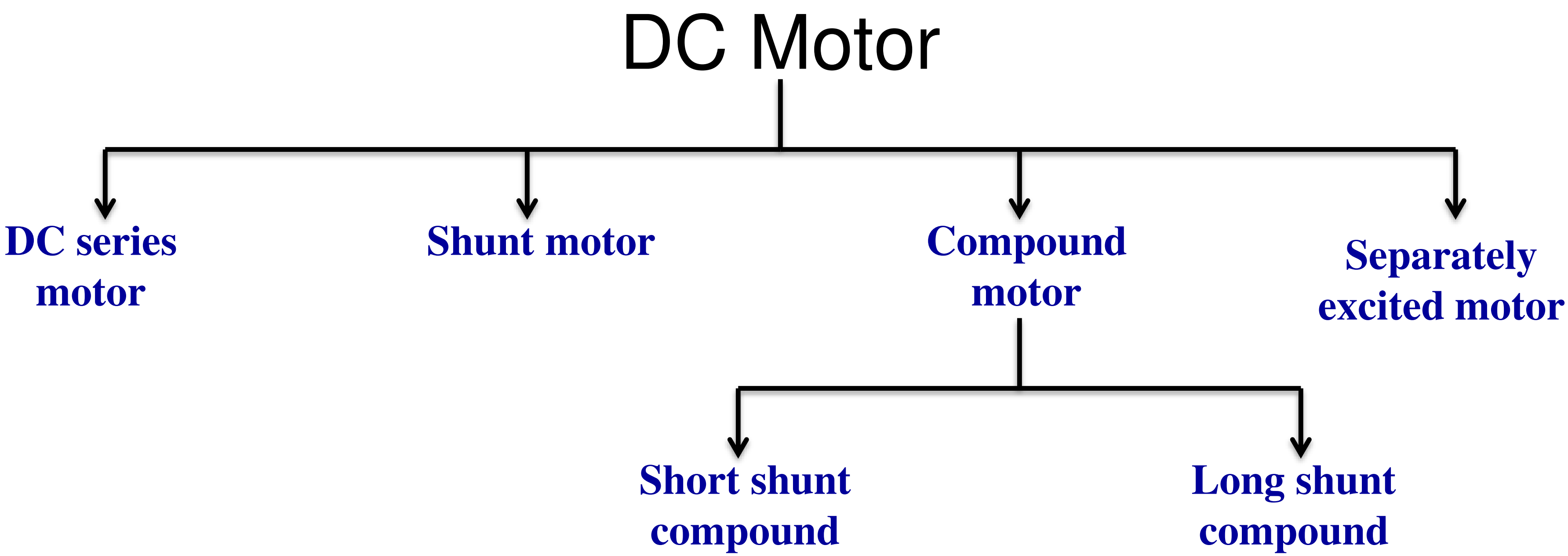
$$V = E_b + I_a R_a + V_b \qquad \text{.......(1)}$$

- But voltage drop across brushes is negligible.

$$\therefore V = E_b + I_a R_a \qquad \text{......(2)}$$

Types of DC Motors

- Depending on the way of connecting the armature and field windings of a d.c. motors are classified as follows:



DC Shunt Motor

- In DC shunt type motor, field and armature winding are connected in parallel as shown in fig.(1), and this combination is connected across a common dc power supply.
- The resistance of shunt field winding (R_{sh}) is always much higher than that of armature winding (R_a).
- This is because the number of turns for the field winding is more than that of armature winding.

- The field current I_{sh} always remains constant. Since V and R_{sh} both are constant. Hence flux produced also remains constant. Because field current is responsible for generation of flux.

$$\therefore \phi \propto I_{sh}$$

- This is why the shunt motor is also called as the constant flux motors.

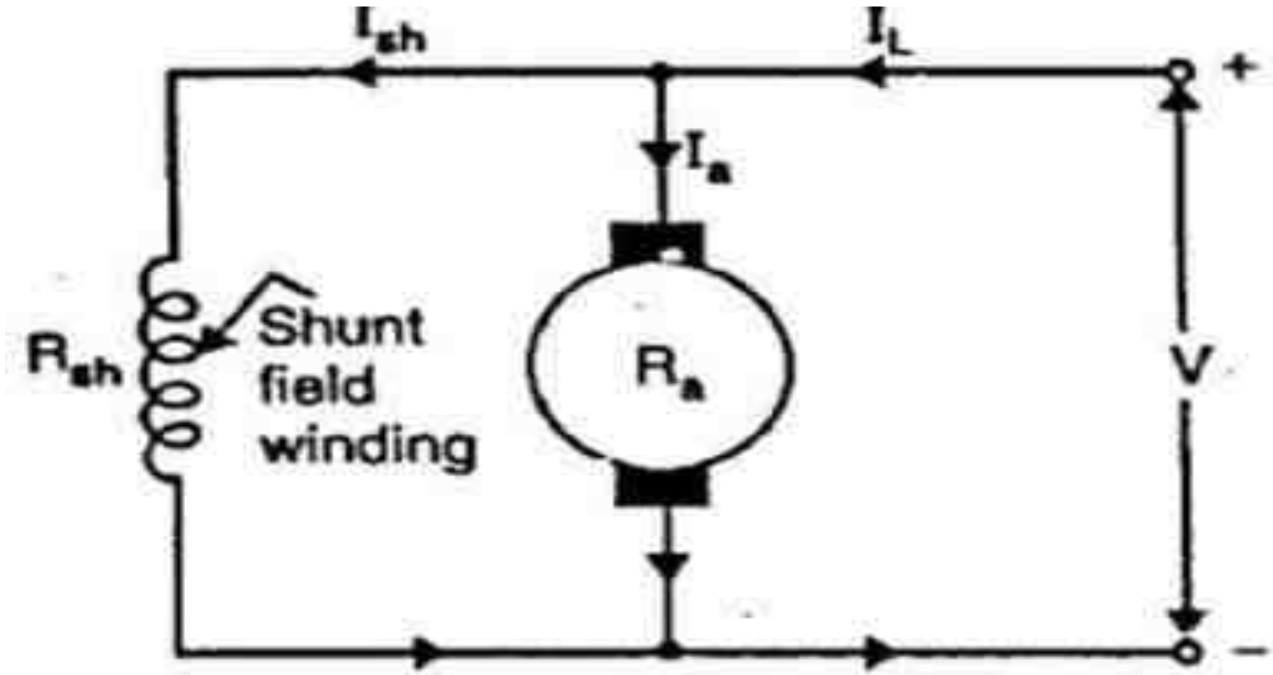


Fig.(1):DC shunt motor schematic diagram

DC Series Motor

- In DC series motor, the armature and field windings are connected din series with each other as shown in fig.(1).
- The resistance of the series field winding (R_s) is much smaller as compared to that of the armature resistance (R_a).
- The flux produced is proportional to the field current. But in series motor, the field current is same as armature current.

$$\therefore \phi \propto I_a \quad \text{or}$$

$$\therefore \phi \propto I_s$$

- The armature current I_a and hence field current Is will be dependent on the load.
- Hence in DC series motor the flux does not remains constant.

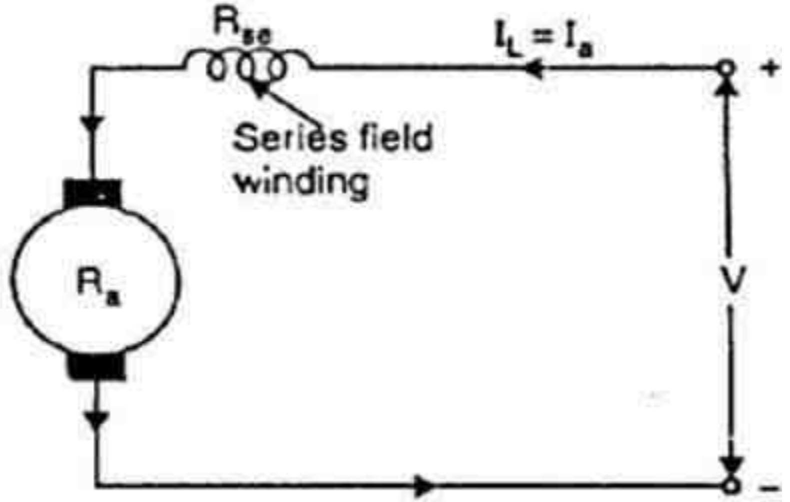


Fig.(1):DC series motor schematic diagram

DC Compound Motor

1. **Long Shunt Compound Motor:**

- As shown in fig.(1), in long shunt dc motor, shunt field winding is connected across the series combination of the armature and series field winding.

2. **Short Shunt Compound Motor:**

- In short shunt compound motor, armature and field windings are connected in parallel with each other and this combination is connected din series with the series filed winding. This is shown in fig.(2).

➢ The long shunt and short shunt compound motors are further classified as **cumulative and differential compound motors**

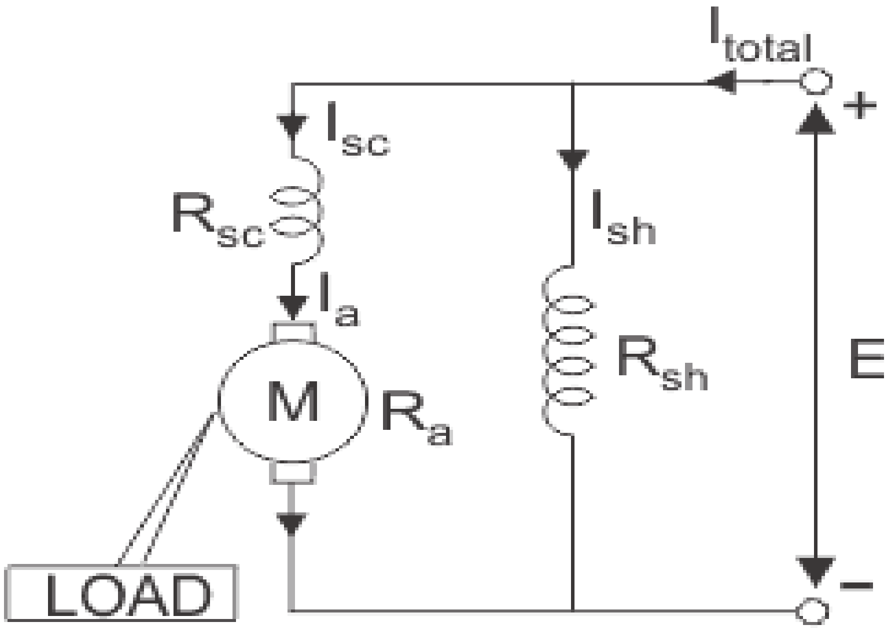


Fig.(1): Long shunt compound dc motor

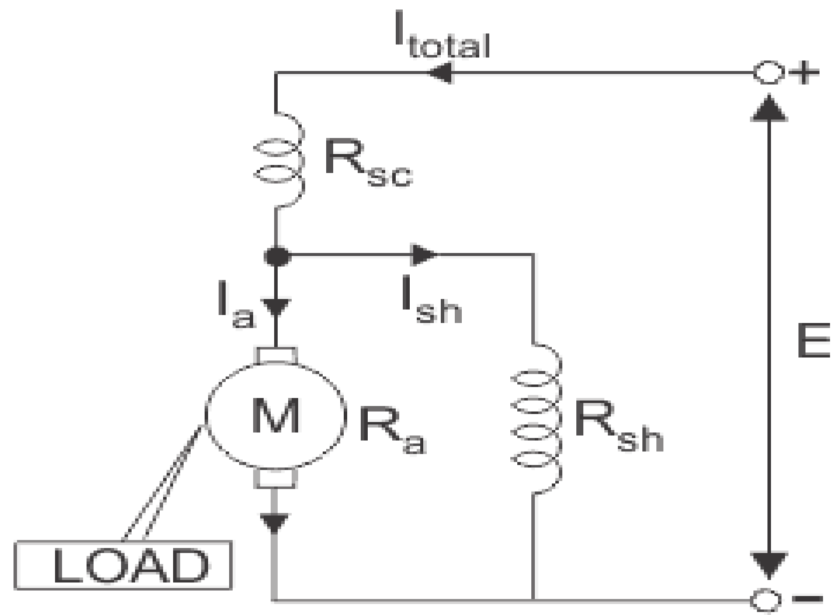


fig.(2):Short shunt compound dc motor

Torque & Speed Equations

- **Torque equations:**

- Torque produced by a motor will always be proportional to the air gap flux ø and the current flowing through the armature winding (I_a).
- That means $T \propto ø\, I_a$
- The flux is produced by the field current hence ø will be proportional to field current. That means,

$$ø \propto I_{field}$$

- hence torque produced by a dc motor is proportional to the product of I_a and I_{field}. That means,

$$T \propto I_a I_{field} \qquad \ldots\ldots\ldots..(1)$$

- For various types of dc motors the expression for field current will be different. We will substitute them into eq.(1) to get the torque equations.

1. **Torque equation of DC shunt motor:**

- For DC shunt motor Ifield = V/ R_{sh} = constant
- Hence the flux ø is constant.

$$\therefore T \propto I_a \qquad \text{........(2)}$$

- Hence in dc shunt motor, torque is proportional to only to the armature current.

2. Torque equation DC series motor:

- For DC series motor, the field current is equal to the armature current i.e. $I_{field} = I_a$.
- Hence $T \propto I_a \, I_a$

$$\therefore T \propto I_a^2 \qquad \text{.........(3)}$$

- Hence in dc series motor, torque is proportional to the square of armature current.

- **Speed Equations:**

➢ We know that the expression for the back emf is,

$$E_b = \frac{NP\varphi Z}{60\,A}$$

➢ But P, Z and 60A a… Therefore we can write that,

$$E_b \propto ø\, N \quad \ldots(4)$$

➢ Therefore the speed can be expressed as,

$$N \propto E_b / ø \qquad \ldots\ldots.(5)$$

$$N = k\, E_b / ø \qquad \ldots\ldots\ldots(6)$$

➢ But $V = E_b + I_a R_a$

$$\therefore E_b = V - I_a R_a \qquad \ldots\ldots\ldots..(7)$$

➢ Substituting eq.(7) into eq.(5) we get,

$$N \propto (V - I_a R_a) / ø \qquad \ldots\ldots.(8)$$

➢ Since $ø \propto I_{field}$, we can write,

$$N \propto (V - I_a R_a) / I_{field} \quad \ldots\ldots.(9)$$

1. DC shunt motor:

- For dc shunt motor, the flux ø is constant.

$$\therefore N \propto (V - I_a R_a) \qquad .....(10)$$

2. DC series motor:

- For dc series motor $I_{field} = I_a$. Therefore

$$N \propto (V - I_a R_a - I_s R_s) / I_a \qquad ....(11)$$

where $E_b = V - I_a R_a - I_s R_s$

Torque-speed characteristics

1. **DC shunt motor:**

- The torque-speed characteristics of dc shunt motor is as shown in fig.(1).
- At no load, the torque produced by the motor is T_{a0} and the motor rotates at the no load speed N_0.
- As the load increased, the torque requirement also increase. To generate the required amount of torque, the motor has to draw more armature current.

- And more armature current can be drawn if the more speed decreases.
- Therefore, as the load increases, torque will also increase and the speed decreases.
- However the reduction in speed is not significant as the load is increased from no load to full load. Therefore practically the dc shunt motor is called as a constant speed motor.

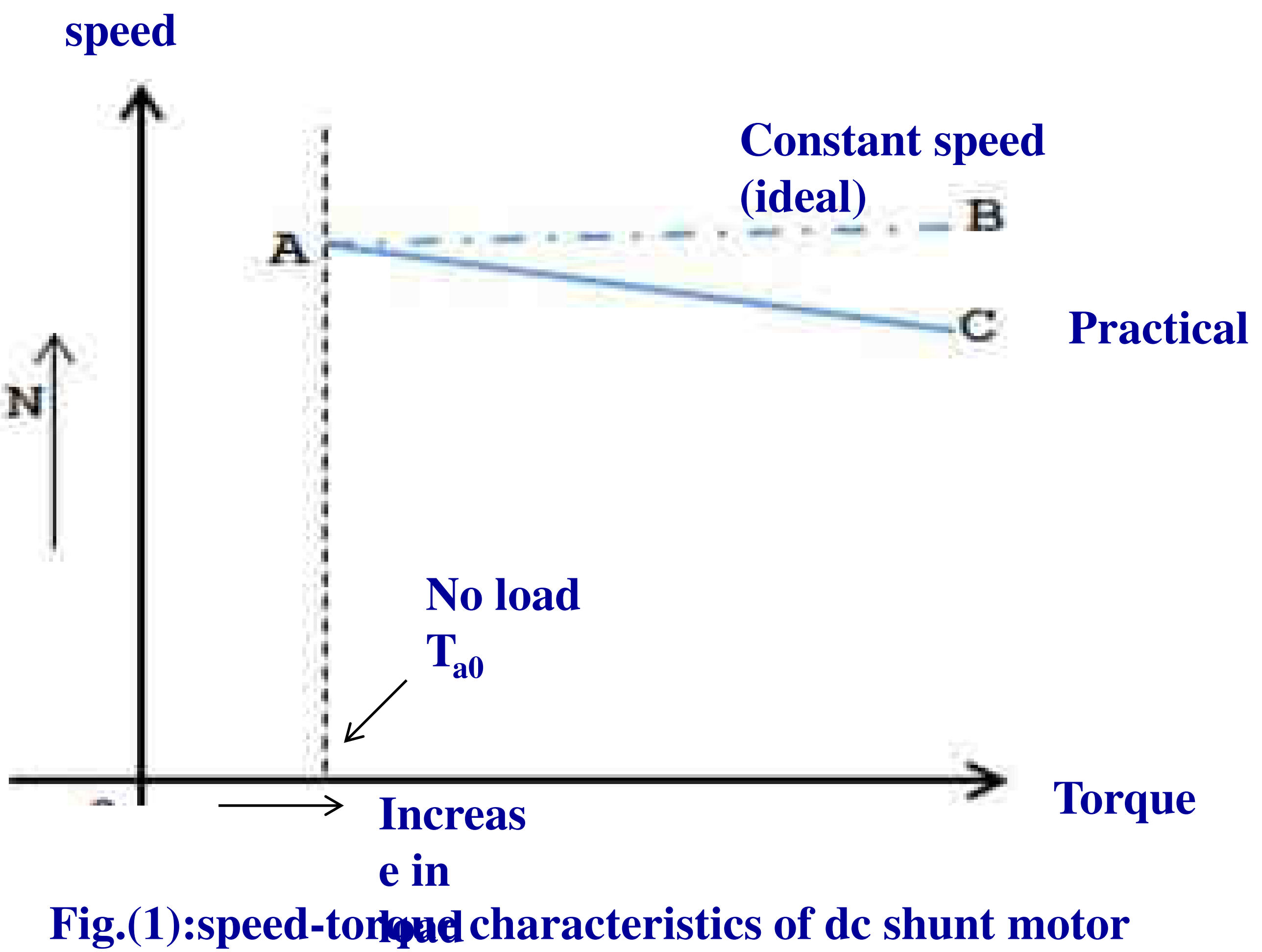


Fig.(1):speed-torque characteristics of dc shunt motor

2. DC series motor:

- The speed –torque characteristics of DC series motor is as shown in fig.(2).
- We know that

$$N \propto 1/ I_a \quad \text{and} \quad T \propto I_a^2$$

$$N \propto 1/\sqrt{T} \quad \text{and} \; I_a \propto \sqrt{T}$$

- This shows that the speed decreases with increase in the value of torque.

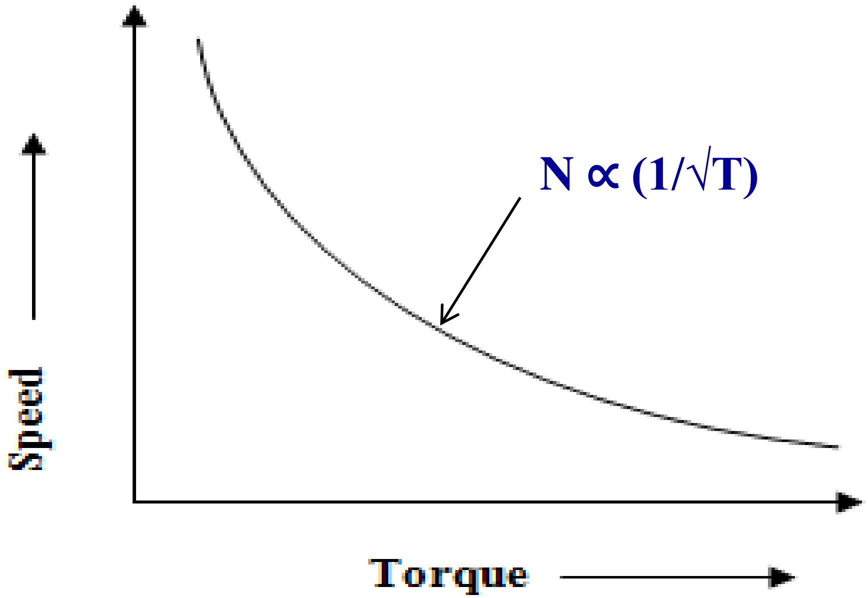


Fig.(2): speed-torque characteristics of dc series motor

3. DC compound motor:

- The torque- speed characteristics of the DC compound motor is as shown in fig.(3).
- It is combination of characteristics of DC series and DC shunt motor.
- The exact shape of these characteristics is dependent on the precise effects of series and shunt field winding.

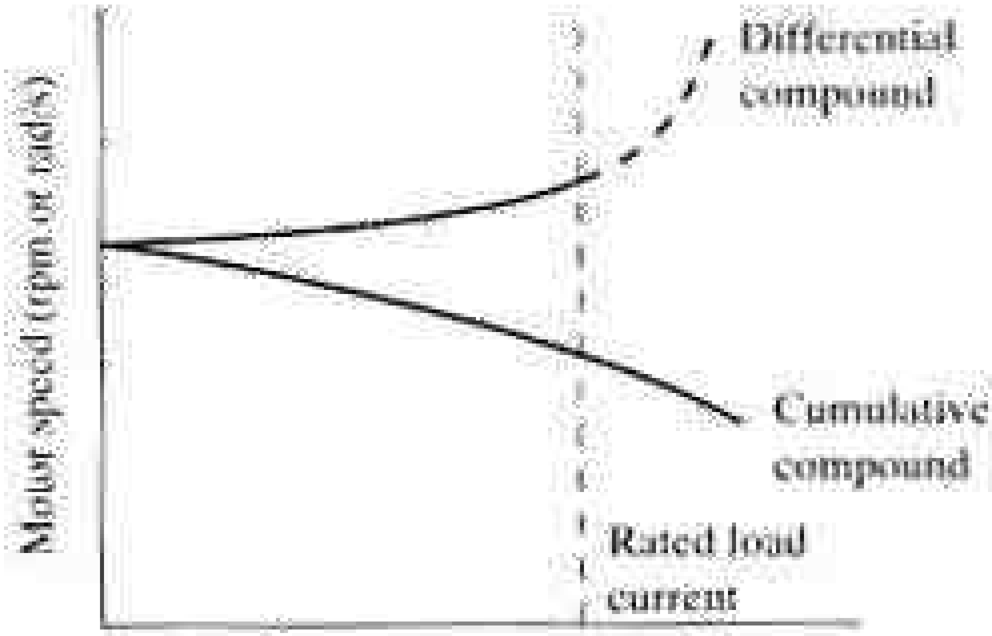


Fig.(3): speed torque characteristics of dc compound motor

Applications of DC Motor

1. Shunt motor applications:

i. Various machine tools such as lathe machines, drilling machines, milling machines etc.

ii. Printing machines

iii. Paper machines

iv. Centrifugal and reciprocating pumps

v. Blowers and fans etc.

2. Series motor applications:

i. Electric trains
ii. Diesel-electric locomotives
iii. Cranes
iv. Hoists
v. Trolley cars and trolley buses
vi. Rapid transit systems
vii. Conveyers etc.

3. Cumulative compound motor applications:

i. Elevators
ii. Rolling mills
iii. Planers
iv. Punches
v. Shears

4. Differentials compound motors applications:

- The speed of these motors will increase with increase in the load, which leads to an unstable operation.
- Therefore we can not use this motor for any practical applications

Specifications of DC Motor

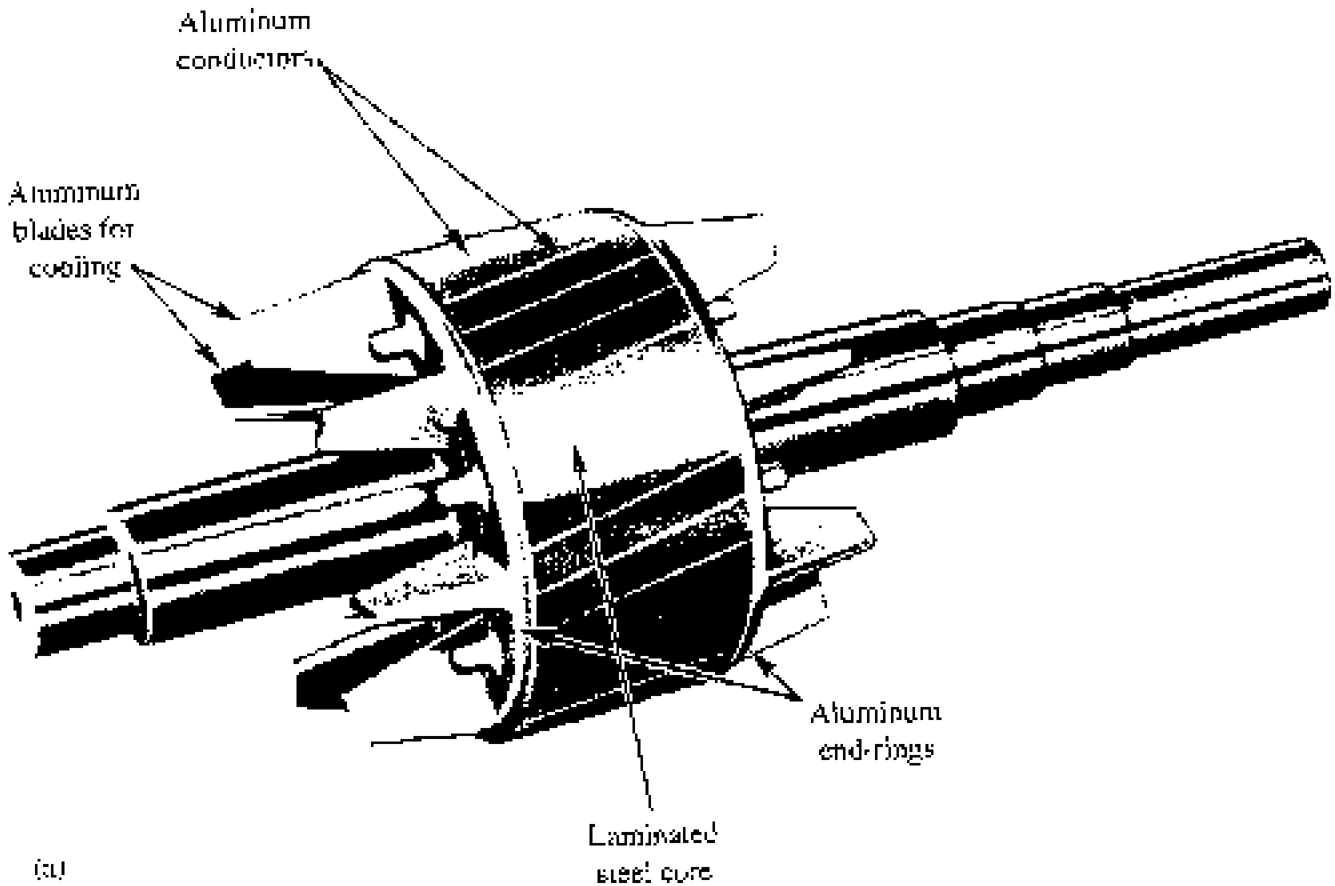
- Some of important specifications of a DC motor:

1. Output power in horse power(H.P.)
2. Rated voltage
3. Type of field winding
4. Excitation voltage
5. Base speed in RPM
6. Current
7. Frame size
8. Rating

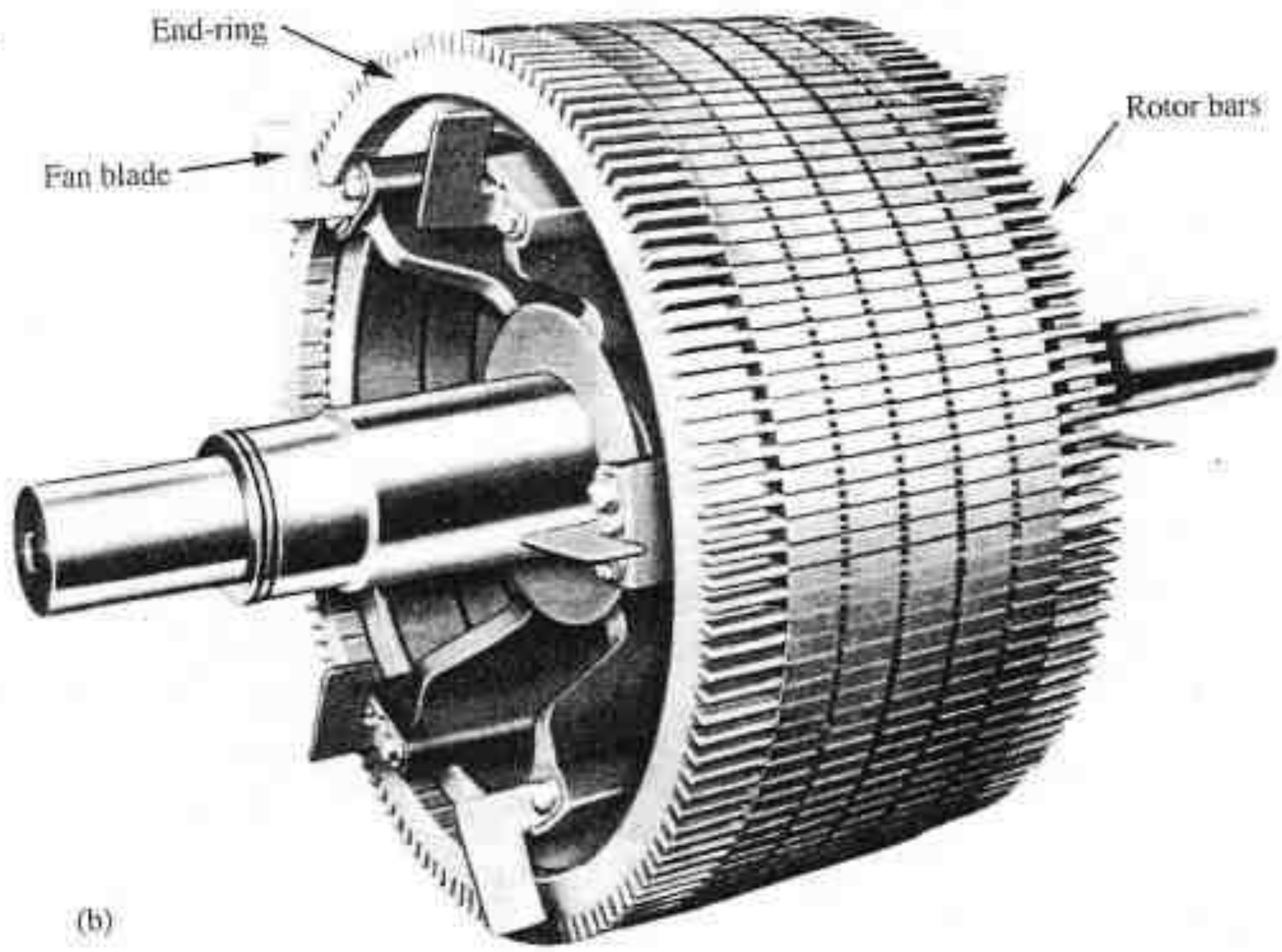
- **Typical specifications of DC series motor:**

Sr. No.	Specifications/Rating	Value
1.	Output power in horse power	3HP
2.	Rated voltage	230V
3.	Type of field winding	Series
4.	Excitation voltage	230V
5.	Insulation	B
6.	Base speed	1000RPM
7.	Current	11Amp
8.	Frame size	132 S
9.	Rating	Continous
10.	S.R.Number	840858

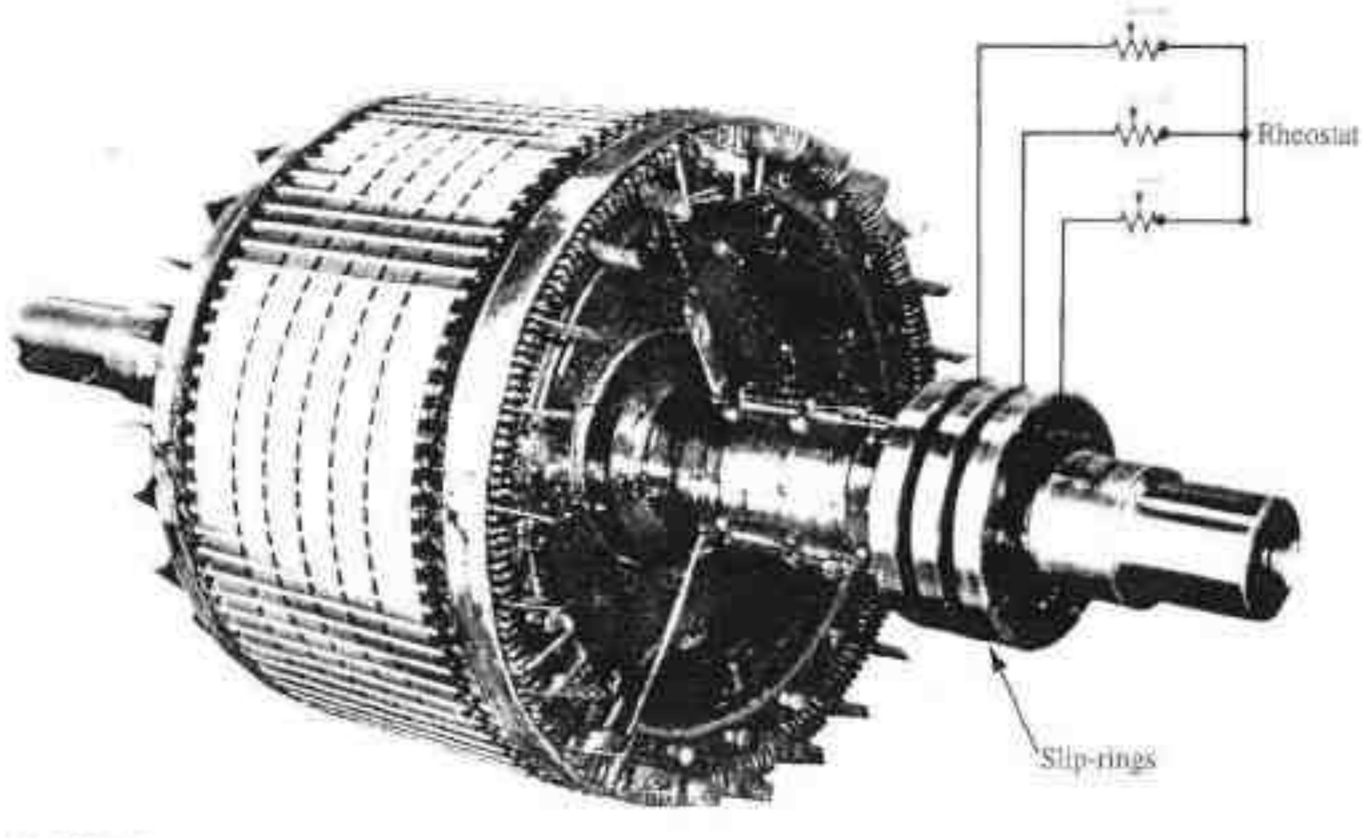
Squirrel-Cage Rotor



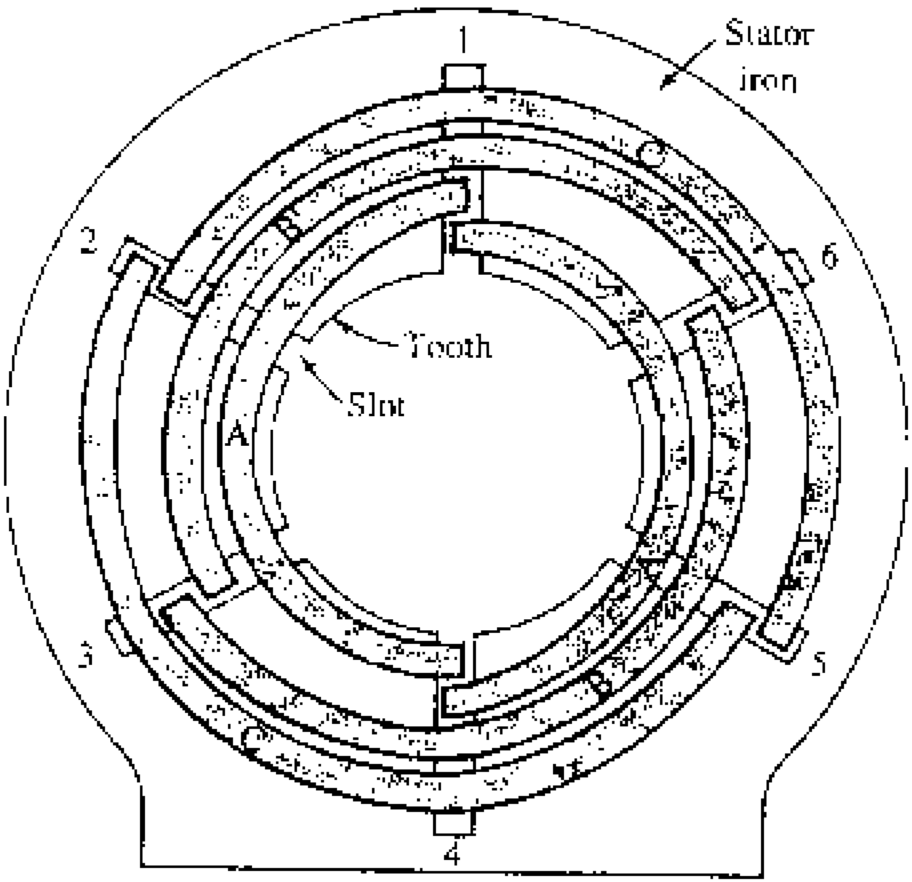
Another Squirrel-Cage Rotor

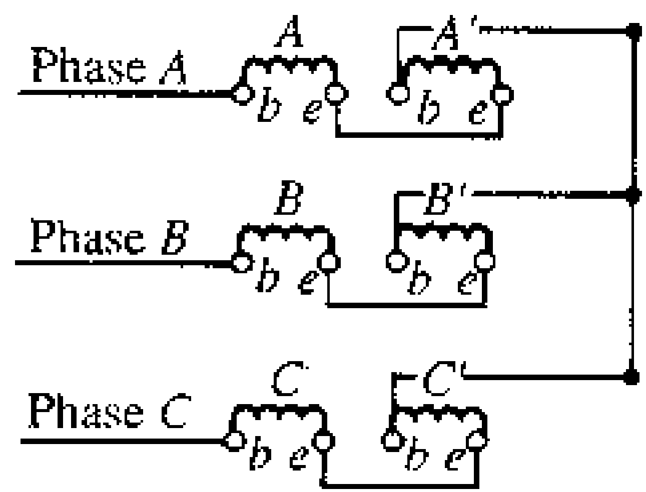


Wound-Rotor



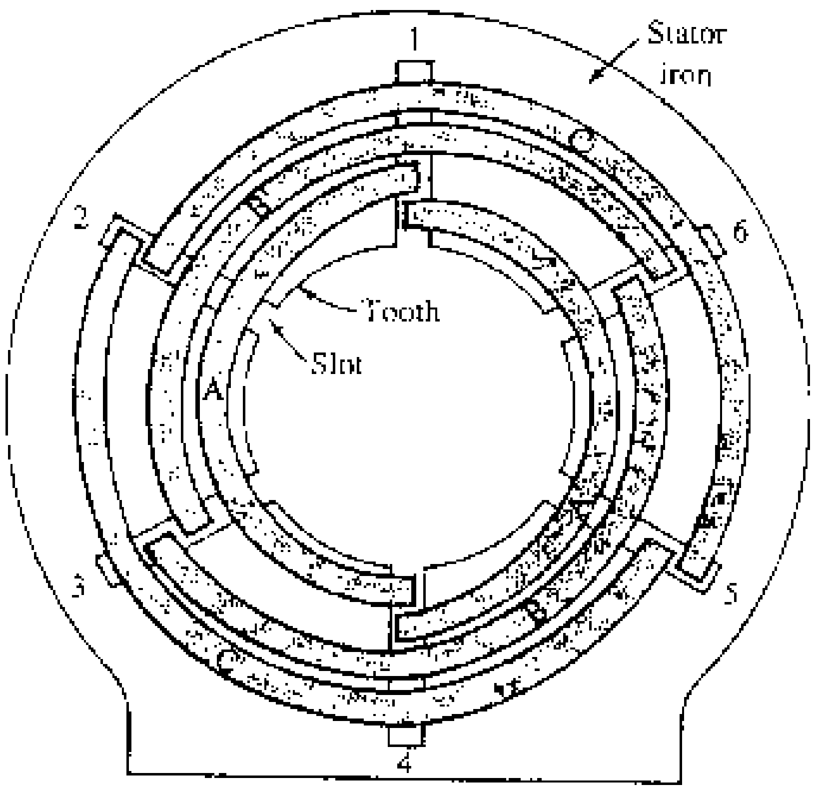
Stator Coils for a 2-pole 3-Φ induction motor

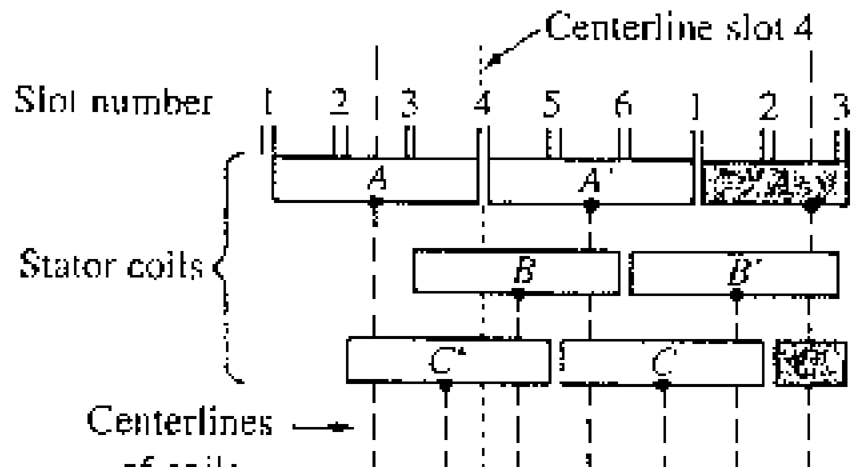




Connection diagram

Stator Coils for a 2-pole 3-Φ induction motor



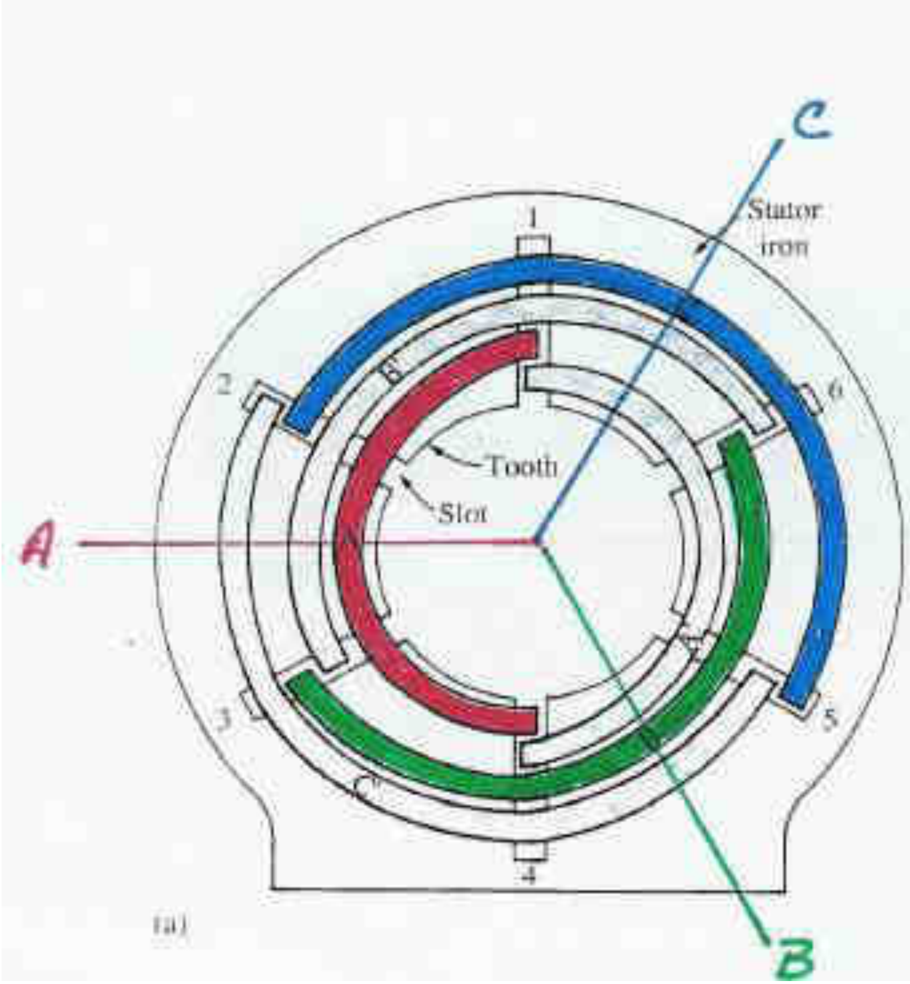


One cycle

θ°	A	C'	B	A'	C	B'	A
0	N	n	s	S	s	n	N
60	n	N	n	s	S	s	n
120	s	n	N	n	s	S	s
180	S	s	n	N	n	s	S
240	s	S	s	n	N	n	s
300	n	s	S	s	n	N	n
360	N	n	s	S	s	n	N

Coil Span and distance between center lines

Coil Span = Stator circumference / # of stator poles
Distance between center lines = 120°/ # of pole pairs



For a 2-pole machine,

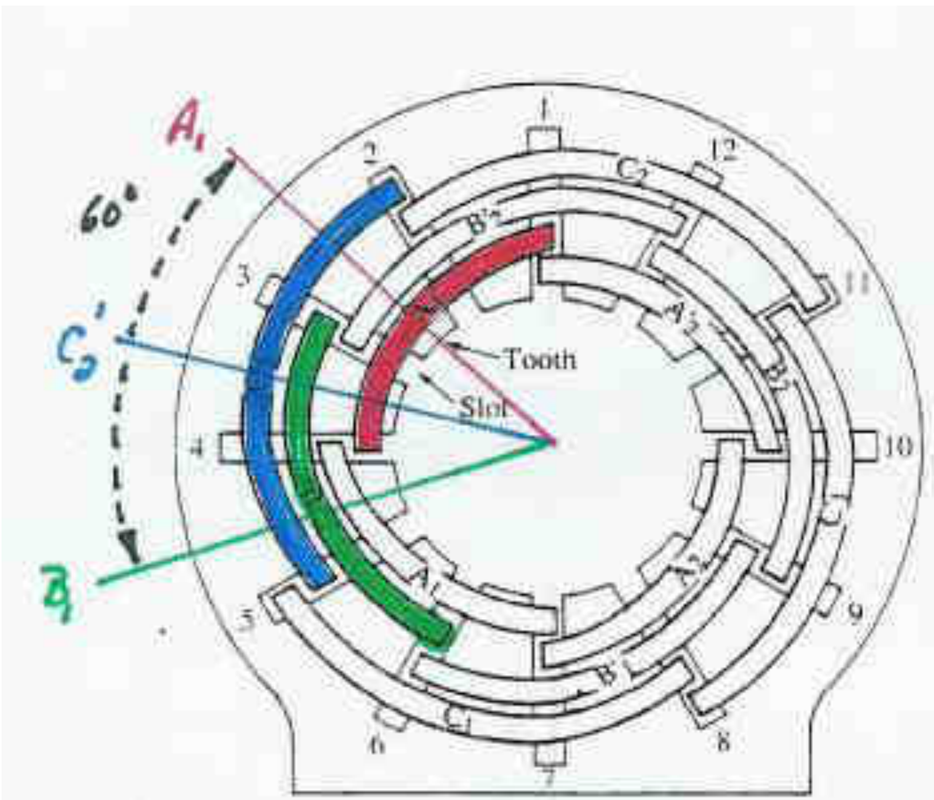
Coil Span = 360°/2 = 180°

Center line distance = 120°

Coil Span and distance between center lines

Coil Span = Stator circumference / # of stator poles

Distance between center lines = 120°/ # of pole pairs



For a 4-pole machine,

Coil Span = 360°/4 = 90°

Center line distance = 60°

Synchronous Speed

- n_s = synchronous speed (r/min)
  - the speed of the rotating magnetic flux
- $n_s = f_s/(P/2)$ (r/s)
  - where
    - f_s = frequency of the 3-Φ supply
    - n_s = synchronous speed
    - P = number of poles formed by the stator winding
- $n_s = 120(f_s)/P$ (r/min)

Slip

- n_s = synchronous speed of the rotating flux
- n_r = speed of the rotor
- slip speed = $n = n_s - n_r$
- slip = $s = (n_s - n_r) / n_s$ = per-unit slip
- % slip = s x 100%
- solving for n_r ,
- $n_r = n_s(1-s)$

Effect of slip on rotor frequency

- frequency of the voltage induced in the rotor, f_r
- $f_r = Pn/120$, where
  - P = the number of stator poles
  - n = the slip speed (r/min)
  - f_r = rotor frequency (Hz) = $P(n_s - n_r)/120$
  - $f_r = P(sn_s)/120 = s(Pn_s/120)$ = proportional to s!

“Blocked rotor” condition (n_r=0)

- $s = (n_s – n_r)/n_s = (n_s - 0)/n_s = 1$

- $f_r = s(Pn_s/120) = Pn_s/120$ = same as source

- $f_r = f_{BR} = f_{stator}$

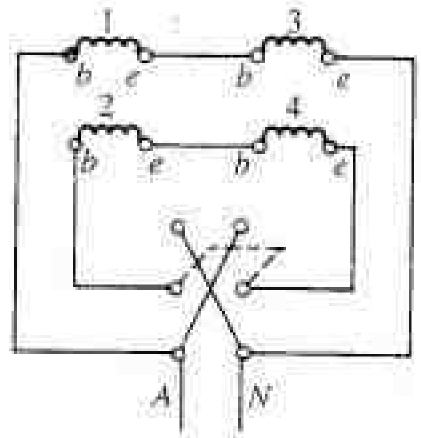
- In general, $f_r = sf_{BR}$

Effect of slip on rotor voltage

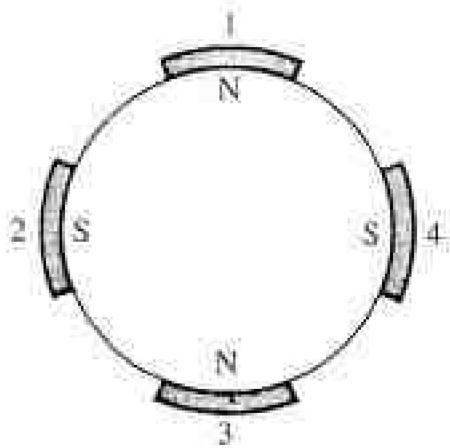
- For a squirrel-cage rotor,
  - –>$E_r = 4.44Nf_r\Phi_{max} = 4.44Nsf_{BR}\Phi_{max}$

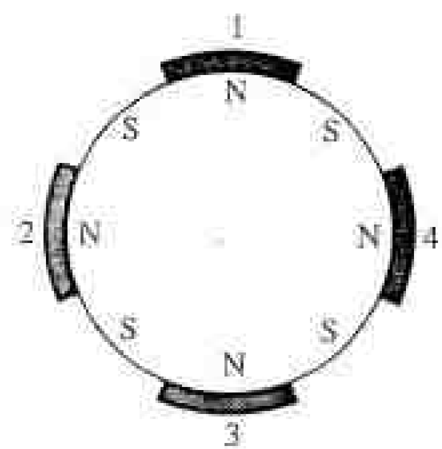
- at blocked rotor, s=1
  - –>$E_{BR} = 4.44Nf_{BR}\Phi_{max} \Rightarrow E_r = sE_{BR}$

Consequent-Pole Motor



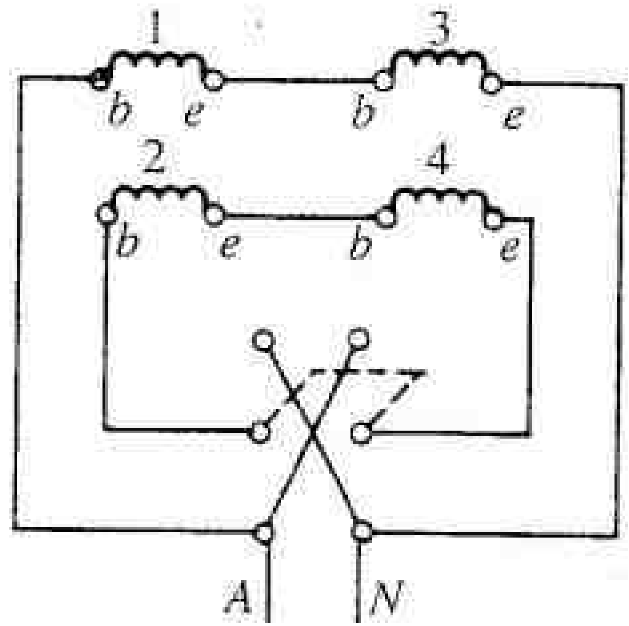
(a)





4-pole machine **8-pole machine**

Winding Connections



Switch "up", coils 1 & 3 have opposite polarity to coils 2 & 4. Looks like a 4-pole machine. (Fast)

Switch "down", all coils have the same polarity. Looks like an 8-pole machine.

SYNCHRONOUS GENERATORS
Summary

1. **Synchronous Generator Construction**
2. **Speed of Rotation of a Synchronous Generator**
3. **Internal Voltage of a Synchronous Generator**
4. **Equivalent Circuit of a Synchronous Generator**
5. **Phasor Diagram of a Synchronous Generator Eq. cct.**
6. **Power and Torque in Synchronous Generator**
7. **Measuring Synchronous Generator Model Parameters**

SYNCHRONOUS GENERATOR CONSTRUCTION

- SYN. GEN. USED to CONVERT MECHANICAL ENERGY TO AC ELECTRIC ENERGY: GENERATORS IN POWER PLANTS
- STEADY STATE OPERATION of SYNCHRONOUS GENERATORS DISCUSSED HERE
- **GENERATOR CONSTRUCTION**

  - in synchronous generator, rotor winding energized by dc source to develop rotor magnetic field

  - rotor is turned by a prime mover, producing a rotating magnetic field which induce 3 phase voltages in stator windings

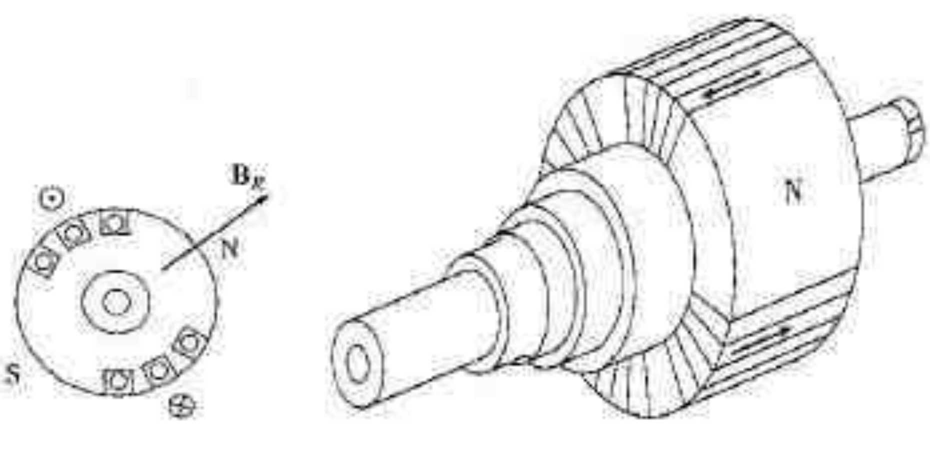
  In general rotor carry the "field windings" , while "armature windings" (or "stator windings") carry the main voltages of machine
- **therefore:**

- rotor windings ≡ field windings
- stator windings ≡ armature windings

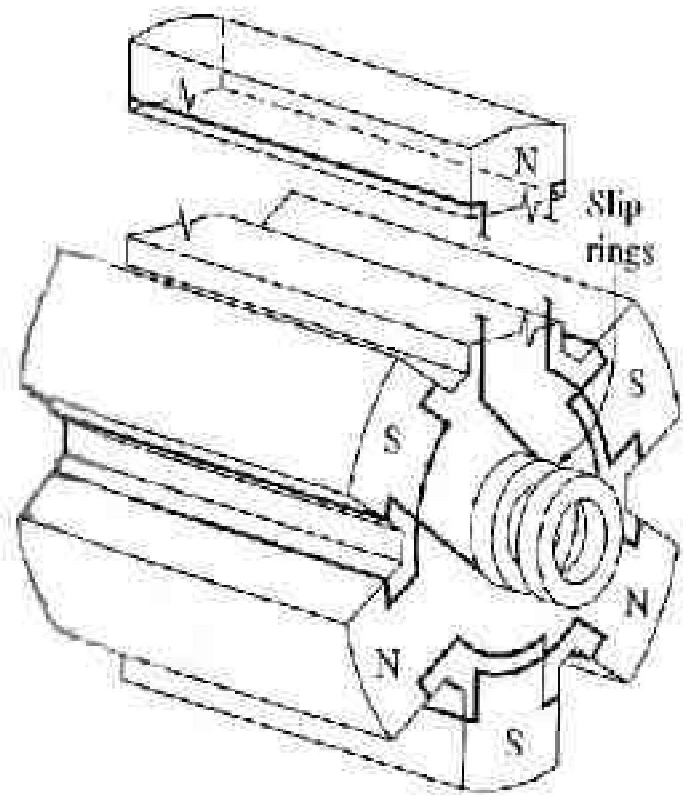
SYNCHRONOUS GENERATOR CONSTRUCTION

- Rotor of synchronous machine can be

Nonsalient: 2 pole rotor **Salient:** six-pole rotor

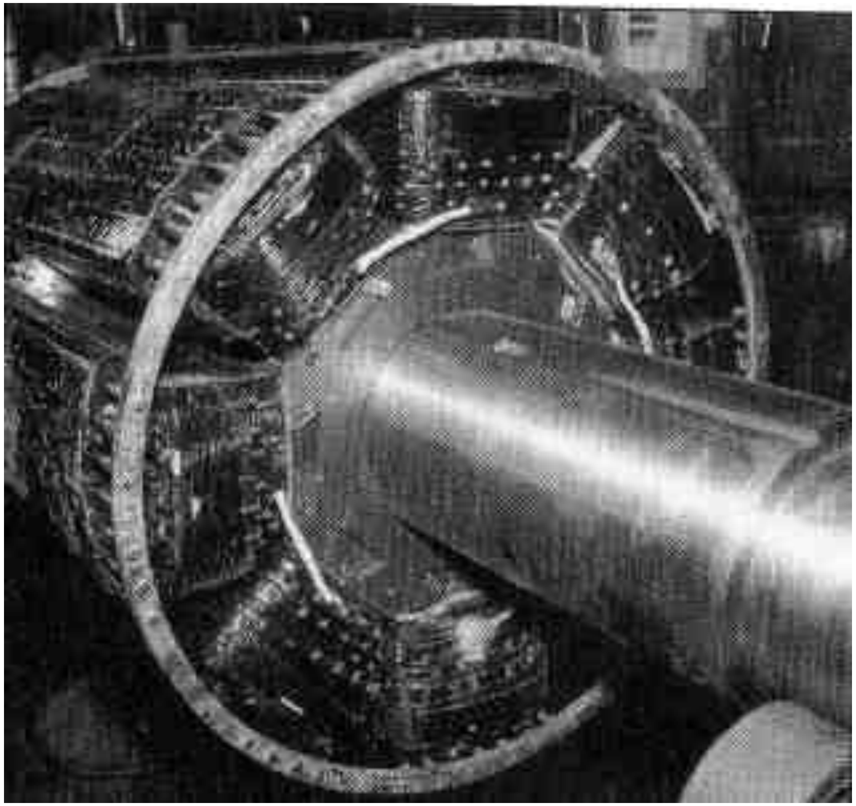


Side View



SYNCHRONOUS GENERATOR CONSTRUCTION

- Photograph of a salient 8-pole synchronous machine rotor



SYNCHRONOUS GENERATOR CONSTRUCTION

- **Rotor** experience varying magnetic fields, therefore is constructed of thin laminations to reduce eddy current losses
- To supply the rotor winding while it is rotating, special arrangement employed to connect its terminal to dc supply

1. supply dc power from an external dc source to rotor by means of slip rings
2. supply dc power from a special dc power source mounted on shaft of rotor

SYNCHRONOUS GENERATOR CONSTRUCTION

- **SLIP RINGS**: are metal rings encircling shaft and are insulated from it
  - one end of rotor winding is connected to each of the 2 slip rings
  - and a stationary brush mounted on the machine casing ride on each slip ring
- **Brush:** a block of graphite like carbon compound that conducts and has low friction
- same dc voltage is applied to field winding during rotation

SYNCHRONOUS GENERATOR CONSTRUCTION

- Problems associated with slip rings and brushes:

  1- increase the required maintenance (brushes should be examined for wear regularly)

  2- brush voltage drop results in significant power losses if field current is high

- Despite of above problems, SLIP RINGS & BRUSHES used for smaller synchronous machines since is cost-effective

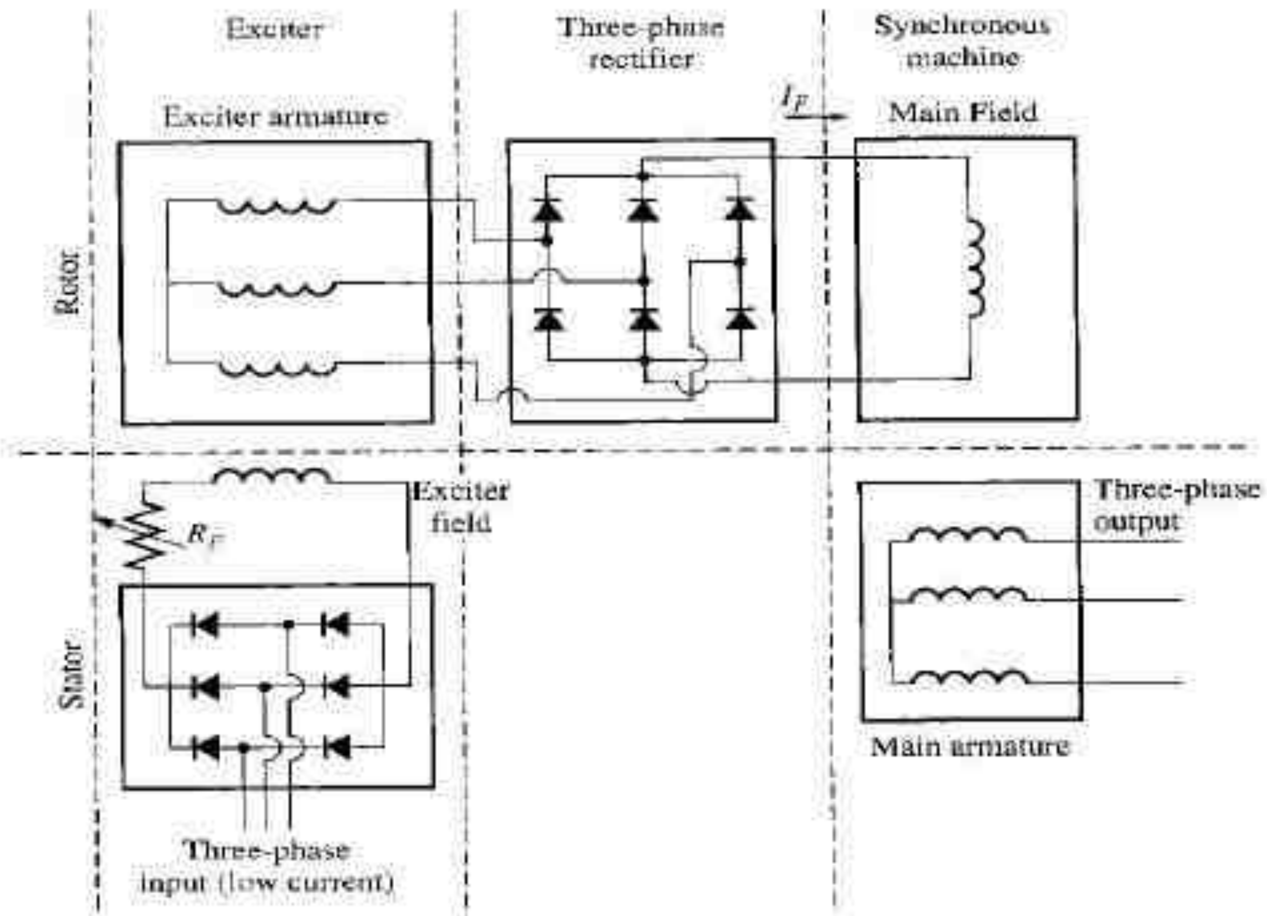
SYNCHRONOUS GENERATOR CONSTRUCTION

- on larger generator & motors, brushless exciters are used
- **Brushless Exciter:** is a smaller ac generator with its field circuit mounted on stator & its armature circuit mounted on rotor shaft

  - 3 phase output of exciter generator rectified by a 3 phase rectifier mounted also on shaft
- By controlling small dc field current of exciter generator, it is possible to fed (and also adjust) field current of main machine without slip rings and brushes

SYNCHRONOUS GENERATOR CONSTRUCTION

- Schematic arrangement of a brushless exciter



SYNCHRONOUS GENERATOR CONSTRUCTION

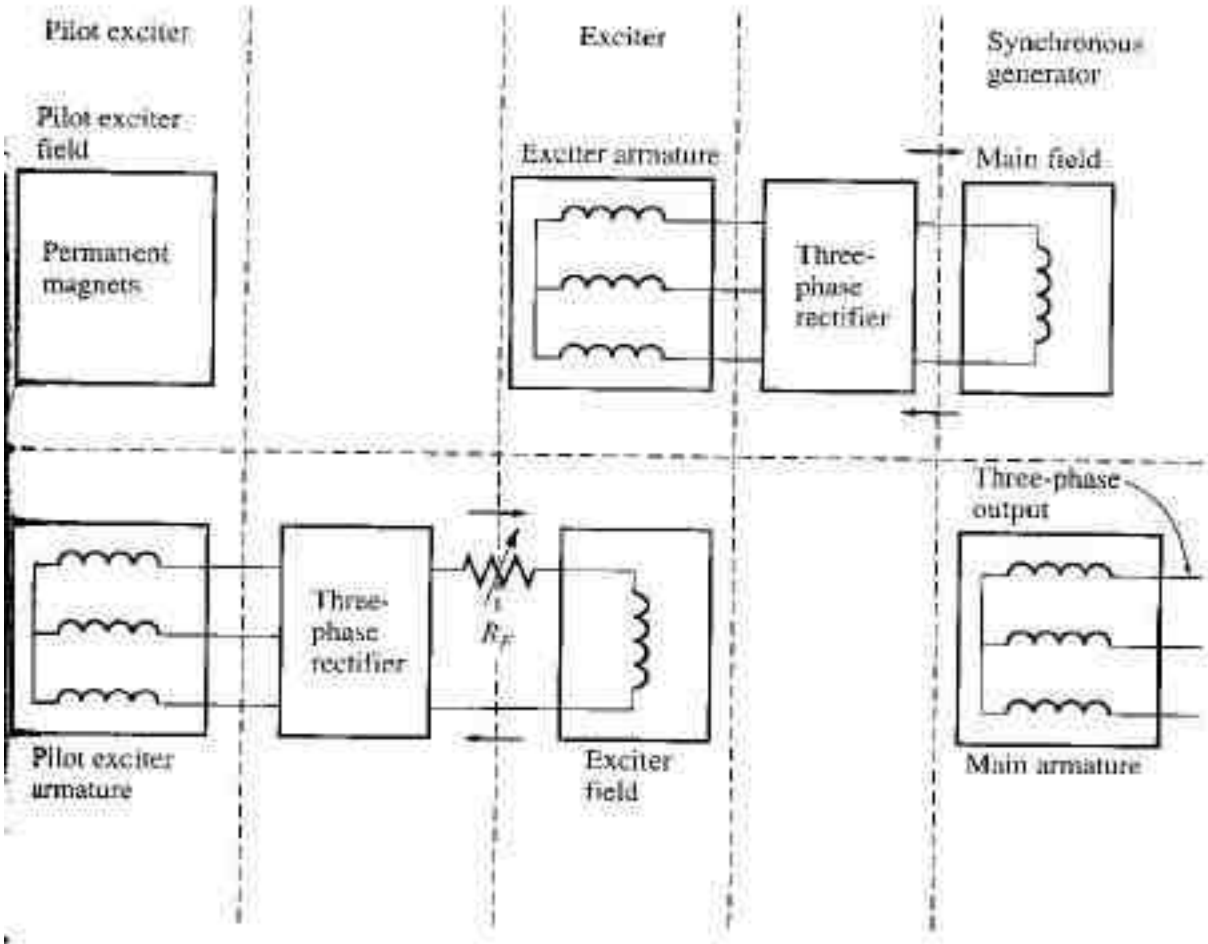
- Photograph of a synchronous machine with brushless exciter

SYNCHRONOUS GENERATOR CONSTRUCTION

- a small pilot exciter often included in system to have the excitation of generator independent of any external power sources
- A pilot exciter is a small ac generator with permanent magnets mounted on rotor shaft & a 3 phase winding on stator
- It produces power for field circuit of exciter, which in turn controls the field circuit of main machine
- With pilot exciter on shaft of generator, no external electric power is required to run generator
- Many Syn. Gen.s with brushless exciters also have slip rings and brushes, as an auxiliary source of dc field in emergencies

SYNCHRONOUS GENERATOR CONSTRUCTION

- Brushless exciter including a pilot exciter



SYNCHRONOUS GENERATOR

Speed of rotation of synchronous generator

- synchronous generators are *synchronous, during their operation*

means: electrical frequency is synchronized with mechanical speed of rotor

- Relation between electrical frequency of stator and mechanical speed of rotor as shown before: $f_e = n_m \, p / 120$

f_e : electrical frequency in Hz

n_m: speed of rotor in r/min

p: number of poles

SYNCHRONOUS GENERATOR

Speed of rotation of synchronous generator

- Electric power generated at 50 or 60 Hz, so rotor must turn at fixed speed depending on number of poles on machine
- To generate 60 Hz in 2 pole machine, rotor must turn at 3600 r/min, and to generate 50 Hz in 4 pole machine, rotor must turn at 1500 r/min
- **INTERNAL GENERATED VOLTAGE OF A SYNCHRONOUS GENERATOR**
- magnitude of induced voltage in one phase determined in last section: $E_A = \sqrt{2}\,\pi\, N_C\, \varphi\, f$

SYNCHRONOUS GENERATOR

INTERNAL GENERATED VOLTAGE

- Induced voltage depends on flux φ, frequency or speed of rotation f, & machine's construction
- Last equation can be rewritten as:

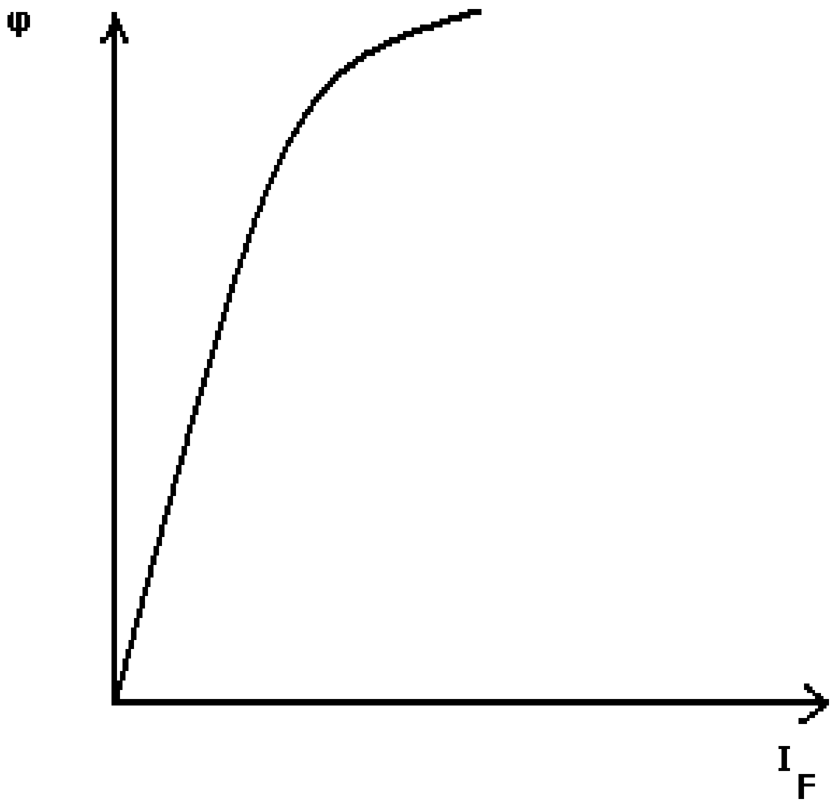
  $E_A = K \varphi \omega$

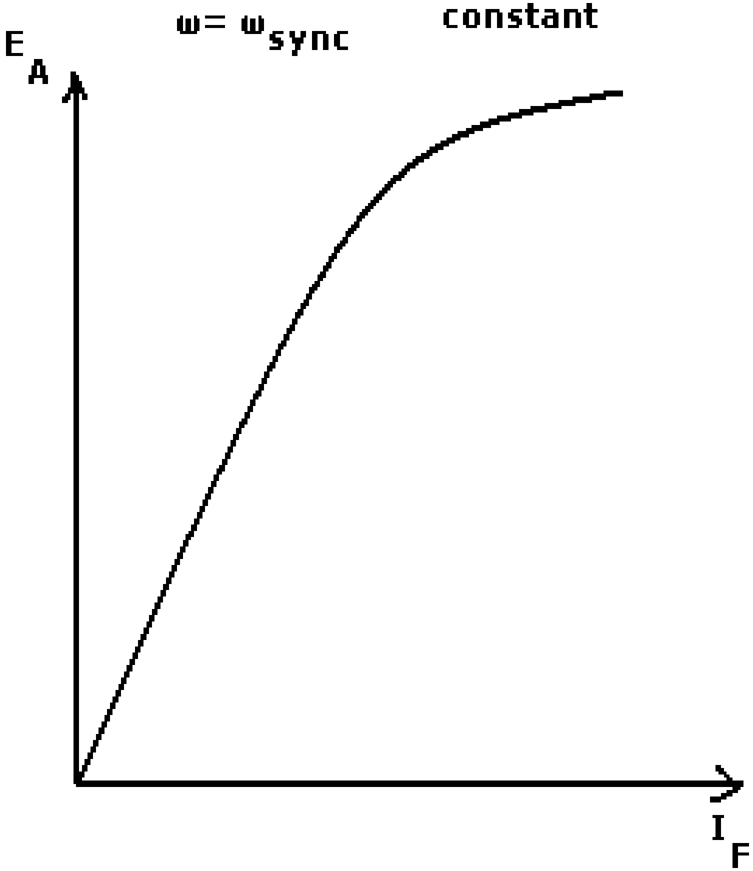
  $K = N_C/\sqrt{2}$ (if $\omega = \omega_e$)

  $K = N_C\, p/\sqrt{2}$ (if $\omega = \omega_m$)
- Note: E_A proportional to flux & speed, while flux depend on current in rotor winding I_F , therefore E_A is related to I_F & its plot named: magnetization curve, or O/C characteristic

SYNCHRONOUS GENERATOR INTERNAL GENERATED VOLTAGE

- Plots of flux vs I_F and magnetization curve





SYNCHRONOUS GENERATOR EQUIVALENT CIRCUIT

- To develop a relation for V_φ as terminal voltage of generator which is different from internal voltage E_A equivalent circuit is needed
- Reasons for V_φ to be different from E_A

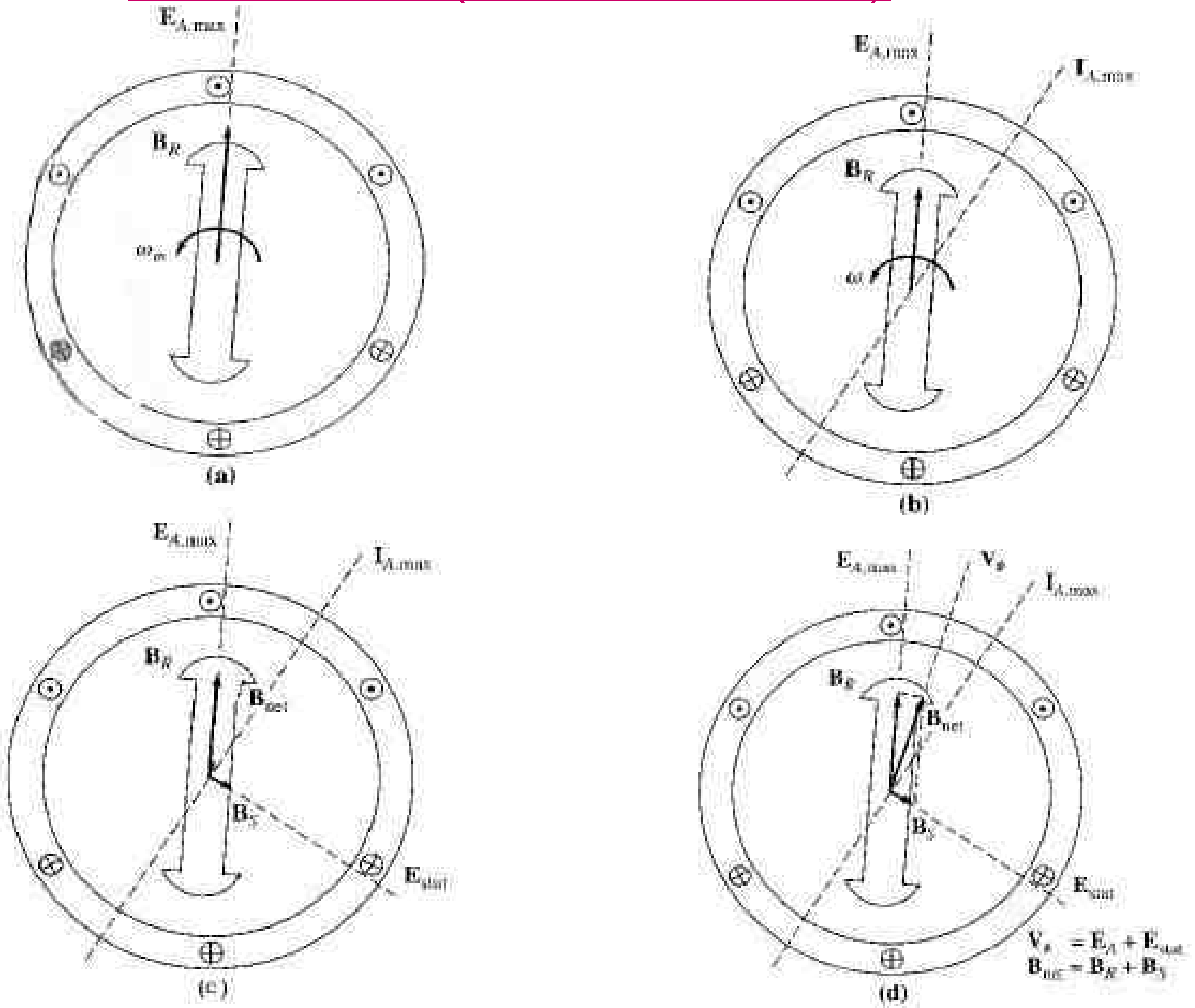
1- distortion of air-gap magnetic field magnetic field due to current flowing in stator, called *armature reaction*

2- self-inductance of armature coils

3- resistance of armature coils

4- effect of salient-pole rotor shapes (ignored as machines have cylindrical rotors)

SYNCHRONOUS GENERATOR EQ. CCT. (ARM. REAC.)



SYNCHRONOUS GENERATOR EQ. CCT. (ARM. REAC)…

- Last figure shows a 2 pole rotor spinning inside a 3 phase stator, without load
- Rotor magnetic field B_R develop a voltage E_A as discussed in last chapter voltage is positive out of conductors, at top, and negative into the conductors at bottom of figure
- When there is no load on generator, armature current zero, $E_A = V_\varphi$
- If generator be connected to a lagging load, peak current occur at an angle behind peak voltage as in fig (b)

SYNCHRONOUS GENERATOR EQ. CCT. (ARM. REAC)…

- Current flowing in stator windings produces its magnetic field
- Stator magnetic field named B_S & its direction found by R.H.R. as shown in fig(c) this B_S produces another voltage in stator, named E_{stat} and shown in figure
- Having these 2 voltage components in stator windings, total voltage in one phase is sum of E_A and E_{stat} :

$V_\varphi = E_A + E_{stat}$ and $B_{net} = B_R + B_S$

angle of B_{net} coincide with angle of V_φ shown in fig (d)

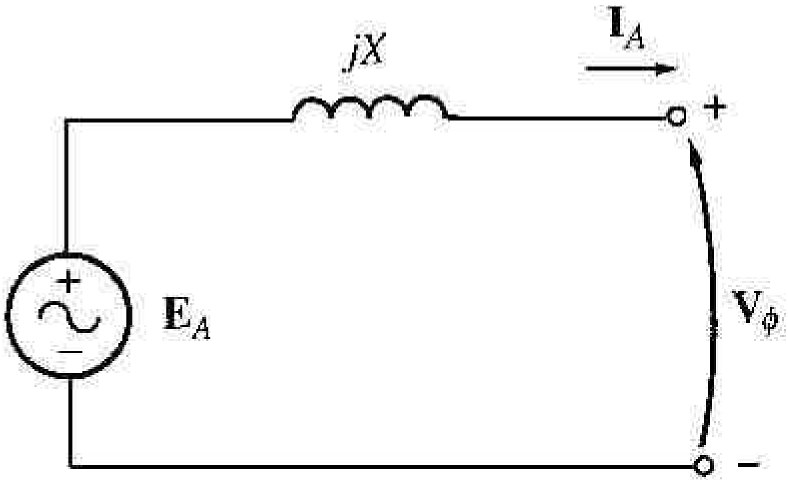
SYNCHRONOUS GENERATOR EQ. CCT. (ARM. REAC)…

- To model effect of armature reaction, note:
  1- E_{stat} lies at an angle of 90° behind plane of maximum current I_A
  2- E_{stat} directly proportional to I_A and X is constant of proportionality

➔ $E_{stat} = -j X I_A$

➔ voltage in one phase $V_\varphi = E_A - j X I_A$

- Following eq. cct. can be developed



SYNCHRONOUS GENERATOR EQ. CCT. (ARM. REAC)…

- Armature reaction voltage can be modeled as an inductor in series with internal induced voltage
- In addition to armature reaction, stator coils have a self-inductance and a resistance
- stator self-inductance named L_A (its reactance X_A) and stator resistance is R_A :

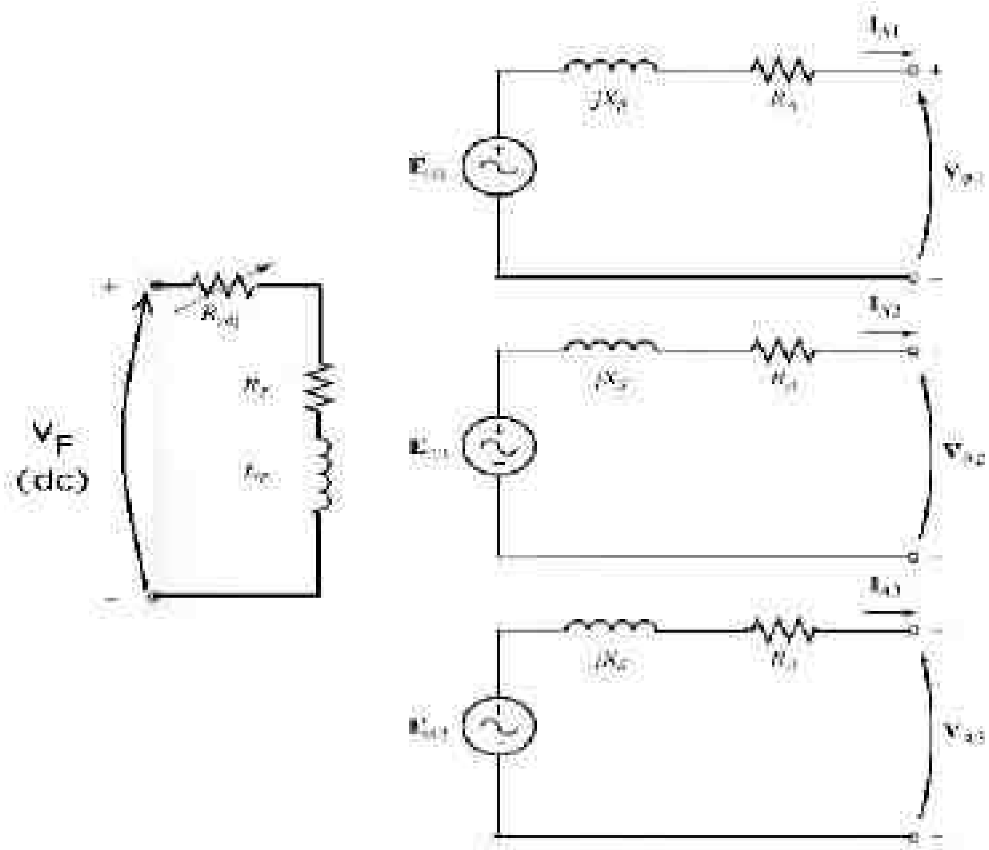
$$V_\varphi = E_A - jXI_A - jX_AI_A - R_AI_A$$

- Armature reaction & self-inductance in machine both represented by reactance, normally they are combined to a single reactance as : $X_S = X + X_A$

$$V_\varphi = E_A - jX_S I_A - R_AI_A$$

SYNCHRONOUS GENERATOR EQ. CCT. (ARM. REAC)…

- equivalent circuit of a 3 phase synchronous generator can be shown as follows:

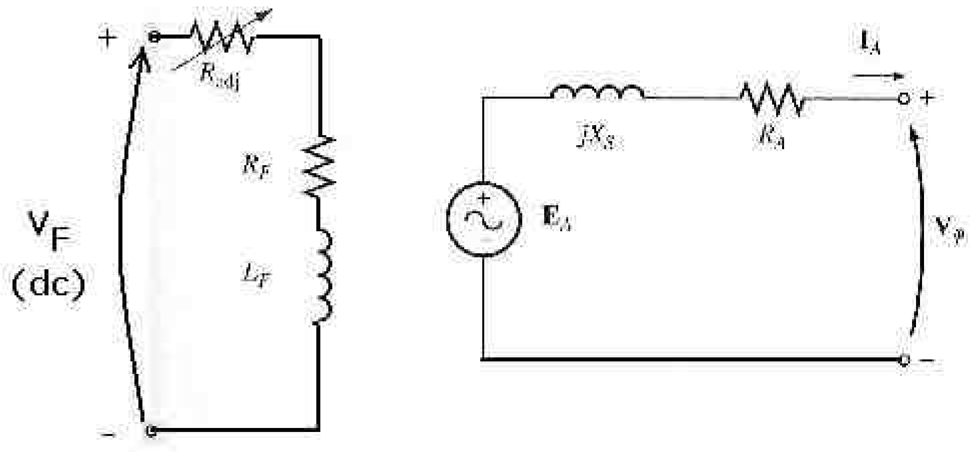


SYNCHRONOUS GENERATOR EQ. CCT. ...

- Figure shows a dc source, supplying rotor winding, modeled by coil inductance & resistance in series with an adjustable resistor R_{adj} that controls current
- Rest of equivalent circuit consists of model for each phase
- the voltages and currents of each phase are 120° apart with same magnitude
- Three phases can be connected in Y or Δ
- If connected in Y : $V_T = \sqrt{3}\ V_\varphi$
- If connected in Δ: $V_T = V_\varphi$

SYNCHRONOUS GENERATOR EQ. CCT…

- The per phase equivalent circuit is shown below



- can be employed when loads of 3 phase are balanced

Battery Overview

Steve Garland
Kyle Jamieson

Outline

- Why is this important?
- Brief history of batteries
- Basic chemistry
- Battery types and characteristics
- Case study: ThinkPad battery technology

Motivation

- To exploit properties of batteries in low-power designs
  - Protocols (Span , MAC layer)
  - Hardware (Cricket)
  - Example: *n* cells; discharge from each cell, round-robin fashion [Chiasserini and Rao, INFOCOM 2000]

Battery (Ancient) History

1800	Voltaic pile: silver zinc
1836	Daniell cell: copper zinc
1859	Planté: rechargeable lead-acid cell
1868	Leclanché: carbon zinc wet cell
1888	Gassner: carbon zinc dry cell
1898	Commercial flashlight, D cell
1899	Junger: nickel cadmium cell

Battery History

1946	Neumann: sealed NiCd
1960s	Alkaline, rechargeable NiCd
1970s	Lithium, sealed lead acid
1990	Nickel metal hydride (NiMH)
1991	Lithium ion
1992	Rechargeable alkaline
1999	Lithium ion polymer

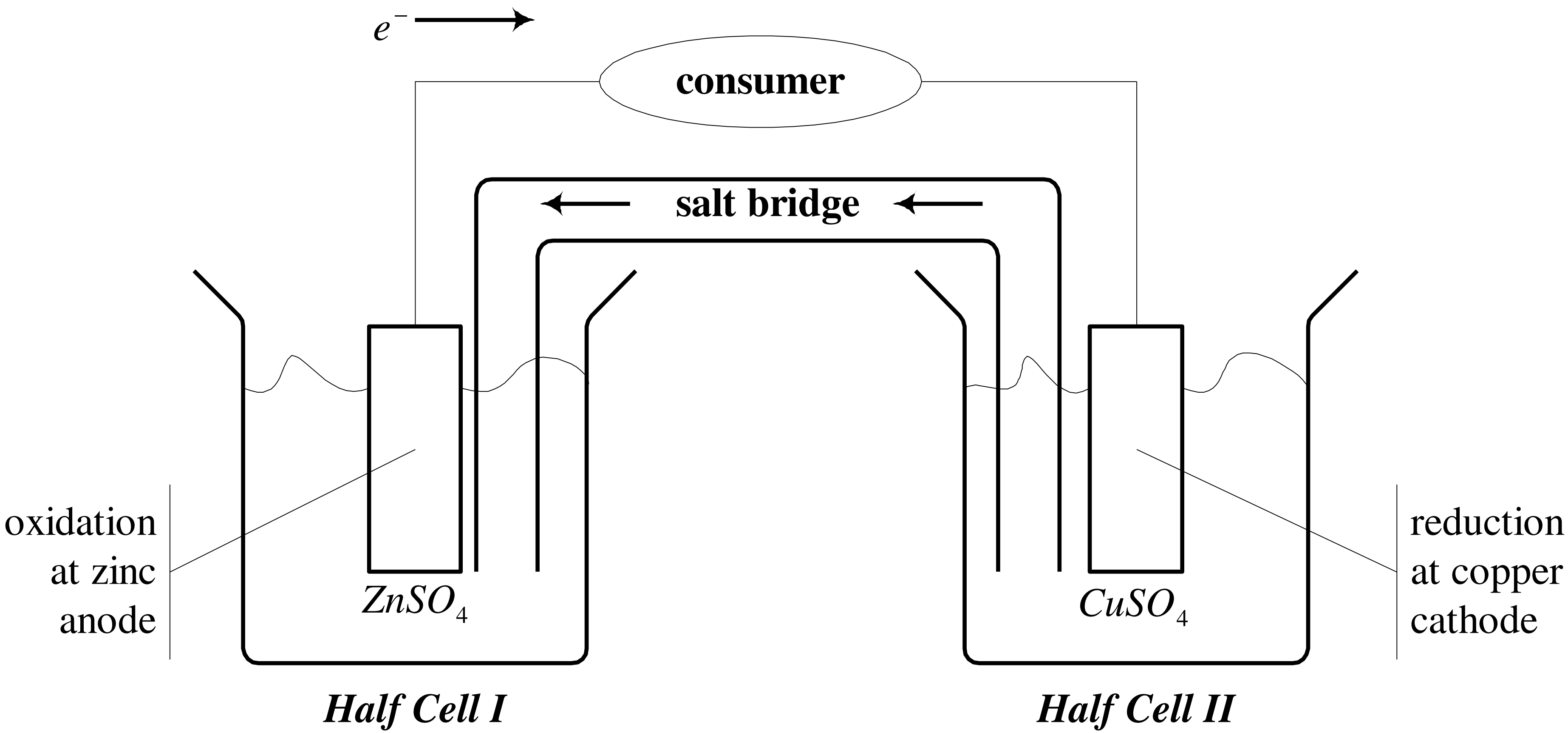
Battery Nomenclature

Duracell batteries | **9v battery** | **6v dry cell**

Two cells | **A real battery** | **Another battery**

More precisely

The Electrochemical Cell



The Electrochemical Cell (2)

- Zinc is (much) more easily oxidized than Copper

$$Zn \longrightarrow Zn^{2+} + 2e^{-} \quad (I.)$$

$$Cu^{2+} + 2e^{-} \longrightarrow Cu \quad (II.)$$

- Maintain equilibrium electron densities
    - Add copper ions in solution to Half Cell II
- Salt bridge only carries negative ions
    - – This is the limiting factor for current flow
    - – Pick a low-resistance bridge

The Electrochemical Series

Most wants to reduce (gain electrons)

- Gold
- Mercury
- Silver
- Copper
- Lead
- Nickel
- Cadmium

But, there's a reason it's a *sodium* drop

- Iron
- Zinc
- Aluminum
- Magnesium
- Sodium
- Potassium
- ***Lithium***

Most wants to oxidize (lose electrons)

Battery Characteristics

- Size
  - Physical: button, AAA, AA, C, D, ...
  - Energy density (watts per kg or cm^3)
- Longevity
  - Capacity (Ah, for drain of C/10 at 20°C)
  - Number of recharge cycles
- Discharge characteristics (voltage drop)

Further Characteristics

- Cost
- Behavioral factors
  - Temperature range (storage, operation)
  - Self discharge
  - Memory effect
- Environmental factors
  - Leakage, gassing, toxicity
  - Shock resistance

Primary (Disposable) Batteries

- Zinc carbon (flashlights, toys)
- Heavy duty zinc chloride (radios, recorders)
- Alkaline (all of the above)
- Lithium (photoflash)
- Silver, mercury oxide (hearing aid, watches)
- Zinc air

Standard Zinc Carbon Batteries

- Chemistry

  Zinc (-), manganese dioxide (+)

  Zinc, ammonium chloride aqueous electrolyte

- Features

  \+ Inexpensive, widely available

  – Inefficient at high current drain

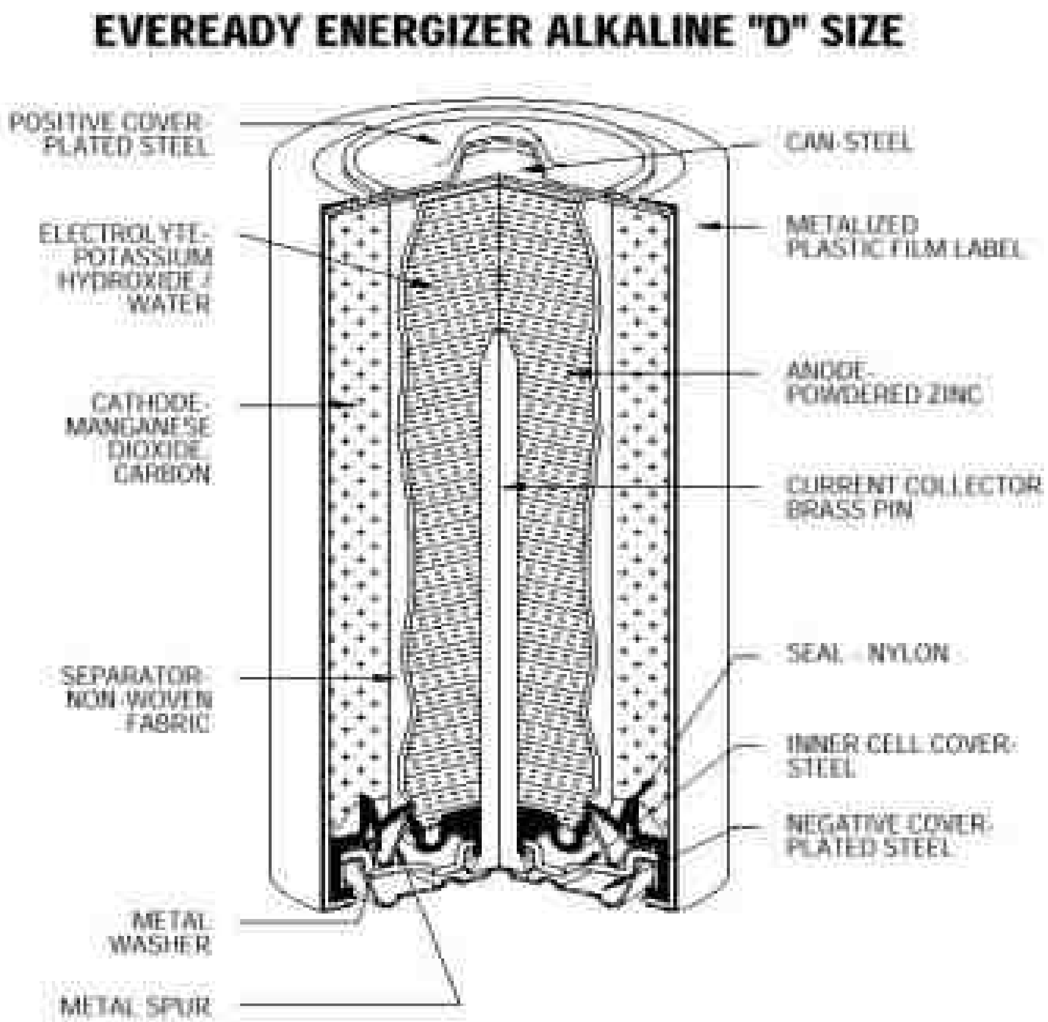
  – Poor discharge curve (sloping)

  – Poor performance at low temperatures

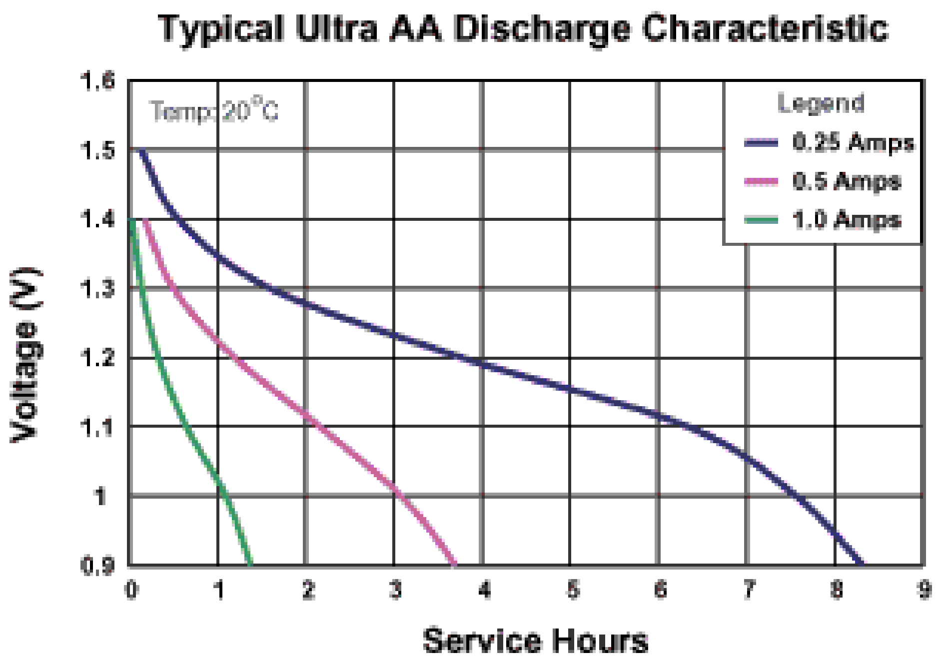
Standard Alkaline Batteries

- Chemistry
  - Zinc (-), manganese dioxide (+)
  - Potassium hydroxide aqueous electrolyte
- Features
  - + 50-100% more energy than carbon zinc
  - + Low self-discharge (10 year shelf life)
  - ± Good for low current (< 400mA), long-life use
  - – Poor discharge curve

Alkaline-Manganese Batteries (2)



Alkaline Battery Discharge



Lithium Manganese Dioxide

- Chemistry

  Lithium (-), manganese dioxide (+)

  Alkali metal salt in organic solvent electrolyte
- Features

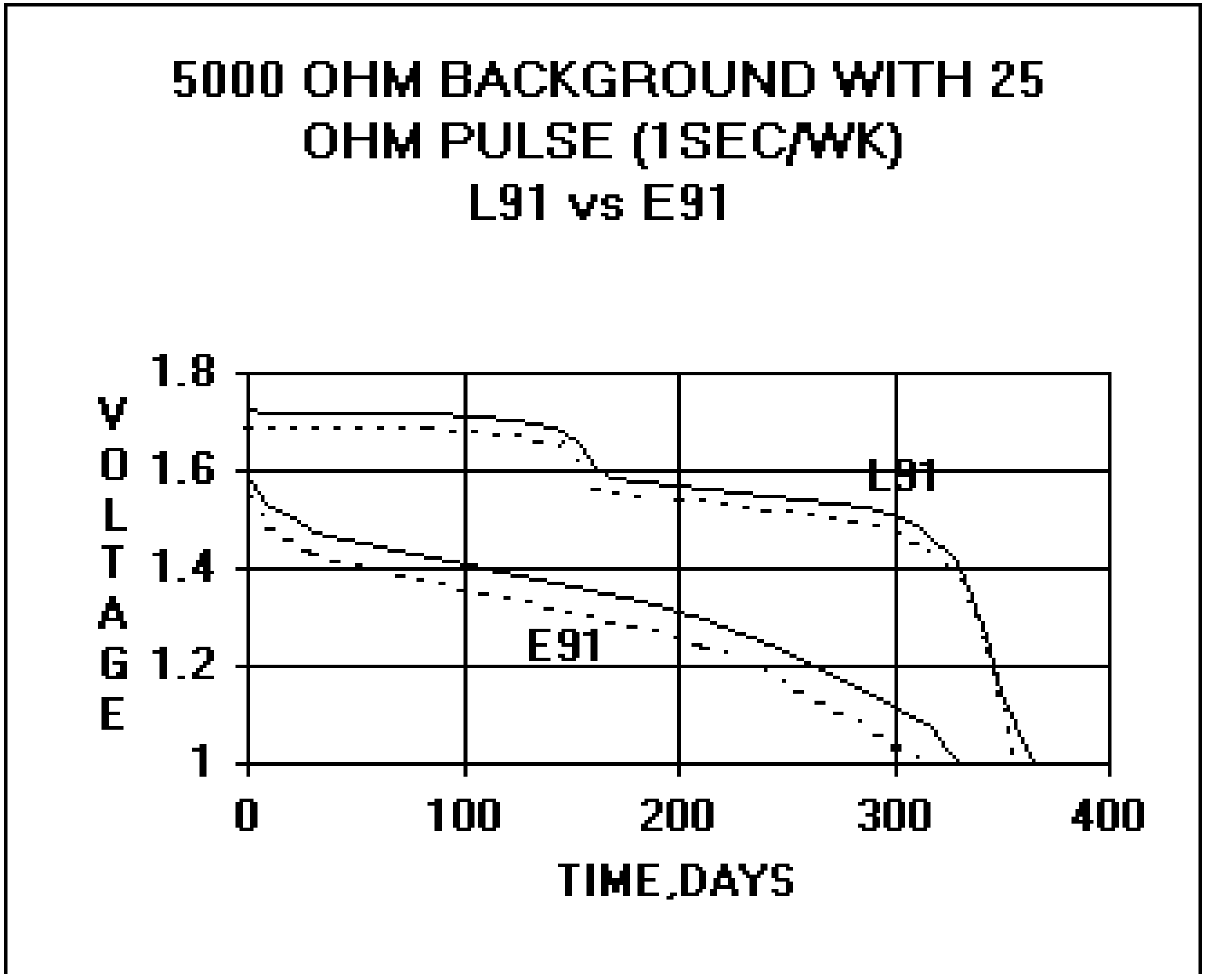
  + High energy density

  + Long shelf life (20 years at 70°C)

  + Capable of high rate discharge

  – Expensive

Lithium v Alkaline Discharge



Secondary (Rechargeable) Batteries

- Nickel cadmium
- Nickel metal hydride
- Alkaline
- Lithium ion
- Lithium ion polymer
- Lead acid

Nickel Cadmium Batteries

- Chemistry

  Cadmium (-), nickel hydroxide (+)

  Potassium hydroxide aqueous electrolyte

- Features

  + Rugged, long life, economical

  + Good high discharge rate (for power tools)

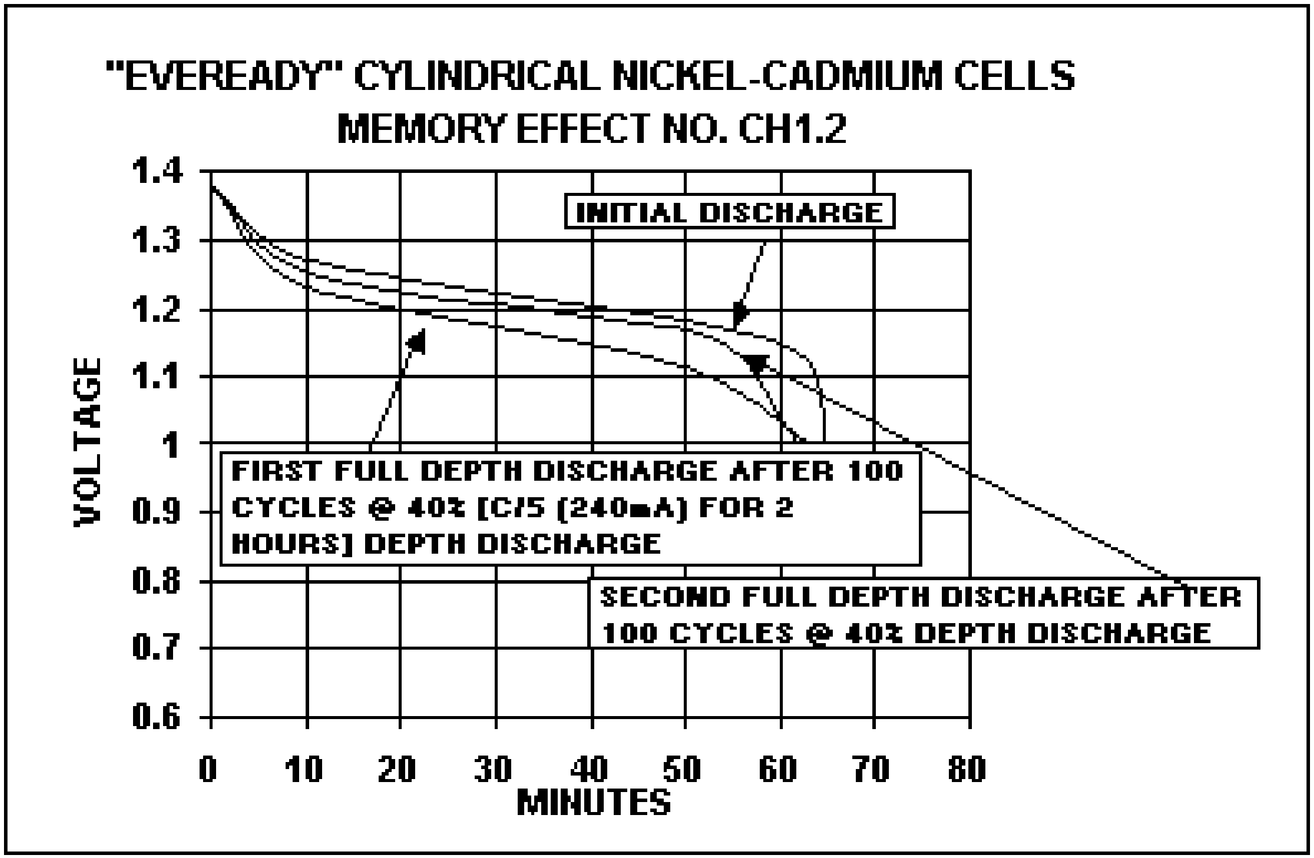
  – Relatively low energy density

  – Toxic

NiCd Recharging

- Over 1000 cycles (if properly maintained)
- Fast, simple charge (even after long storage)
  - C/3 to 4C with temperature monitoring
- Self discharge
  - 10% in first day, then 10%/mo
  - Trickle charge (C/16) will maintain charge
- Memory effect
  - Overcome by 60% discharges to 1.1V

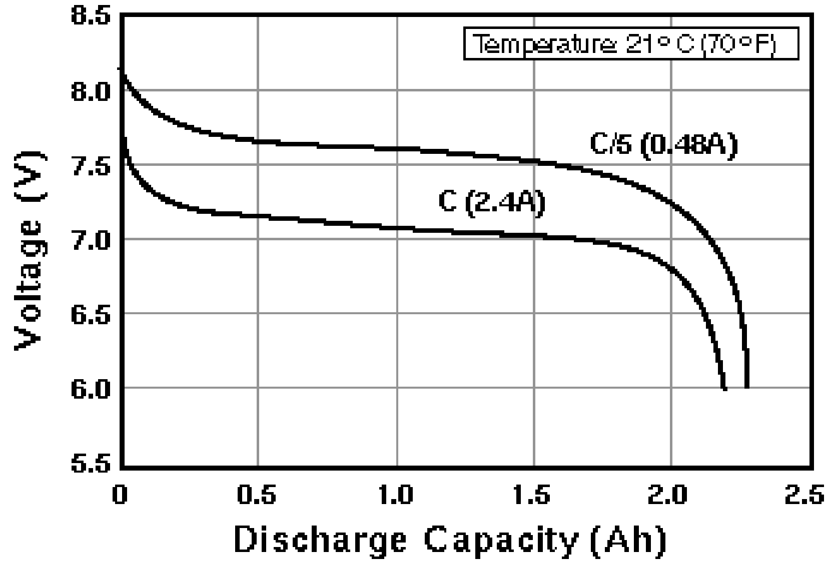
NiCd Memory Effect



Nickel Metal Hydride Batteries

- Chemistry
  $LaNi_5$, $TiMn_2$, $ZrMn_2$ (-), nickel hydroxide (+)
  Potassium hydroxide aqueous electrolyte
- Features
  + Higher energy density (40%) than NiCd
  + Nontoxic
  – Reduced life, discharge rate (0.2-0.5C)
  – More expensive (20%) than NiCd

NiMH Battery Discharge

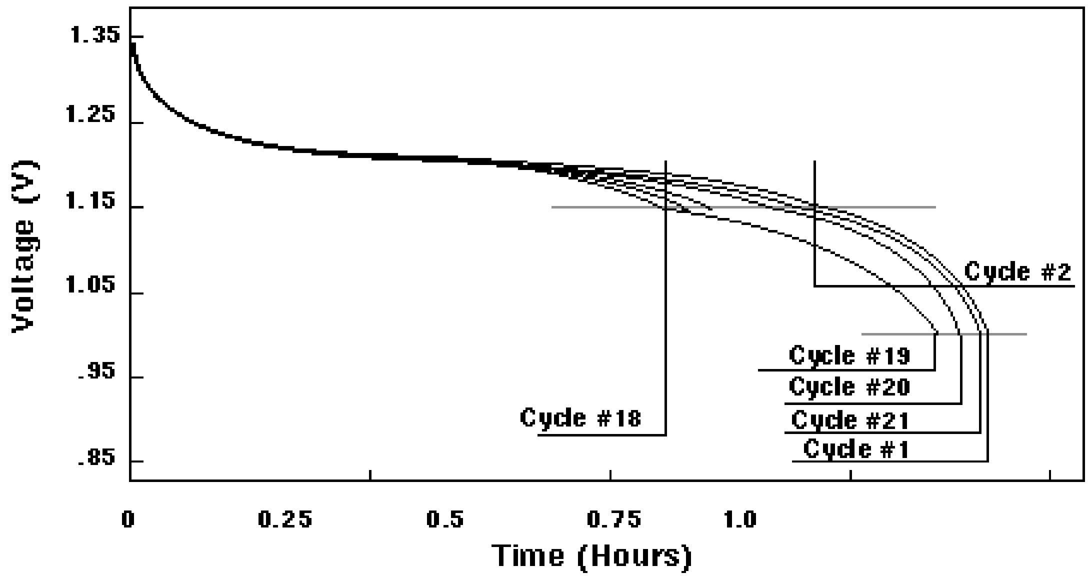


Voltage and capacity of DURACELL DR30 Ni-MH batteries at various discharge temperatures and rates.
[Conditions: Charge: 1C to -ΔV = 60mV @ 21°C (70°F)]

NiMH Recharging

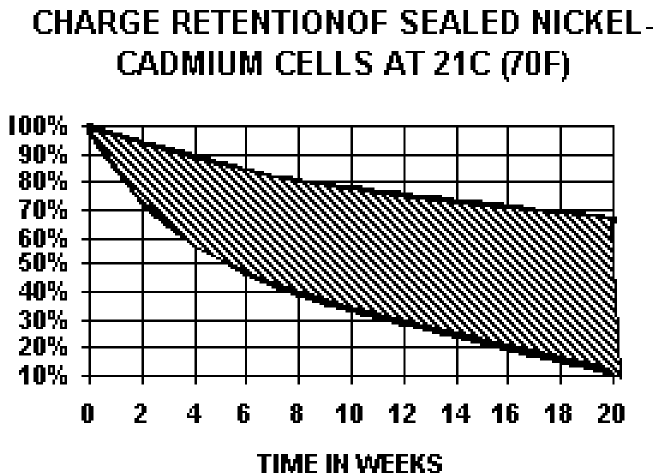
- Less prone to memory than NiCd
- Shallow discharge better than deep
  - Degrades after 200-300 deep cycles
  - Need regular full discharge to avoid crystals
- Self discharge 1.5-2.0 more than NiCd
- Longer charge time than for NiCd
  - To avoid overheating

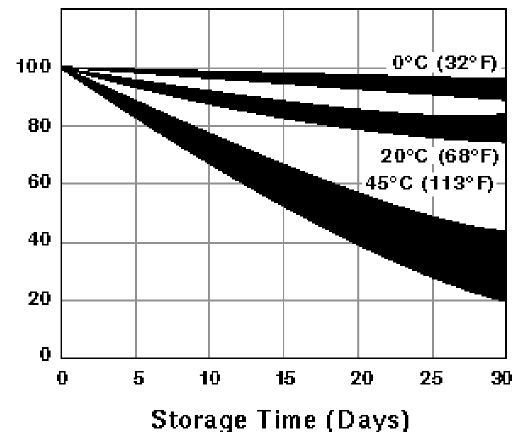
NiMH Memory Effect



Effects on Ni-MH cell capacity due to repetitive partial discharges.
[Conditions: Charge: (Cycle #1 – #21)=1C to -ΔV=12mV. Discharge: Cycle #1=1C to 1.0 V,
(Cycle #2 – #18)=1C to 1.15V, (Cycle #19 – #21)=1C to 1.0V; Temperature: 21°C (70°F)]

NiCd v NiMH Self-Discharge

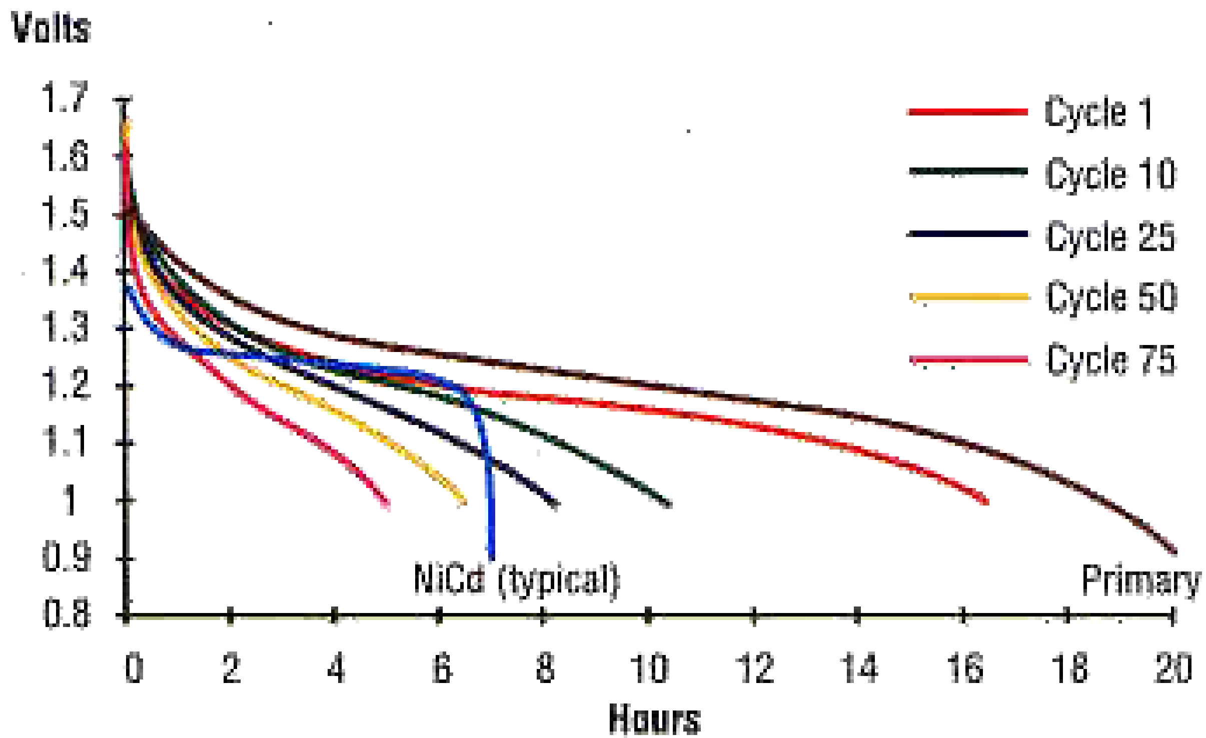




Secondary Alkaline Batteries

- Features
  - 50 cycles at 50% discharge
  - No memory effect
  - Shallow discharge better than deeper

NiCd v Alkaline Discharge



Lead Acid Batteries

- Chemistry
  - Lead
  - Sulfuric acid electrolyte
- Features
  - + Least expensive
  - + Durable
  - – Low energy density
  - – Toxic

Lead Acid Recharging

- Low self-discharge
  - 40% in one year (three months for NiCd)
- No memory
- Cannot be stored when discharged
- Limited number of full discharges
- Danger of overheating during charging

Lithium Ion Batteries

- Chemistry
  - Graphite (-), cobalt or manganese (+)
  - Nonaqueous electrolyte
- Features
  - \+ 40% more capacity than NiCd
  - \+ Flat discharge (like NiCd)
  - \+ Self-discharge 50% less than NiCd
  - – Expensive

Lithium Ion Recharging

- 300 cycles
- 50% capacity at 500 cycles

Lithium Ion Polymer Batteries

- Chemistry

  Graphite (-), cobalt or manganese (+)

  Nonaqueous electrolyte

- Features
  - + Slim geometry, flexible shape, light weight
  - + Potentially lower cost (but currently expensive)
  - – Lower energy density, fewer cycles than Li-ion

Battery Capacity

Type	Capacity (mAh)	Density (Wh/kg)
Alkaline AA	2850	124
Rechargeable	1600	80
NiCd AA	750	41
NiMH AA	1100	51
Lithium ion	1200	100
Lead acid	2000	30

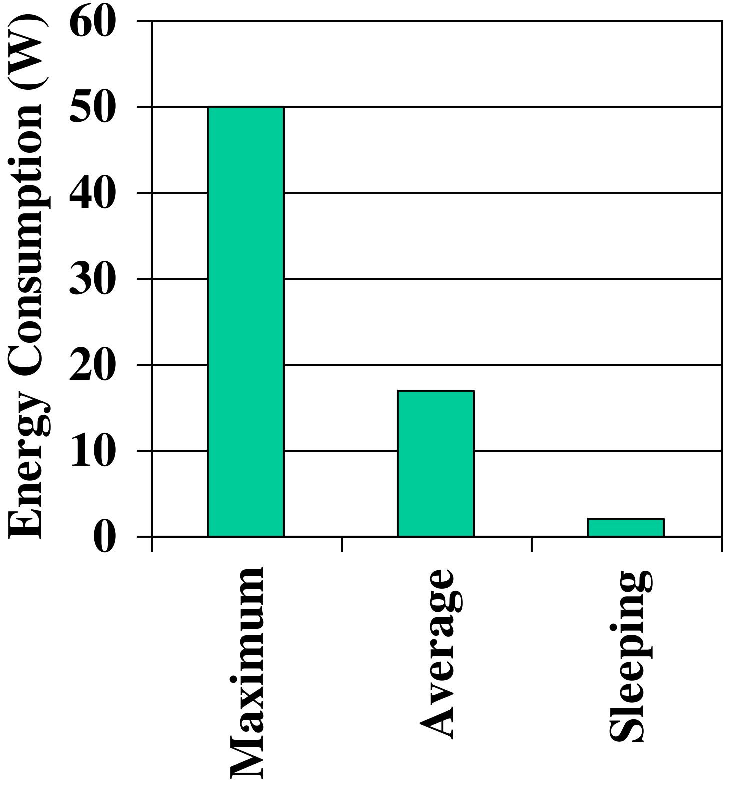
Discharge Rates

Type	Voltage	Peak Drain	Optimal Drain
Alkaline	1.5	0.5C	< 0.2C
NiCd	1.25	20C	1C
Nickel metal	1.25	5C	< 0.5C
Lead acid	2	5C	0.2C
Lithium ion	3.6	2C	< 1C

Recharging

Type	Cycles (to 80%)	Charge time	Discharge per month	Cost per kWh
Alkaline	50 (50%)	3-10h	0.3%	$95.00
NiCd	1500	1h	20%	$7.50
NiMH	300-500	2-4h	30%	$18.50
Li-ion	500-1000	2-4h	10%	$24.00
Polymer	300-500	2-4h	10%	
Lead acid	200-2000	8-16h	5%	$8.50

Example: IBM ThinkPad T21 Model 2647



- Source: IBM datasheet
- Relatively-constant discharge

Lithium-ion Batteries in Notebooks

- Lithium: greatest electrochemical potential, lightest weight of all metals
  - But, Lithium metal is explosive
  - So, use Lithium-{cobalt, manganese, nickel} dioxide
- Overcharging would convert lithium-*x* dioxide to metallic lithium, with risk of explosion

IBM ThinkPad Backup Battery

- Panasonic CR2032 coin-type lithium-magnesium dioxide primary battery
  - Application: CMOS memory backup
  - Constant discharge, ~0.1 mA
  - Weight: 3.1g
  - 220 mA-h capacity

IBM ThinkPad T21 Main Battery

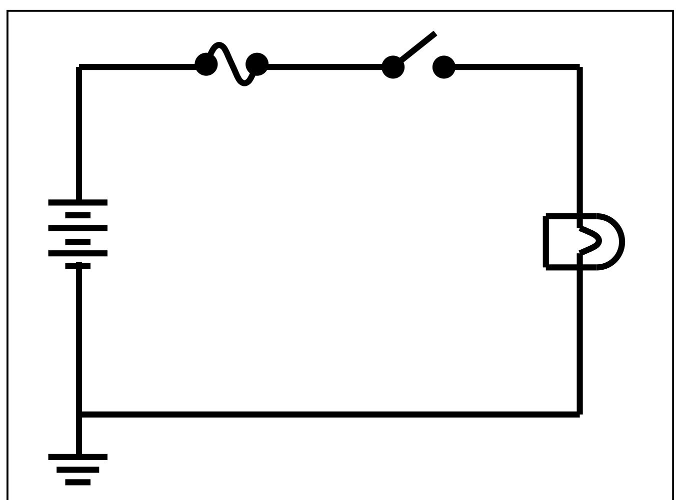
- Lithium-ion secondary battery
- 3.6 A-h capacity at 10.8V
- Back-of-the-envelope calculations from workload shown earlier:
  - Maximum: 47 minutes
  - Average: 2 hours, 17 minutes
  - Sleep: 19 hours?

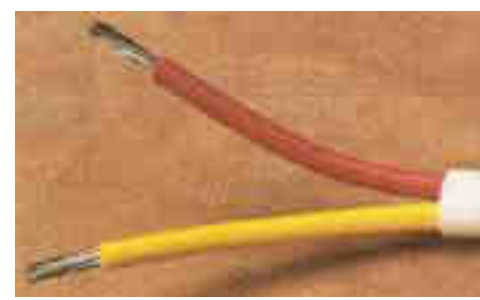
References

- Manufacturers
  www.duracell.com/OEM
  data.energizer.com
  www.rayovac.com/busoem/oem
- Books
  T. R. Crompton, *Battery Reference Book*, Newnes, 2000
  D. Berndt, *Maintenance-Free Batteries*, Wiley, 1997
  C. Vincent & B. Scrosati, *Modern Batteries*, Wiley, 1997
  I. Buchmann, *Batteries in a Portable World*, www.buchmann.ca

Chapter 2

Electrical Wiring Practices and Diagrams





Overview

- Safety
- Standards
- Wiring Considerations
- Wire Terminations
- Coaxial Cable
- Wiring Installations
- Wiring Diagrams

Safety

- Lethal Current
- Safety Precautions

Lethal Current

- Fundamental policy of the USPS is **SAFETY**

- Human Body
  - Resistance – 4 KΩ (moist skin) to 24 KΩ (dry skin)
  - Safe current (through chest) – less than 20 milliamps

  - E = 120 VAC R = 4 KΩ I = ?
  - I = 30 milliamps - NOT SAFE

  - Don't want current through chest cavity (may be lethal)

Safety Precautions

- Turn circuit off
  - Disconnect service cord
  - Disconnect negative battery cable
- If must work on live AC circuit
  - Need 2nd safety person
- Remove metal jewelry
- Know your boat and its wiring
- Use outlet tester on AC outlets
- Use 3-wire extension cord from GFI outlet

Standards

- American Boat and Yacht Council (ABYC)
  - AC and DC Electrical Systems is E-11
  - Minimum standards
    - Construction
    - Repair
- Marine Dept. of Underwriters Laboratory
  - Test and certify commercial products
  - Safety, not function

Wiring Considerations

- Conductors
- Wire Types
- Wire Size
- Wire Insulation
- Wire Color Code

Conductors

- Connects power sources to power loads
- Characteristics
  - Safe
  - Dependable
  - Efficient (minimal voltage drop)
- Boat environment
  - Worse than either house or car
  - High humidity
  - Vibration
  - Corrosive conditions

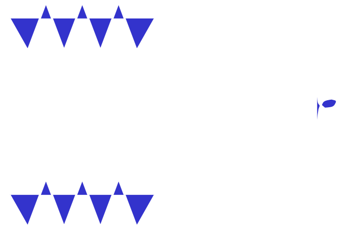
Wire Types

- Marine Grade
  - Type 3 is recommended
- Stranded copper
  - Tinned is preferred

Wire Size

- 3% voltage drop
  - Critical circuits (Nav lights)
  - Electronic Equipment
- 10% voltage drop
  - Cabin lights
  - Motorized Equipment
- Minimum size AWG # 16

Wire Has Resistance



- Inadvertent Resistors
  - Wire too small (min of #16 - properly size using table)
  - Bad connections (or corroded connections)
    - Clean and tighten battery connectors
    - Tighten lug screws and inspect wire to lug connection
  - Why do wires get warm / hot?
    - Low resistance circuits pass high current ($P = I^2 \times R$)
    - Wires can account for much of the overall resistance

Wire Size Comparison

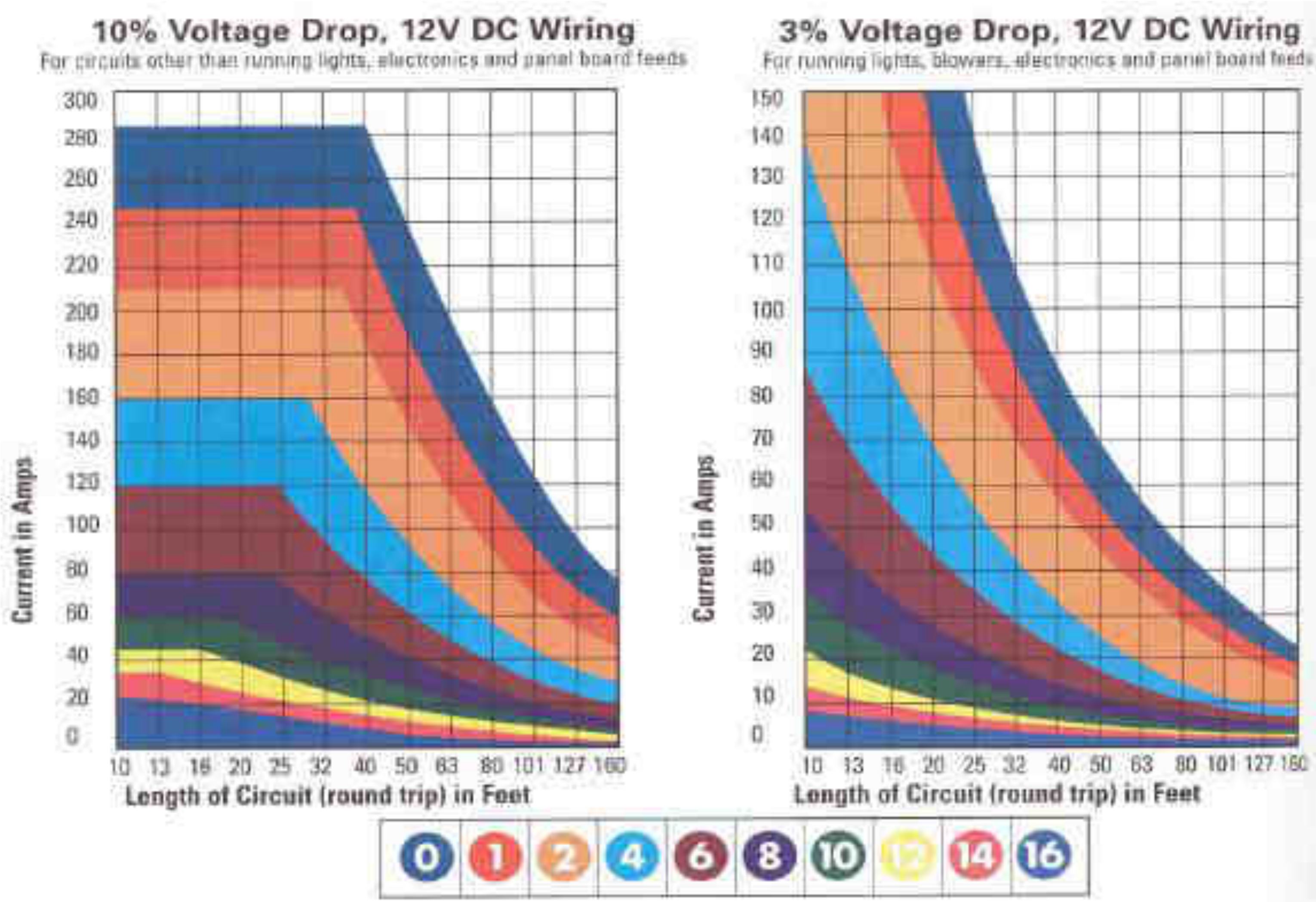
#16 top to #10 bottom

#2 top to #10 bottom

Copper Wire Characteristics

American Wire Gauge #	NEC Ampacity TW insul.	Solid Wire Diameter in Mils	Nominal Cross Section Area in Circular Mils	Minimum # of Strands	Resistance Ohms per 1000 feet
18	7	40	1,620	16	6.39
16	10	51	2,580	19	4.02
14	15	64	4,110	19	2.53
12	20	81	6,530	19	1.59
10	30	102	10,380	19	1.00
8	40	129	16,510	19	0.628
6	55	162	26,240	37	0.395
4	70	204	41,740	61	0.249
3	85	229	52,640	61	0.197
2	95	258	66,360	127	0.1563
1	110	289	83,690	127	0.1239
0	125	325	105,600	127	0.0983
00	145	365	133,100	127	0.0779

12- VDC Wire Size Selection



12 VDC Wire Size Selection

Wire Size Selection Table for 12 Volt Systems

Maximum length of run, in feet, of two-wire cable or dual conductors from battery terminals to equipment terminals.*

Current Amperes	Wire Size AWG# 16	14	12	10	8	6	4	3	2	1	0	00
5	8	14	24	38	61	96						
10	4	7	12	19	30	48	76					
15	-	4	8	13	20	32	51	64				
20	-	-	6	10	15	24	38	48	61			
30	-	-	-	6	10	16	25	32	41	51		
40	-	-	-	-	8	12	19	24	30	38	48	
55	-	-	-	-	-	9	14	18	22	28	35	44
70	-	-	-	-	-	-	11	14	17	22	28	35
80	-	-	-	-	-	-	-	12	15	19	24	30
95	-	-	-	-	-	-	-	-	13	16	20	26
110	-	-	-	-	-	-	-	-	-	14	18	22
125	-	-	-	-	-	-	-	-	-	-	15	20
145	-	-	-	-	-	-	-	-	-	-	-	17

Wire Size Selection Table for Starter Motor Circuit Only

Maximum length of single wire, in feet, from battery positive terminal to main battery switch, to starter motor, to common negative bus, to battery negative terminal.

Current Amperes	Wire Size AWG# 12	10	8	6	4	3	2	1	0	00
150	-	-	-	-	10	13	16	20	26	32
200	-	-	-	-	8	10	12	15	19	24
250	-	-	-	-	6	8	10	12	15	19
300	-	-	-	-	5	6	8	10	13	16
400	-	-	-	-	-	5	6	8	10	12
500	-	-	-	-	-	-	5	6	8	10
600	-	-	-	-	-	-	-	5	6	8
800	-	-	-	-	-	-	-	-	5	6
1,000	-	-	-	-	-	-	-	-	-	5

120 VAC Wire Size Selection

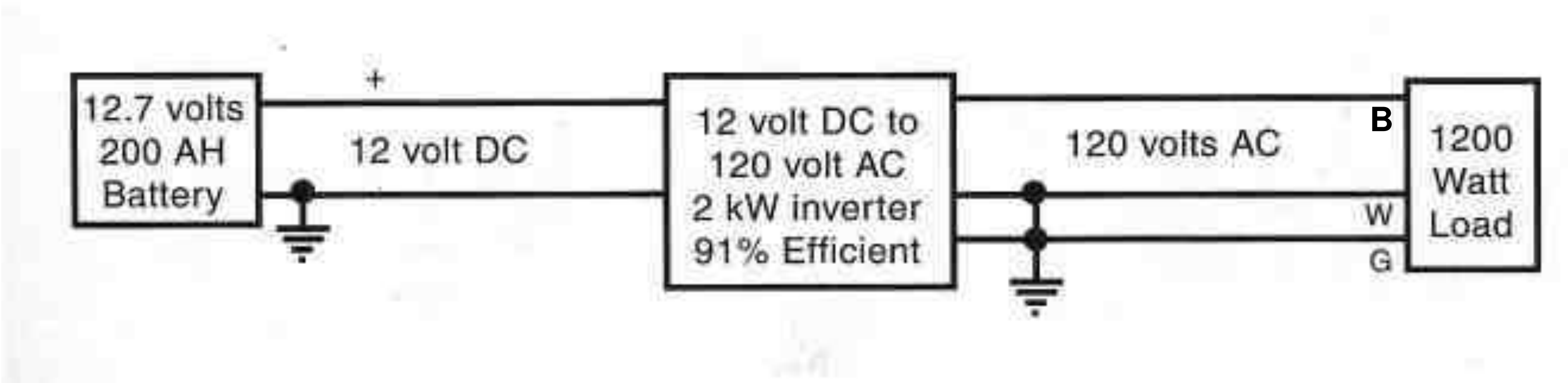
Wire Size Selection Table for 120-Volt Systems

Maximum length of run, in feet, of two-wire cable or dual conductors from power source to equipment terminals.*

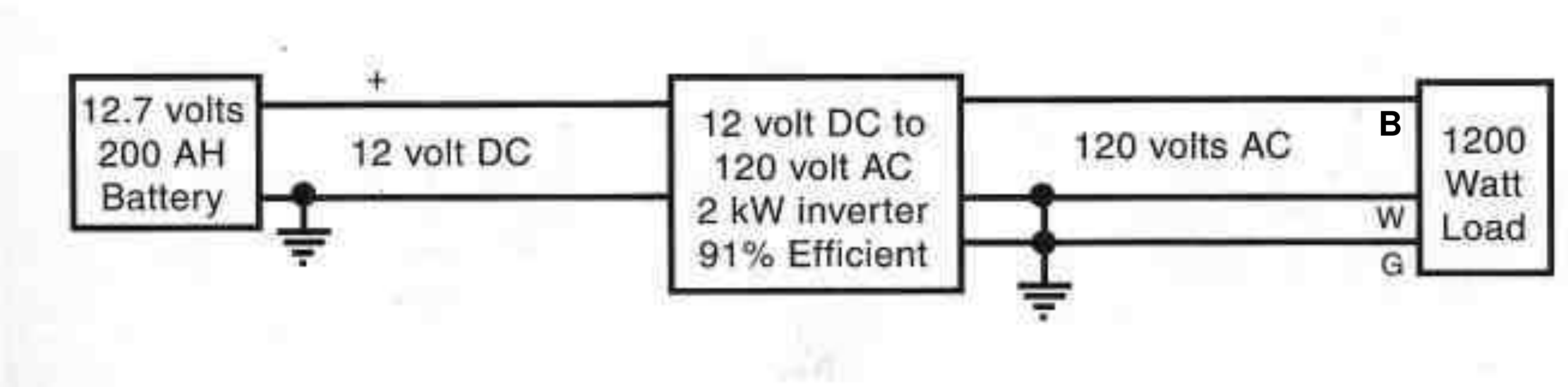
Current Amperes	16	14	12	10	8	6	4	3	2	1	0
	Wire Size AWG#										
5	88	142	226	360	573						
10	44	71	113	180	287	456					
15		47	76	120	191	304	483				
20	-		57	90	143	228	362	457			
30	-	-	-	60	96	152	241	305	384		
40	-	-	-	-	72	114	181	228	288	363	
55	-	-	-	-	-	83	132	166	209	264	
70	-	-	-	-	-	-	103	131	165	208	262
80	-	-	-	-	-	-	-	114	144	182	229
95	-	-	-	-	-	-	-	-	121	153	193
110	-	-	-	-	-	-	-	-	-	132	167
125	-	-	-	-	-	-	-	-	-	-	147

* Based on a Maximum Voltage Drop of 3% from source to load and a Supply Rating of 120 volts for American Wire Gauge Copper Conductors. If more current or a longer run is required, you must use a larger wire size to maintain the voltage drop at 3% or less.

What Size Wires?



Step 1



What current to Load? I = 10 Amps

P = E * I I = P / E I = 1200/120

From Table 2-1 – For 10A need #16 wire

From Table 2-3 – Maximum of 44 feet (for 10A in #16 wire)

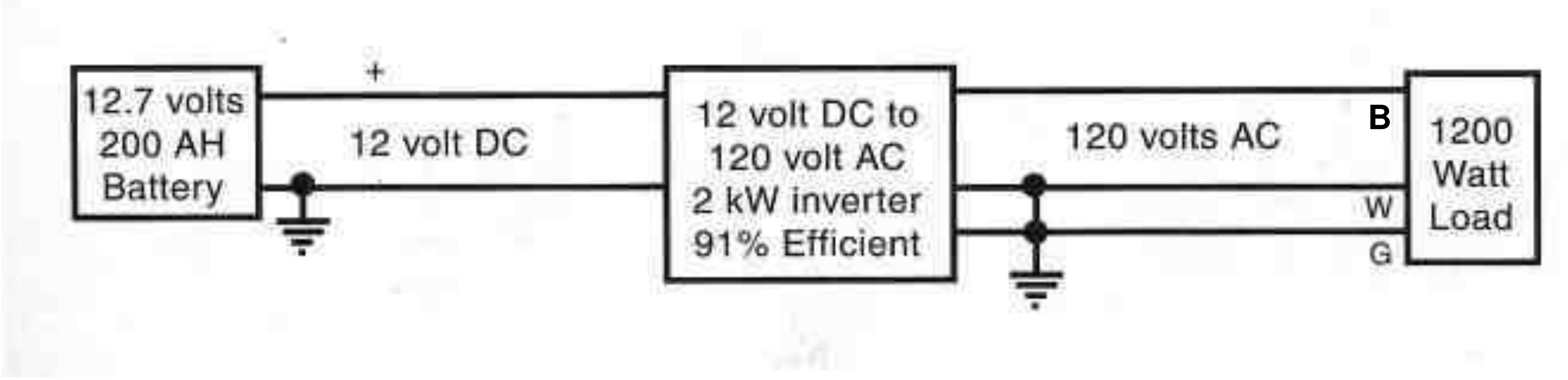
Step 1 Answers

AMPACITY

10 Amperes

#16 AWG TW

by Table 2-1

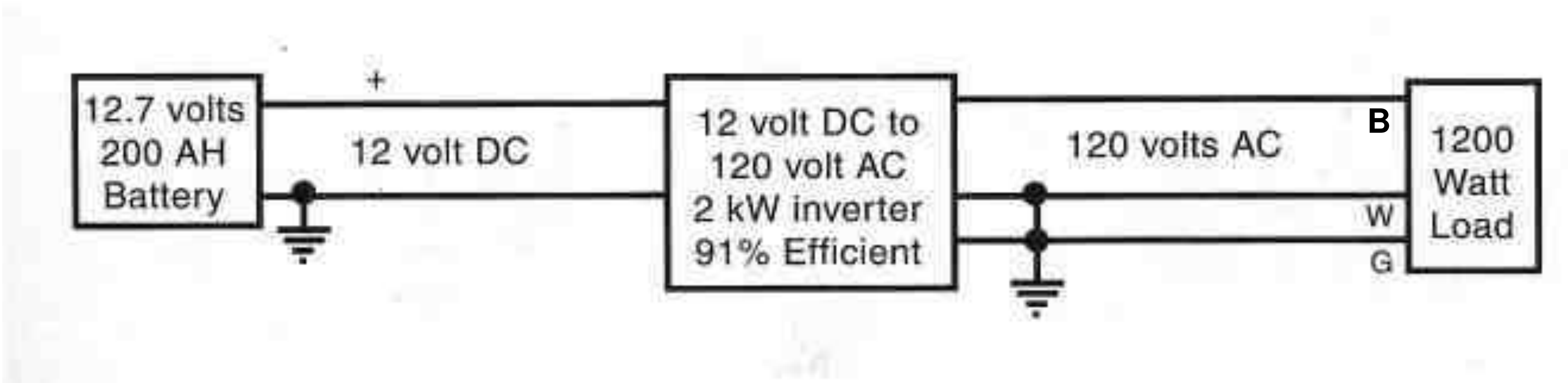


for 3% voltage drop

44 feet maximum

by Table 2-3

Step 2



What current to Inverter? I_{load} = 100 Amps @ 12 V

$I_{load} = I_{out} = I_{in} * 0.91$ $I_{in} = I_{out} / 0.91 = 100 / 0.91 = 110$ Amps

From Table 2-1 – For 110A need #1 wire

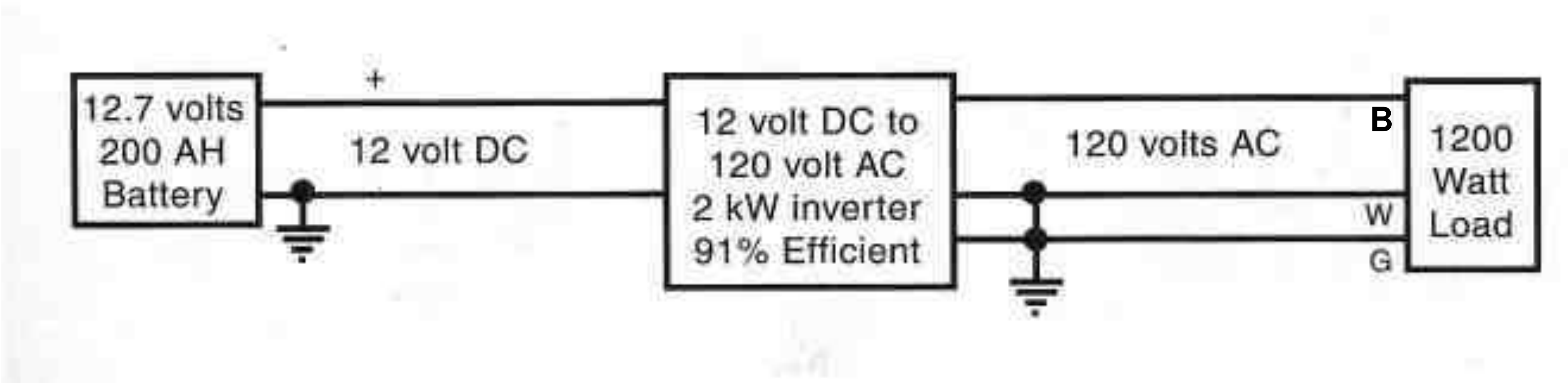
From Table 2-3 – Maximum of 14 feet (for 110A in #1 wire)

Step 2 Answers

AMPACITY

110 Amperes

#1 AWG TW



for 3% voltage drop

14 feet maximum

by Table 2-2A

Wire Insulation

- AC cables must be type UL 1426 BC
  - 600 volt insulation
  - Gasoline and Oil resistant
  - Won’t absorb moisture
- DC wires & cables must be Marine Grade
  - 600 volt insulation
  - Gasoline and Oil resistant
  - Won’t absorb moisture
- Color coded wires

Wire Color Code

Color	AC (Hot)	AC (Neut)	AC (Gnd)	DC +	DC -
Black	**X**				**X**[1]
White		**X**			
Green (may have a yellow stripe)			**X**		
Red	**X**[2]			**X**	
Yellow					**X**[1]

Footnotes:

1 – Yellow preferred for DC negative to avoid confusion with AC Hot wire

2 – 2nd hot wire in 220 VAC is Red

Wire Color Coding

Color Coding for DC and AC Wiring

Wire Color	DC Wiring*
Black or Yellow	DC Negative Conductors
Red	DC Positive Conductors
Yellow with Red Stripe	Starter Switch to Solenoid
Yellow	Bilge Blower (See note below)
Brown with Yellow Stripe	Bilge Blower (See note below)
Dark Gray	Navigation Lights, Tachometer Sensor to Indicator
Brown	Pump Circuits and from (1) Generator Armature to Regulator, or (2) Alternator Auxiliary Terminal to Regulator
Orange	Distribution Panel to Accessory Switch; Ammeter to Alternator or Generator
Purple	Ignition Switch to Coil & Instruments; Distribution Panel to Instruments
Light Blue	Oil Pressure Sensor to Gauge
Dark Blue	Cabin & Instrument Lights
Pink	Fuel Level Sensor to Gauge
Tan	Water Temperature Sensor to Gauge
Green or Green with Yellow Stripe	Bonding (DC Grounding Conductors) wires only
Green with Stripe (Any Stripe Color Stripe Except Yellow)	Tilt Down and/or Trim In
Blue/Stripe	Tilt Up and/or Trim Out

Note: If yellow is used for DC negative, blower must be brown with yellow stripe.
*DC Codes based on American Boat & Yacht Council Recommendations.

Wire Color	AC Wiring
White	Current Carrying Neutral. *Note:* Can also be light blue
Black	Hot Lead 120/240VAC Single Phase
Red	2nd Hot Lead 120/240VAC Single Phase
Green or Green with Yellow Stripe	Safety Grounding Conductor (AC)
Blue	Additional Ungrounded Conductor (Usually Third Phase)
Orange	Additional Ungrounded Conductor (Usually the High Leg on Center Grounded 240 VAC Delta Systems)

Wire Terminations

- Crimping
  - Special Tool
  - Approved Marine Connectors
  - Use of Ratcheting Tool
- Solder
- Heat-shrink Tubing

Wire Terminals

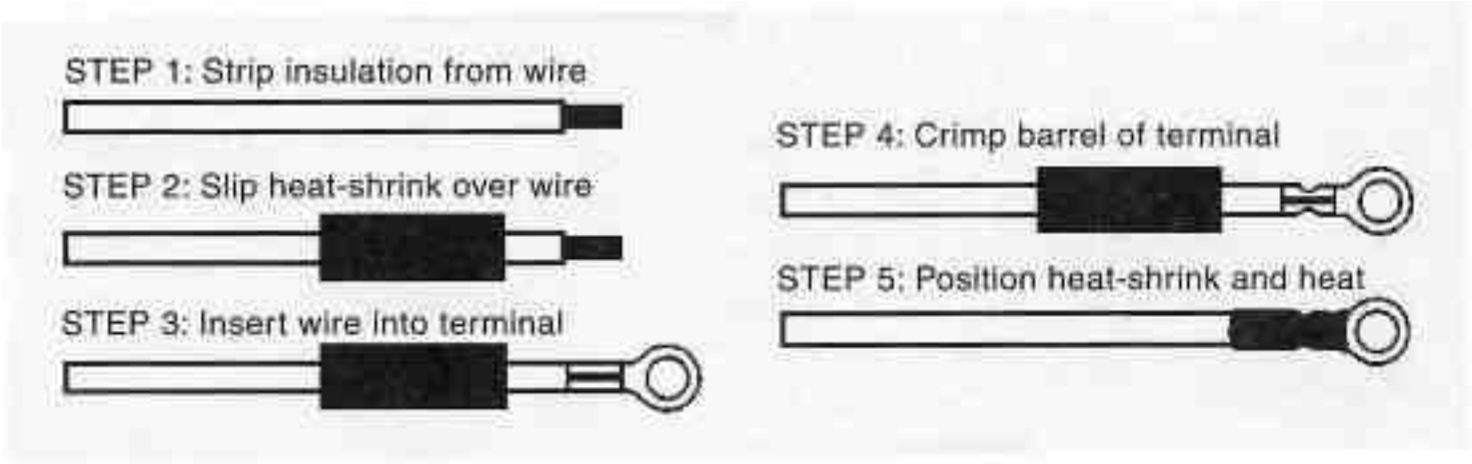
Ratcheting Tool Use

- First select appropriate connector
- Strip insulation length of stem plus 1/16”
- Insert stripped end all way into terminal
  - End should extend 1/16”
- Place terminal in same color slot
  - First crimp end of terminal barrel nearest ring
  - Then crimp wire end of terminal barrel
- Check the connection with a solid tug

Soldering

- Terminal connection can’t be only soldered
  - Must also be crimped
- Soldering is normally not required
  - Crimped connectors are acceptable to ABYC
  - If solder, apply only to ring end of terminal
- Solder changes stranded wire into solid
  - Stranded wire is flexible
- Use 40% lead / 60% tin, rosin core solder
- Battery lugs may be only soldered

Heat-Shrink Tubing



Application Steps

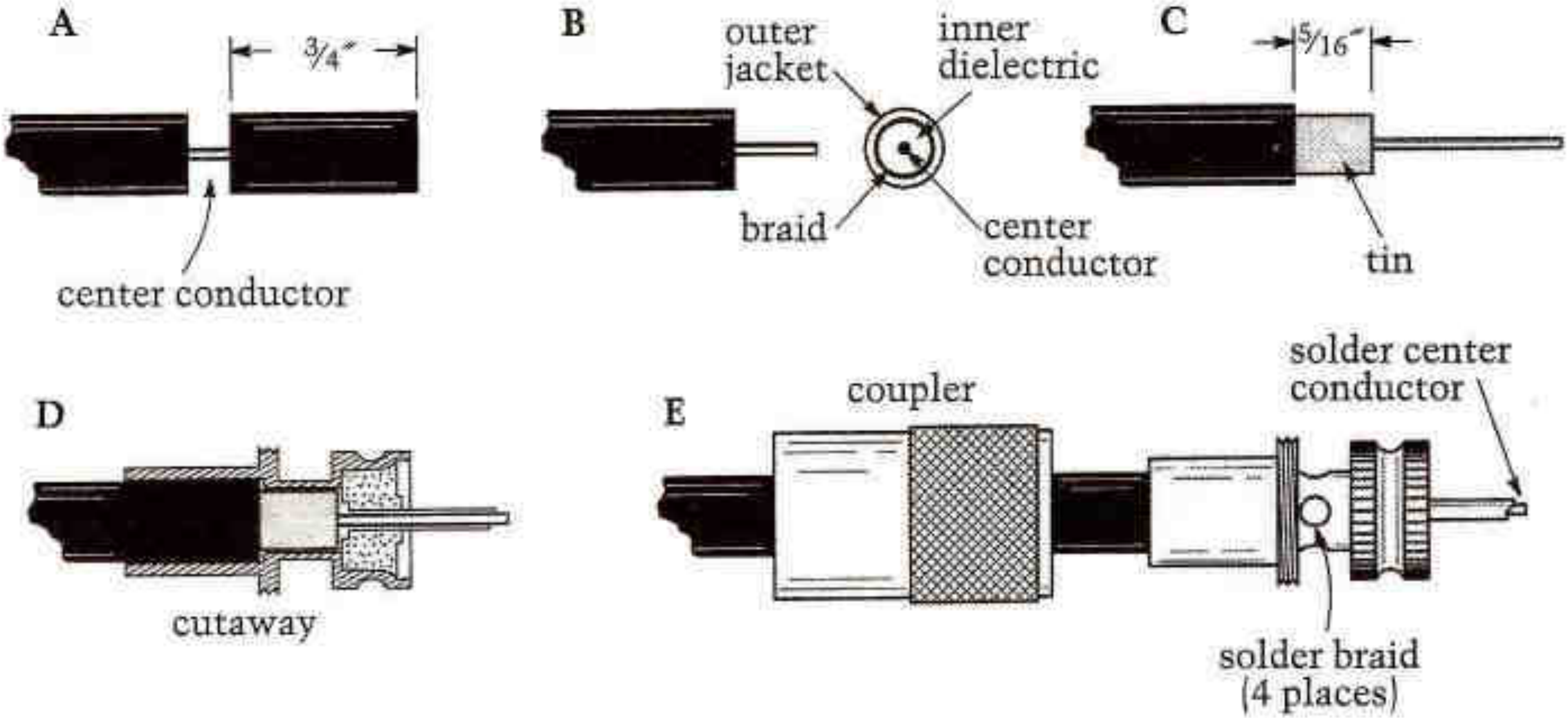
Coaxial Cable

- Antenna cable
- Radio coax is 50 ohm with PL-259
- Radio cable is cut to length
- Want attenuation under 3 db
- TV cable is 75 ohm with “F” connectors
- GPS cable is not cut to length
  - Coil excess in 1-foot loops

Coaxial Cable Information

Cable	Impedance in Ohms	Attenuation @ 150 MHz per 100 ft	Outside Diameter	Bend Radius in inches	Normal Connector	Remarks
RG-8/U	50	2.2	0.403	4	PL-259	
RG-8/X	50	3.2	0.242	2.4	PL-259	with adapter
RG-58A/U	50	5.8	0.194	2	PL-259	with adapter
RG-59/U	75	3.2	0.25	unk	Coaxial "F"	TV Coax
RG-213	50	3.2	0.405	5	PL-259	

Soldering PL-259 Connector



Wiring Installation

- Basic Considerations
- Distribution Panel
- Fuses / Circuit Breakers
- Branch Circuits
  - Wire
  - Outlets
  - Switches
- Grounding Systems
- Bonding Systems

Basic Considerations

- Must have source and return wires
  - Return wires to a common point
  - May use feeder wire from power panel for:
    - engine, helm console, etc.
- Wires above flood level of bilge
  - Waterproof if in bilge
- Insulated support every 18”
- Twist DC wires within 1 meter of compass

Distribution Panel

- Central location of Circuit Breakers / Fuses
  - All branch circuits from this location
- AC and DC may be combined in one panel
- All equipment / circuits should go to panel
  - Not direct to battery (except bilge pump)
    - Noise interference suppression covered in Section 7

DC / AC Power Panel

Front View

Inside Power Panel

Buss Bars

DC Side

Fuses and Circuit Breakers

- Used to protect wiring from over current
  - In positive or hot wire
- Newer boats use circuit breakers
  - Initially more expensive
- Replace blown fuse with correct rating

- Circuit Breakers should be Marine Grade
  - Trip free
  - Manual reset

Branch Circuits - Wires

- Minimum size is 16 AWG
  - See Wire Selection Tables
  - For AC normally #14 for 15A and #12 for 20A
- Must terminate in closed electrical box
- Of sufficient length
- DC negative returned to DC Panel
  - May use several negative feeder terminals
- AC neutrals returned to AC Panel
- Bonding system never used as return wire

Branch Circuits - Outlets

- 120 VAC outlets must be 3-wire polarized
  - Black (hot) to brass or copper colored terminal
- Outlet wires must have crimp terminals
- GFI outlets
  - Required on weather deck, head, galley and machinery spaces
  - Good practice for all AC outlets to be GFI
  - Trip at 5 milliamps
- Different outlets for AC and DC power

Outlets and Plugs

12 VDC

DC Outlet (Receptacle)

120 VAC

15 A Outlet

120 VAC

GFI 15 A Outlet

120 VAC

20 A Outlet

DC Plug

AC Plug 15 A

AC Plug 20 A

Branch Circuits - Switches

- Modern panels use Circuit Breakers
  - Which also double as switches
- Switches / Circuit Breakers
  - Must be Marine Grade
  - Rated for the voltage and current controlled
  - Interrupt the positive (DC) or hot (AC) leg
- Battery Switch
  - Designed for high current service
  - Not located in engine or fuel-tank compartments

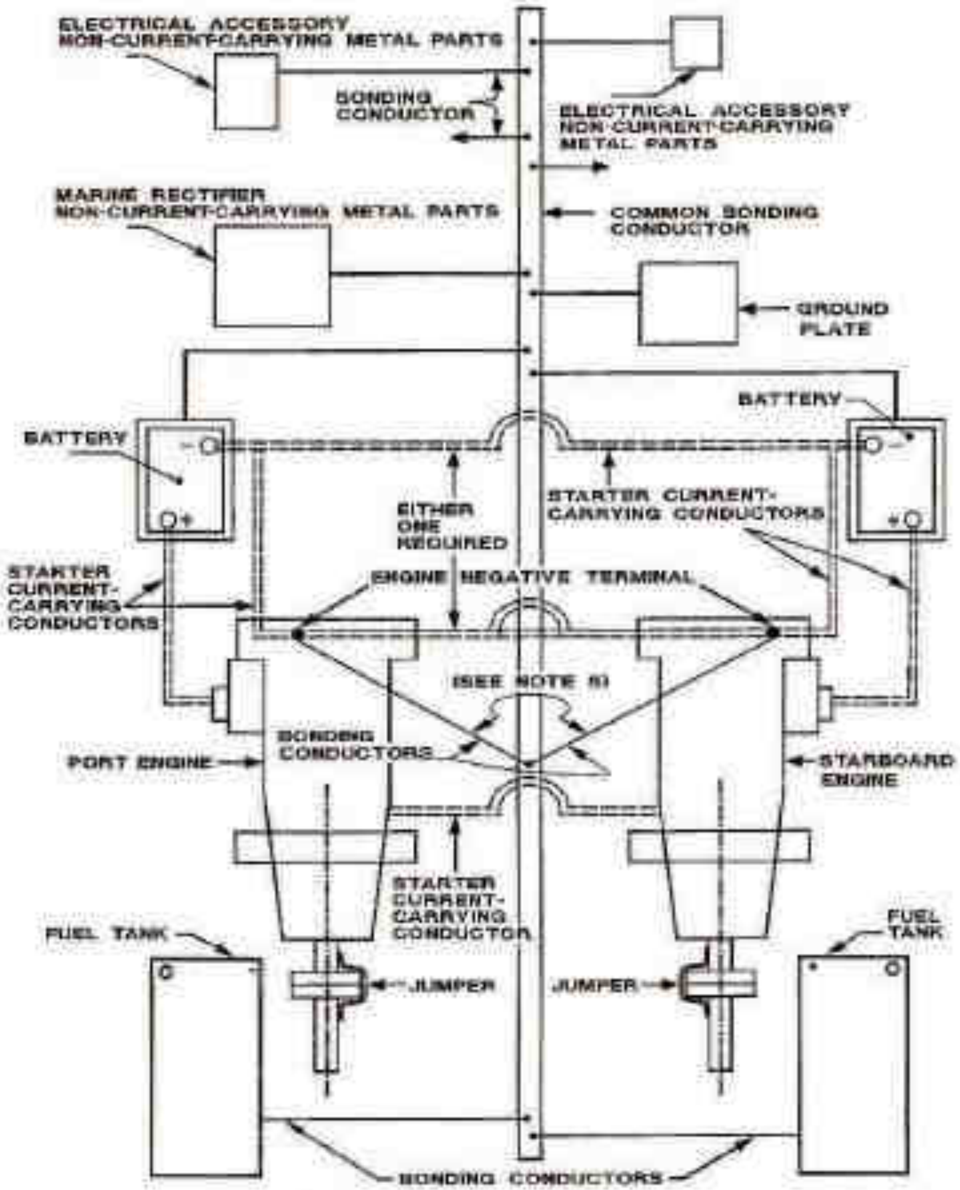
Grounding System

- Ground is potential of water around boat
  - Or potential of earth's surface
- DC – Ground Battery negative terminal(s)
  - Also engine block
  - Wire color is Yellow (or Black)
- AC – Transformer center tap on shore
  - Also connected to ground rod at transformer
  - Wire color is Green and uninterrupted wire
    - Isolation transformers and galvanic isolators are exception and covered in Chapter 4 on AC
- Engine, DC negative & AC ground connected

Bonding System

- For lightning protection
  - More in Chapter 6
- All metal objects should be bonded
  - Keeps all metal at zero potential
  - Engine blocks
  - Battery negative terminals
- Non-current carrying wire
- Through-hull fittings
  - ABYC now recommends they be bonded
  - Electrically isolated from metal hull

Bonding Diagram

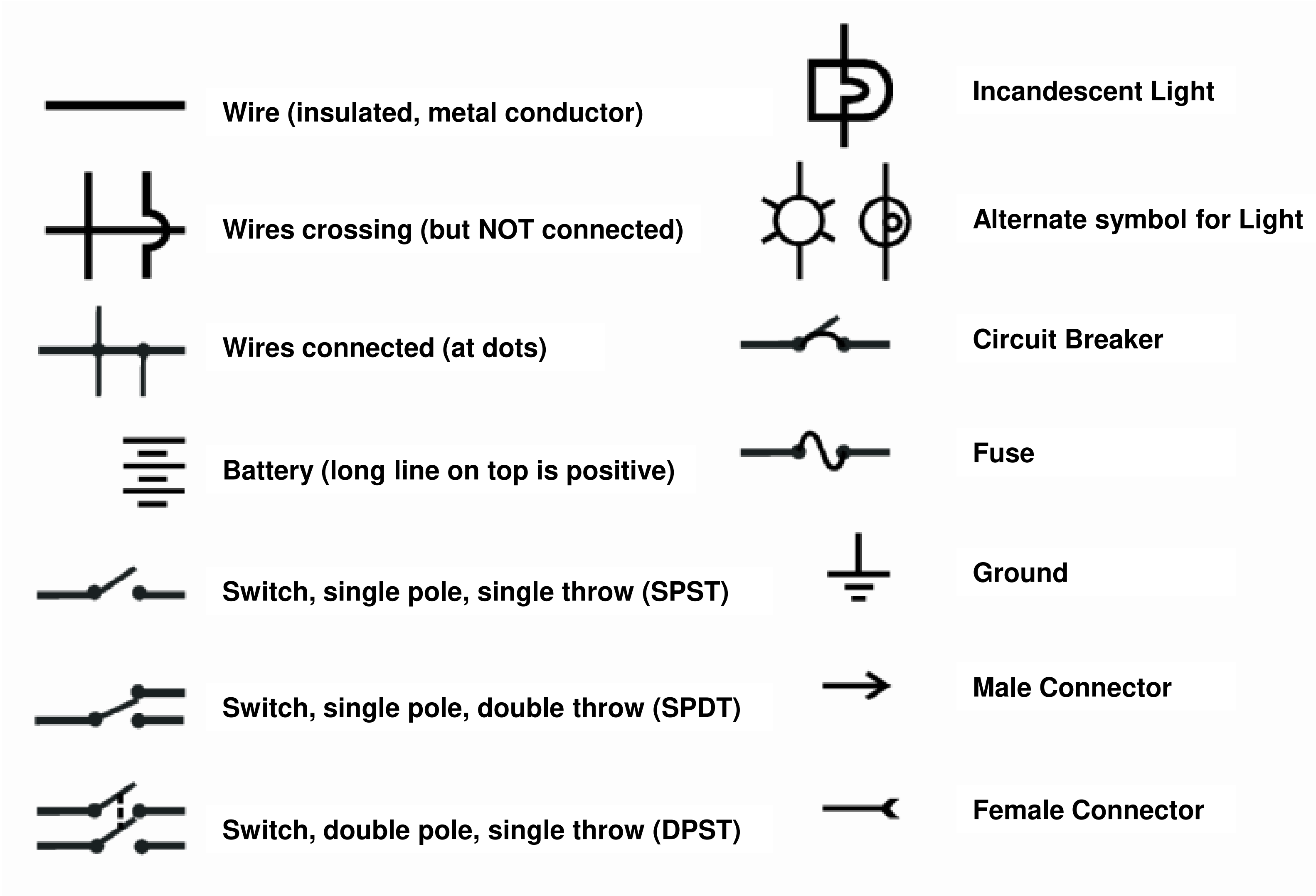


Wiring Diagrams

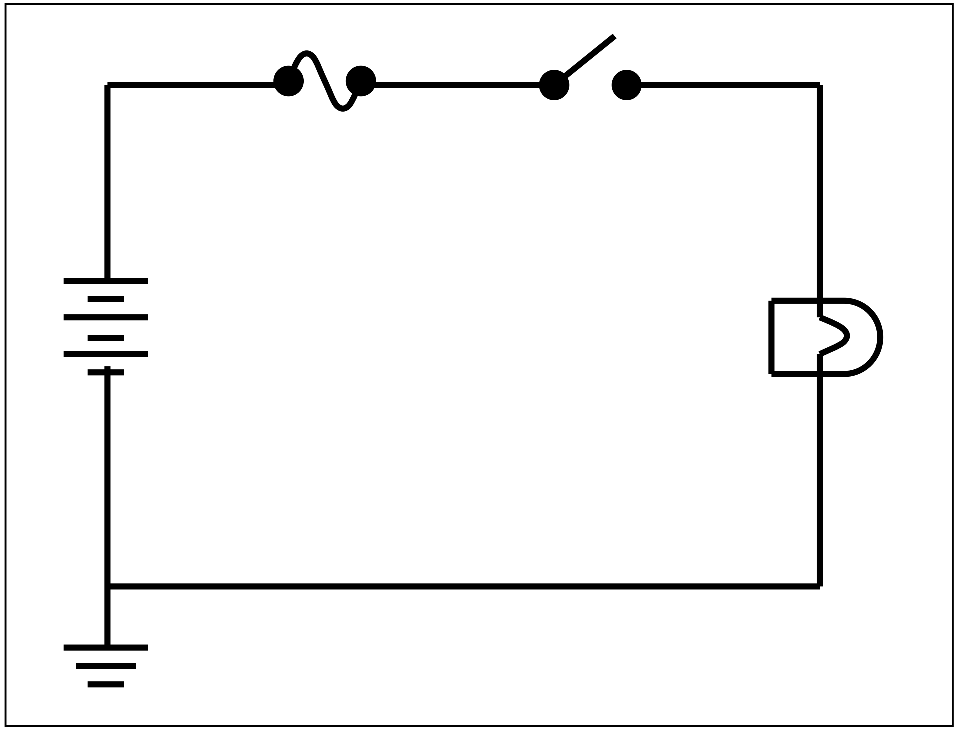
- Elements of a Good Wiring Diagram
  - Documents boat's electrical layout
  - Should be kept current
  - Used for troubleshooting

- Component Identification
  - Physical objects to their symbol
  - Wires are color coded

Wiring Diagram Symbols



Simple DC Wiring Diagram



Summary

- Circuits should be off when working on them
- Use only marine grade properly sized wires
  - Tables will help determine proper wire size
  - Minimum wire size is #16 AWG
- Use wire terminations and ratcheting crimper
- DC circuits are 2 dedicated wires
  - Waterproof wire connection in bilge
- AC circuits are 3 dedicated wires
  - GFCI in galley, head, machine spaces & weather deck
- Separate Grounding & Bonding systems required

- Keep wiring diagram current