Chapter 5

Nonideal Behavior of Components

National Taiwan University of
Science and Technology

Chun-Long Wang

Outline

- Preview
- Wires
- Printed Circuit Board (PCB) Lands
- Effect of Component Leads
- Resistors
- Capacitors
- Inductors
- Ferromagnetic Materials – Saturation and Frequency Response

Outline

- Ferrite Beads
- Common-Mode Chokes
- Electromechanical Devices
- Digital Circuit Devices
- Effect of Component Variability
- Mechanical Switches

Preview

- Why Nonideal Behavior is so Important?
  - For example, if the desired frequency of the emission is above the self-resonant frequency of the capacitor, the behavior of the capacitor will resemble that of an inductor, and the low impedance desired will not be realized.
- Frequency of Interest (FCC)
  - Conducted emissions: 150kHz-30MHz
  - Radiated emissions: 30MHz-40GHz

Wires

- Introduction
  - Lumped Circuit Criterion
    - If the line is electrically short at the frequency of interest ($L < \lambda/10$), then a lumped-circuit model of it will provide adequate prediction.
    - Here, we will assume the length of the line is electrically short and consider the ideal and nonideal elements of a component as lumped circuits.
  - Dielectric Materials
    - Since dielectric materials are not ferromagnetic and thus have relative permeabilities of free space, $\mu_r=1$. Therefore wire insulations do not affect magnetic field properties caused by currents of the wires.

inductance not affected

Wires

- Resistance and Internal Inductance of Wires
  - Resistance
    - The per-unit-length dc resistance of a round wire is

$$r_{\mathrm{lf}} = r_{\mathrm{dc}} \quad \text{for } r_w \ll \delta$$

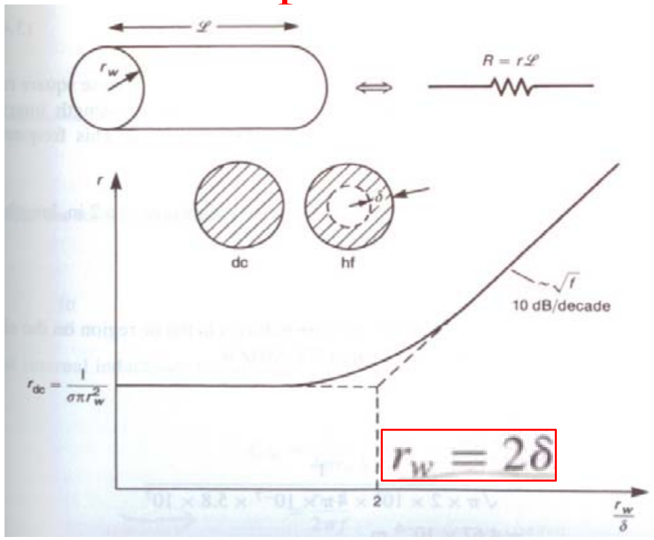
$$= \frac{1}{\sigma \pi r_w^2} \quad (\text{in } \Omega/\mathrm{m})$$

    - As the frequency is increased, the currents tend to concentrate in an annulus of skin depth of

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}}$$

$$= \frac{6.6 \times 10^{-2}}{\sqrt{f}} \quad \mathrm{m}$$

$$= \frac{2.6 \times 10^{3}}{\sqrt{f}} \quad \mathrm{mils}$$



Wires

- Resistance and Internal Inductance of Wires
  - Resistance
    - Thus, the per-unit-length high frequency resistance is

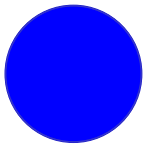
$$
\begin{aligned}
r_{\mathrm{hf}} &= \frac{1}{\sigma[\pi r_w^2 - \pi(r_w-\delta)^2]} \quad \text{for } r_w \gg \delta \\
&\cong \frac{1}{\sigma 2\pi r_w \delta} \\
&= \frac{r_w}{2\delta} r_{\mathrm{dc}} \\
&= \frac{1}{2r_w}\sqrt{\frac{\mu_0}{\pi\sigma}}\sqrt{f} \quad (\text{in } \Omega/\mathrm{m})
\end{aligned}
$$

    - We know that the skin depth decreases with increasing frequency as the inverse square root of the frequency, thus, the high-frequency resistance r_{hf} increases at a rate of 10dB/decade.

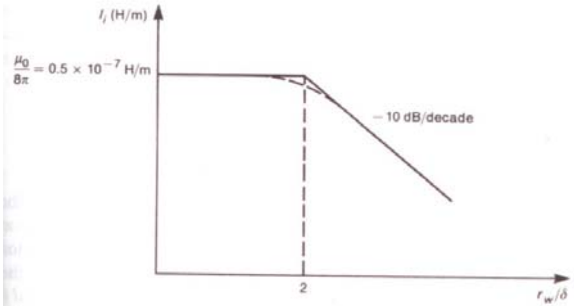
Wires

- Resistance and Internal Inductance of Wires
  - Internal Inductance
    - The isolated wire also has an inductance that is frequency-dependent, which is referred to as the internal inductance.
    - The per-unit-length dc internal inductance is

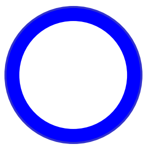
Current distributions



$$
\begin{aligned}
l_{i,\,\mathrm{dc}} &= \frac{\mu_0}{8\pi} \quad \text{for } r_w \ll \delta \\
&= 0.5 \times 10^{-7}\ \mathrm{H/m} \\
&= 50\ \mathrm{nH/m} \\
&= 1.27\ \mathrm{nH/in.}
\end{aligned}
$$



    - For the high frequencies, the per-unit-length hf internal inductance becomes



$$
\begin{aligned}
l_{i,\,\mathrm{hf}} &= \frac{2\delta}{r_w} l_{i,\,\mathrm{dc}} \quad \text{for } r_w \gg \delta \\
&= \frac{1}{4\pi r_w}\sqrt{\frac{\mu_0}{\pi\sigma}}\frac{1}{\sqrt{f}}
\end{aligned}
$$

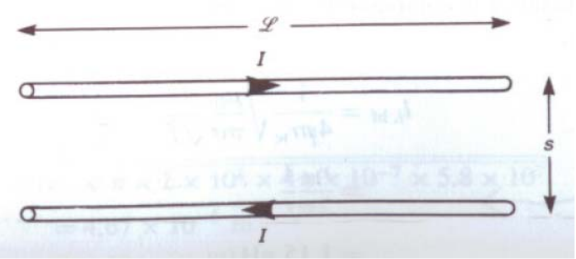
This value decreases at the rate of -10dB/decade for $r_w >> \delta$.

Wires

- External Inductance and Capacitance of Parallel Wires
  - – External Inductance
    - Assuming that the wires are separated sufficiently ($s/r_w > 5$), the per-unit-length external inductance is

Please refer to chapter 4 slide 19 (two wire case)

$$
\begin{aligned}
l_e &= \frac{\psi_m/\mathscr{L}}{I} \\
&= \frac{\mu_0}{\pi}\ln\left(\frac{s}{r_w}\right) \quad \text{(in H/m)} \\
&= 0.4\ln\left(\frac{s}{r_w}\right) \quad (\text{in } \mu\text{H/m}) \\
&= 10.16\ln\left(\frac{s}{r_w}\right) \quad \text{(in nH/in.)}
\end{aligned}
$$



    - The total loop inductance is the sum of internal and external inductances, which is

$$L_{\text{loop}} = 2l_i\mathscr{L} + l_e\mathscr{L}$$

Wires

- External Inductance and Capacitance of Parallel Wires
  - External Capacitance
    - Charge on the wires contributes to a per-unit-length capacitance c between the two wires, which is ($s/r_w > 5$)

Please refer to chapter 4 slide 22 (two wire case)

$$c = \frac{Q/\mathscr{L}}{V}$$

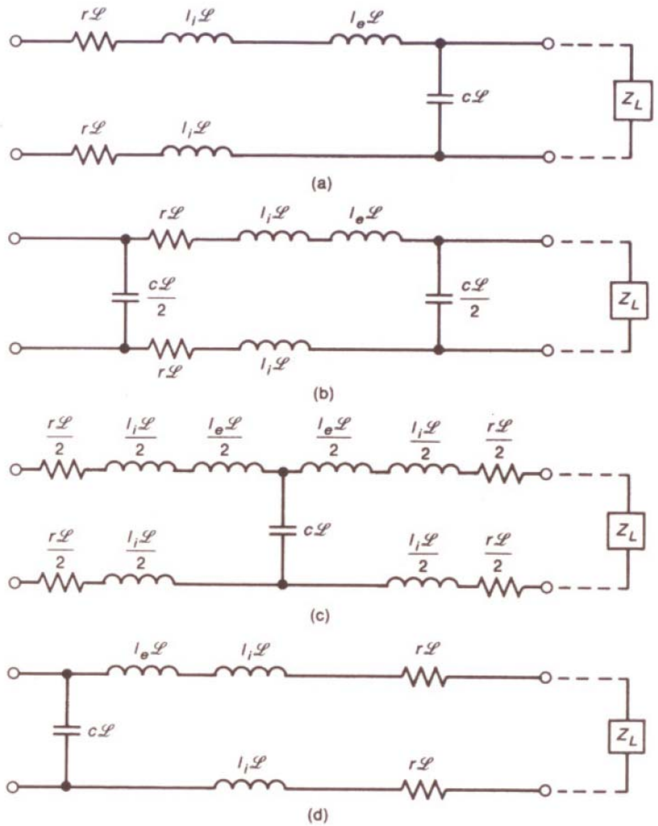
$$= \frac{\pi\epsilon_0}{\ln(s/r_w)} \quad \text{(in F/m)}$$

$$= \frac{27.78}{\ln(s/r_w)} \quad \text{(in pF/m)}$$

$$= \frac{0.706}{\ln(s/r_w)} \quad \text{(in pF/in.)}$$

Wires

- Lumped Equivalent Circuits of Parallel Wires
  - Types of Lumped Equivalent Circuits



Lumped-backward Γ

Lumped π

Lumped T

Lumped Γ

Wires

Additional questions:
When $Z_L=j\omega l$, which one is better?
When $Z_L=1/j\omega c$, which one is better?

- Lumped Equivalent Circuits of Parallel Wires

$$Z_C = \sqrt{\frac{l_e}{c}} = 120 \ln\left(\frac{s}{r_w}\right) \quad \Omega$$

  - Which One is Better?
    - If the load impedance Z_L is a "low impedance," i.e., much less than the characteristic impedance of the line, the lumped-T and lumped-Γ models would extend the frequency range of adequate prediction slightly higher than the lumped-backward Γ and lumped-π models.
    - Since the parallel capacitance elements of the lumped-backward Γ and lumped-π models would be rendered ineffectively by the low load impedance Z_L.
    - Conversely, the lumped-backward Γ and lumped-π models are better choices for large Z_L.

Wires

- Lumped Equivalent Circuits of Parallel Wires
  - Relationship between Internal and External Inductances

$$\boxed{Z_{\text{internal}} = j\omega l_i = j2\pi f l_i}$$

$$l_{i,\text{hf}} = \frac{2\delta}{r_w} l_{i,\text{dc}} \quad \text{for } r_w \gg \delta$$
$$= \frac{1}{4\pi r_w}\sqrt{\frac{\mu_0}{\pi\sigma}}\frac{1}{\sqrt{f}}$$

$$\boxed{Z_{\text{external}} = j\omega l_e = j2\pi f l_e}$$

    - The impedance of the internal inductance increases only as the square root of the frequency where the impedance of the external inductance increases with frequency. Therefore, the impedance of the external impedance increases with frequency at a rate faster than that of the impedance of the internal inductance.
    - Usually, the impedance of the internal inductance is usually smaller than the impedance of the external inductance, thus, could be neglected.

Wires

- Lumped Equivalent Circuits of Parallel Wires
  - Homogeneous → Inhomogeneous
    - The presence of inhomogeneous dielectric media does not affect the external inductance parameter.
    - However, the capacitance is affected by the inhomogeneous dielectric and is usually obtained by using the numerical methods – MoM, FEM, FDTD, etc.

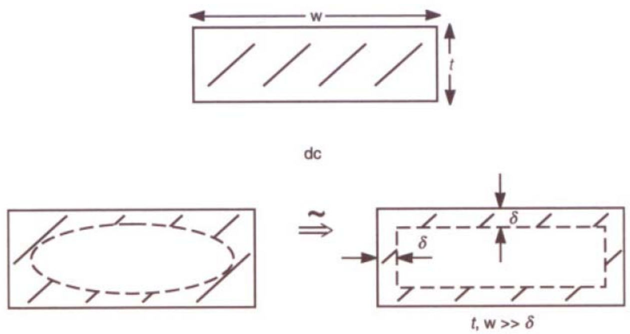
Printed Circuit Board (PCB) Lands

- Line Parameters
  - Resistance
    - The per-unit-length low-frequency resistance of the land is

$$r_{\text{lf}} = r_{\text{dc}} = \frac{1}{\sigma w t} \quad (\text{in } \Omega/\text{m})$$

    - The per-unit-frequency high-frequency resistance is approximated as

$$r_{\text{hf}} = \frac{1}{\sigma(2\delta w + 2\delta t)} = \frac{1}{2\sigma\delta(w+t)} \quad (\text{in } \Omega/\text{m})$$



    - The crossing point of the two resistances is (r_{dc}=r_{hf})

$$\delta = \frac{1}{2}\frac{wt}{(w+t)} \cong \frac{t}{2} \qquad w \gg t$$

Printed Circuit Board (PCB) Lands

- Line Parameters
  - Characteristic Impedance and Phase Velocity
    - Since the external inductance and capacitance are difficult obtained by simple method, thus, usually the line is described by the characteristic impedance

$$Z_C = \sqrt{\frac{l_e}{c}} \quad \Omega$$

    - and the phase velocity

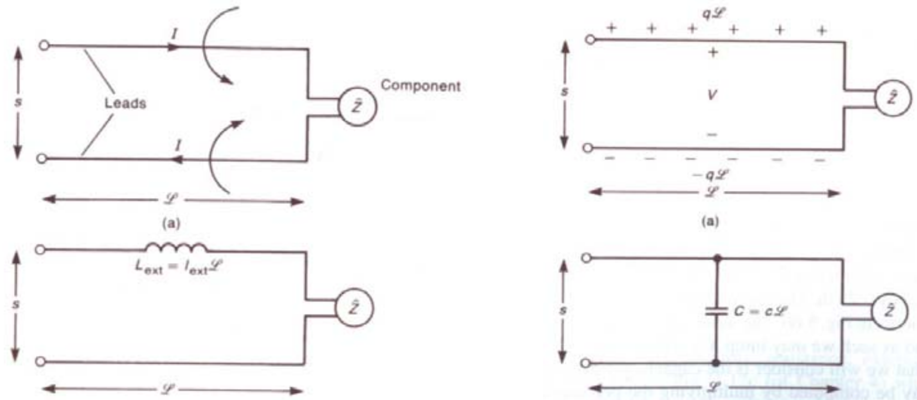
$$v = \frac{1}{\sqrt{l_e c}} = \frac{1}{\sqrt{\epsilon_r' \epsilon_0 \mu_0}} = \frac{v_0 = 3 \times 10^8}{\sqrt{\epsilon_r'}} \quad \text{m/s} = \frac{11.8}{\sqrt{\epsilon_r'}} \quad \text{in./ns}$$

    - The per-unit-length external inductance and capacitance can be obtained from these as

$$l_e = \frac{Z_C}{v} \qquad c = \frac{1}{v Z_C}$$

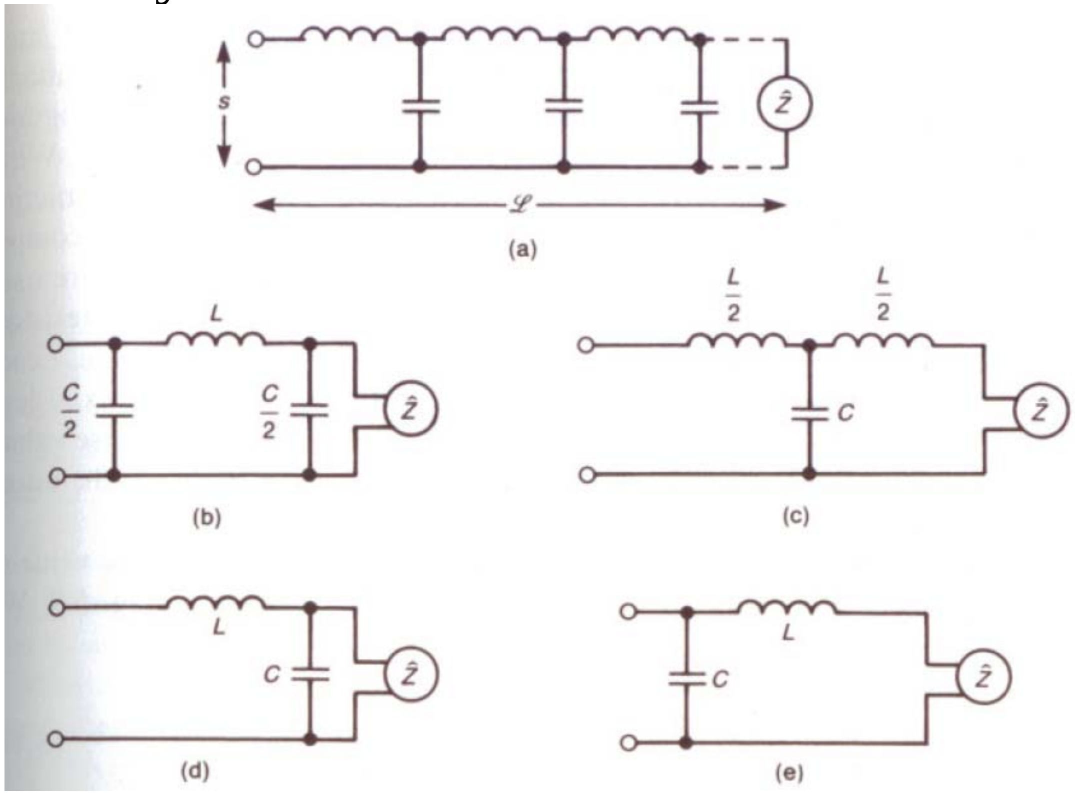
Effect of Component Leads

- Line Parameters
  - External Inductance and Capacitance
    - The length and separation of the component leads cause the components to have, in addition to the ideal behavior, an inductive element and a capacitive element.
    - If the lead length $\mathscr{L}$ and separation s are electrically short at the frequencies of interest, we may lump L and C (per-unit-length values multiplied by the lead length $\mathscr{L}$).



Effect of Component Leads

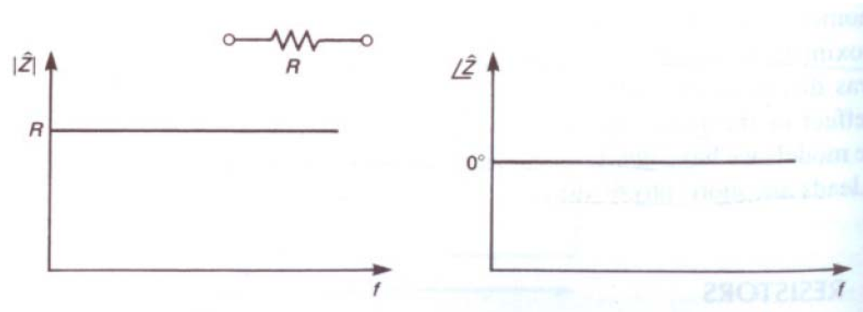
- Line Parameters
  - Distributed Model to Lumped Model
    - The four types of models were mentioned previously.



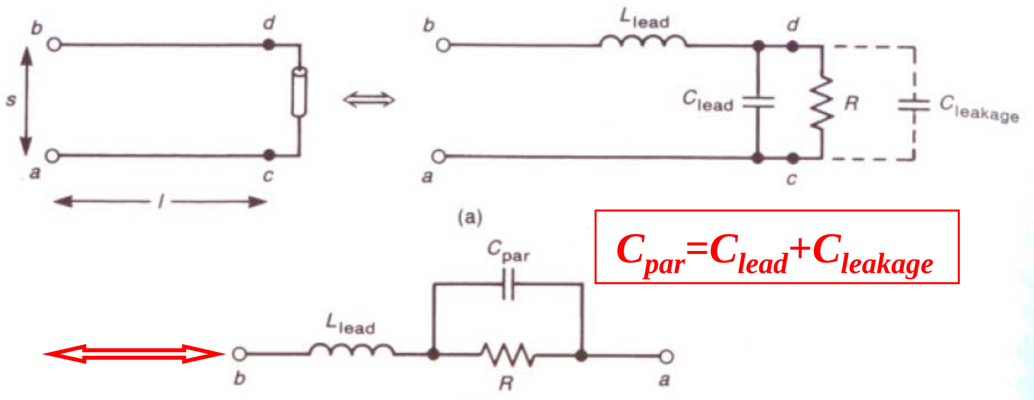
Resistors

- Ideal Resistors
  - Frequency Response of the Impedance
    - The ideal resistor is of the form

$$\hat{Z} = R\angle 0^\circ$$



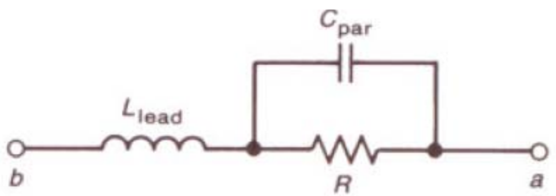
- Nonideal Resistors
  - Model
    - L_{lead}
    - C_{lead}
    - $C_{leakage}$



$C_{par}=C_{lead}+C_{leakage}$

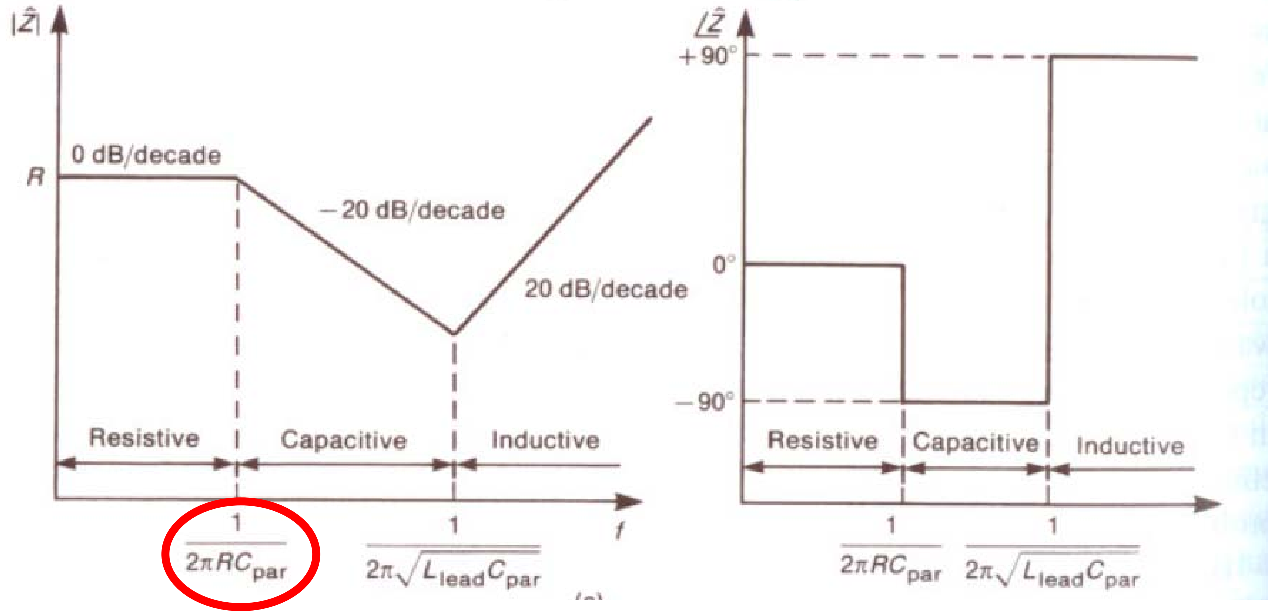
Resistors

- Nonideal Resistors
  - Model



    - The input impedance could be expressed as

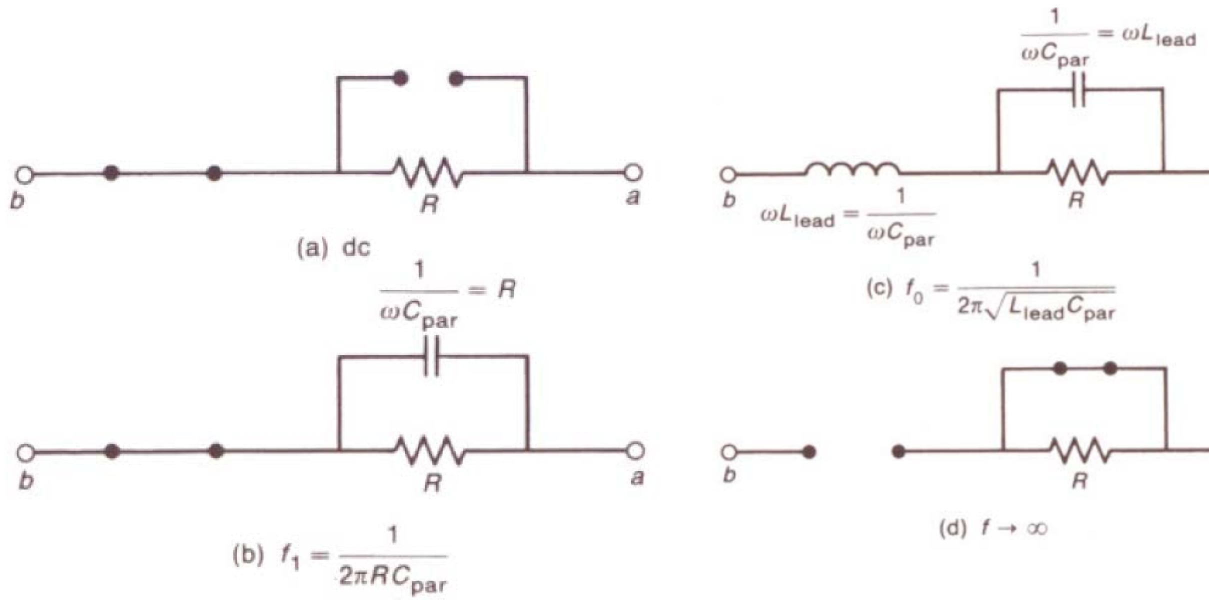
$$\hat{Z}(j\omega) = L_{\text{lead}} \frac{1/L_{\text{lead}}C_{\text{par}} - \omega^2 + j\omega/RC_{\text{par}}}{j\omega + 1/RC_{\text{par}}}$$



Ideal behavior of a resistor is dominated by this value, which means by R and C_{par}. Usually, large R results in lower turning frequency.

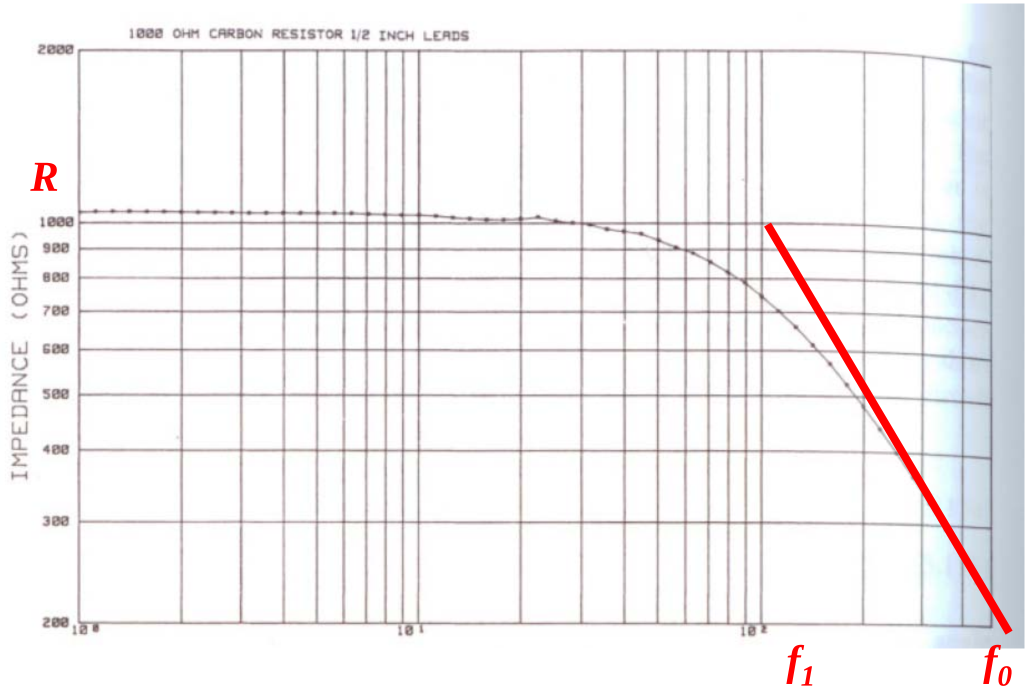
Resistors

- Nonideal Resistors
  - Simplification for Various Frequencies
    - Usually, we only need to know the simplified circuit at the frequency of interest.



Resistors

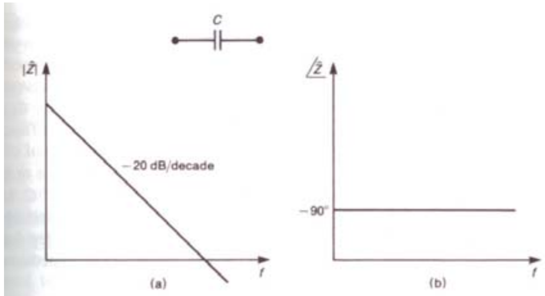
- Nonideal Resistors
  - Example for a 1000-Ω Carbon Resistor Having ½ in. Lead Length
    - The equivalent circuit parameters R, L_{lead} and C_{par} are extracted by matching R, f_1 and f_o.



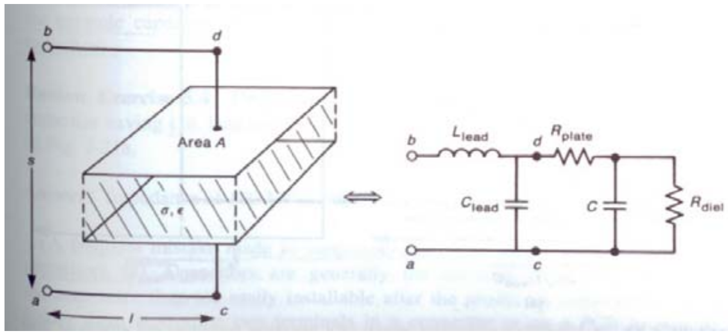
Capacitors

- Ideal Capacitors
  - Frequency of the Impedance
    - The ideal behavior of a capacitor is shown below

$$\hat{Z}(j\omega) = \frac{1}{j\omega C} = -j\frac{1}{\omega C} = \frac{1}{\omega C}\angle{-90^\circ}$$



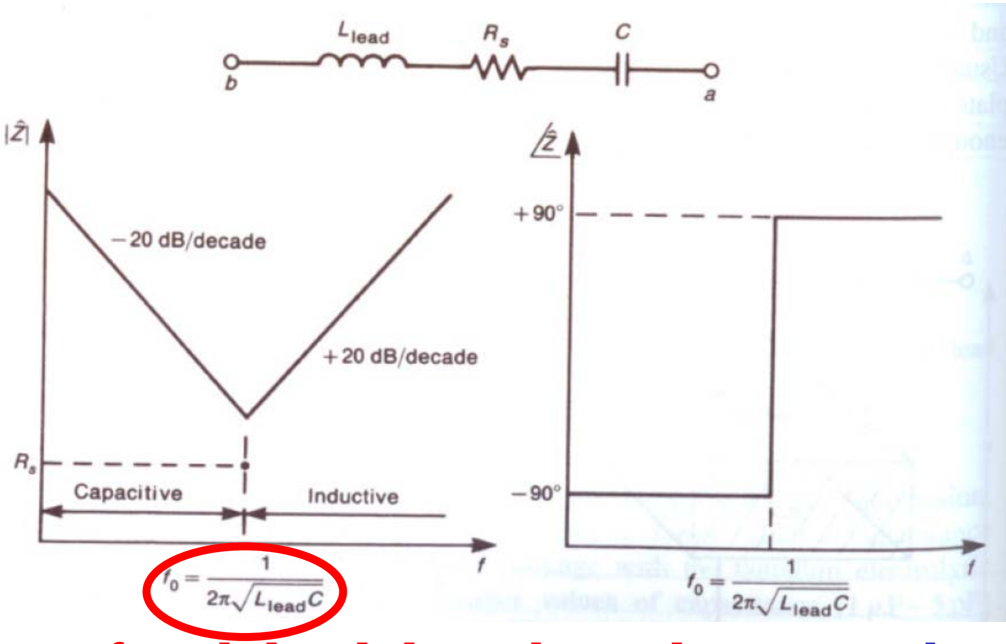
- Nonideal Capacitors
  - Model



    - R_{plate}
    - L_{lead}
    - C_{lead}: small, neglected
    - R_{diel}: large (G_{diel} small), neglected

Capacitors

- Nonideal Capacitors
  - Model
    - The impedance of the model is $\hat{Z}(j\omega) = L_{\text{lead}} \dfrac{1/L_{\text{lead}}C - \omega^2 + j\omega R_s/L_{\text{lead}}}{j\omega}$



    - For a fixed lead length and space, the larger the capacitance value the lower the self-resonant frequency (the usable range is reduced).

Capacitors

- Nonideal Capacitors
  - How to Choose an Adequate Value?
    - One might place a capacitor between the signal and return wires of the cable to divert the high-frequency noise.
    - We may intuitively think that a larger value of capacitance would divert the high-frequency noise more efficiently.
    - This is not exactly true since a larger value of capacitance would drive the resonant-frequency below the operating frequency of the circuit, thus, the capacitor becomes a large inductor and could no more divert the noise.

Capacitors

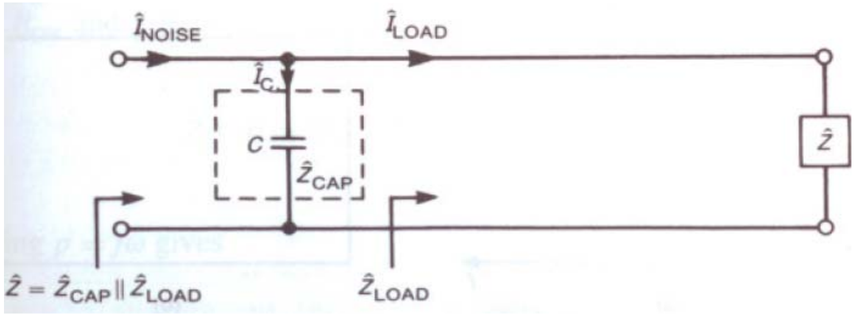
- Nonideal Capacitors
  - Influence on Functional Signals
    - Placing a capacitor across the signal and return leads of a cable in order to divert high-frequency signal components from the cable can produce ringing by virtue of the resonance created by the capacitor in parallel with the mutual inductance of the cable.
    - Usually, an *RC* circuit would form a lowpass filter. The transfer function so formed is flat out to the break frequency of $1/2\pi RC$ and decreases at a rage of -20-dB/decade above that.
    - The break frequency should be larger than the signal spectrum and lower than the noise spectrum.

Capacitors

- Nonideal Capacitors
  - Influence on Functional Signals
    - One must be careful to not adversely affect the functional signal with a suppression scheme, or else passing the regulatory limits will be a moot point.
    - If the added suppression scheme does not produce a sufficient reduction, there is a reason why it does not.
    - Parallel capacitors work best in high-impedance circuits with regard to divert the noise current.

$$\hat{I}_C = \frac{\hat{Z}_{LOAD}}{\hat{Z}_{CAP} + \hat{Z}_{LOAD}} \hat{I}_{NOISE}$$

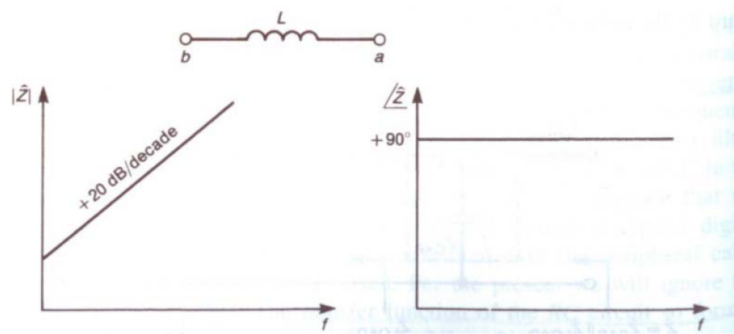
When Z_{LOAD} is large, I_C is large.



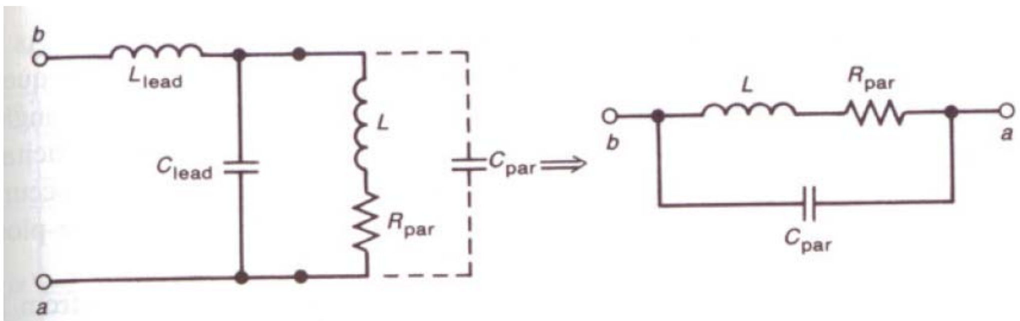
Inductors

- Ideal Inductors
  - Frequency Response of the Impedance
    - The impedance of an ideal inductor against frequency is

$$\hat{Z}_L = j\omega L = \omega L \angle 90^\circ$$

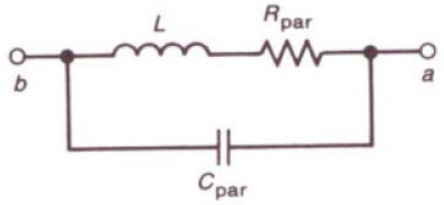


- Nonideal Inductors
  - Model
    - L_{lead}
    - C_{lead}
    - R_{par}

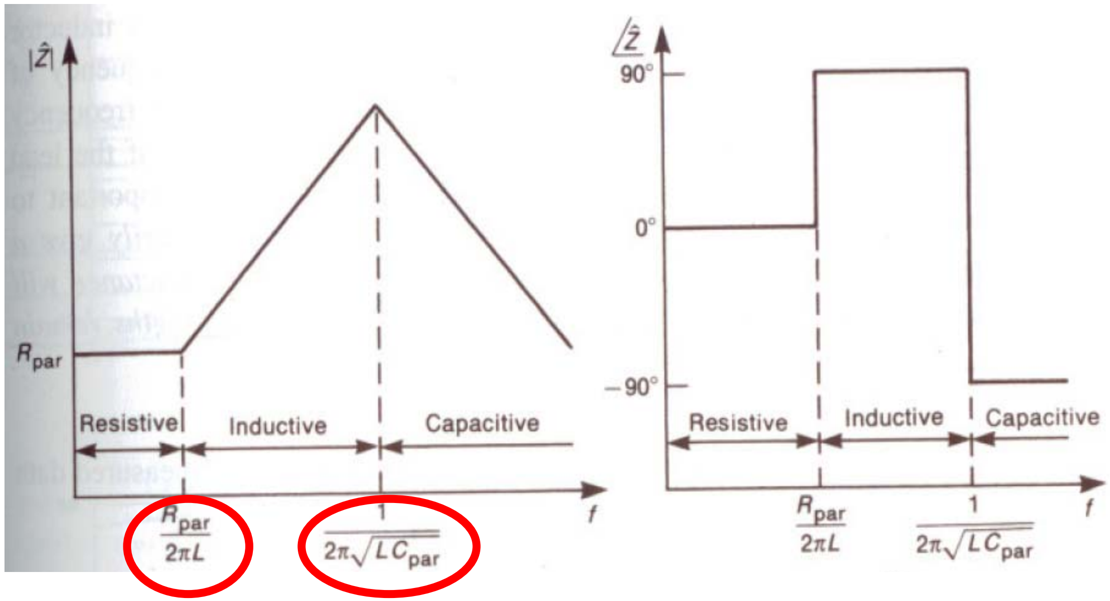


Inductors

- Nonideal Inductors
  - Model



    - The impedance of this model is $\hat{Z}_L(j\omega) = R_{\text{par}} \dfrac{1 + j\omega L/R_{\text{par}}}{1 - \omega^2 L C_{\text{par}} + j\omega R_{\text{par}} C_{\text{par}}}$

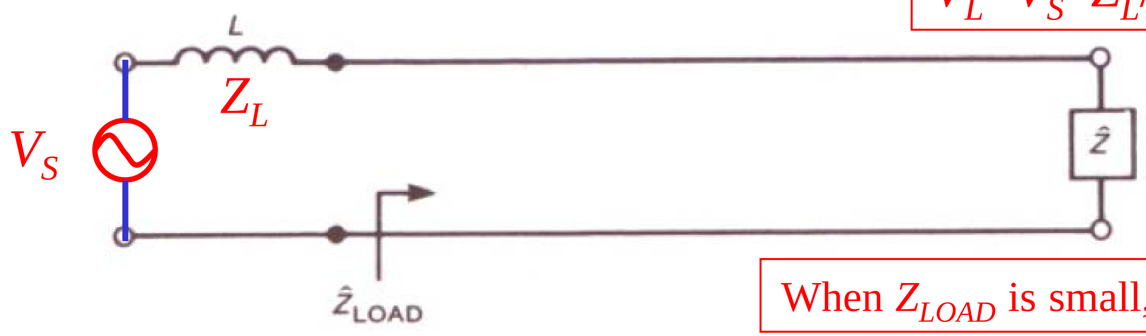


Increasing the value of an inductor will not necessarily give a lower impedance at high frequencies, since the larger value of inductance will serve to lower the self-resonant frequency, thus transforming the inductor to a large capacitor.

Inductors

- Nonideal Inductors
  - Useful in Low Impedance Load
    - Capacitors are placed in parallel to divert noise currents, whereas inductors are placed in series with wires or lands to block noise currents.
    - This will be effective if the impedance of the inductor at the frequency of the noise current is larger than the original series impedance seen looking into the wires or lands, Z_{LOAD}.

$V_L = V_S * Z_L / (Z_L + Z_{LOAD})$



When Z_{LOAD} is small, V_L is large.

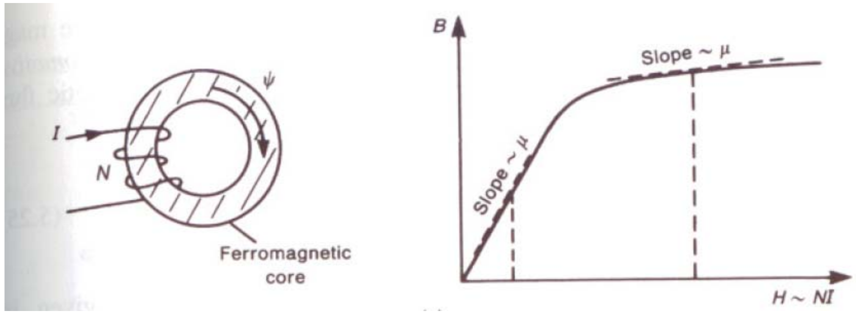
Ferromagnetic Materials

- Saturation and Frequency Response
  - Saturation
    - The permeability is the slope of the *B-H* curve, which is defined as

$$\mu = \frac{\Delta B}{\Delta H}$$

    - At low values of current *I*, the slope of the *B-H* curve is large, as is the permeability. As current is increased, the slope decreases. Thus, the permeability decreases with increasing current *I*, which means that the inductance decreases with increasing current.

I small → *H* small → μ large → *l* large.

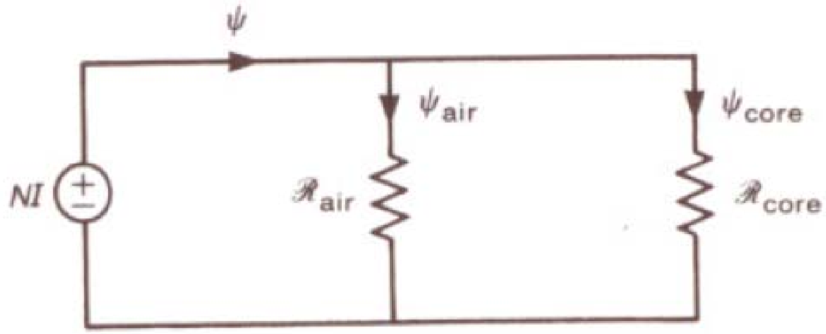


Ferromagnetic Materials

- Saturation and Frequency Response
  - Equivalent Circuit
    - Making the analogy of the voltage to the magnetomotive force (mmf) *NI*, and current to magnetic flux Ψ, the portion of the total flux Ψ that remains in the core is

$$\psi_{core} = \frac{\mathcal{R}_{air}}{\mathcal{R}_{air} + \mathcal{R}_{core}} \psi$$

$$R = \frac{NI}{\psi}$$



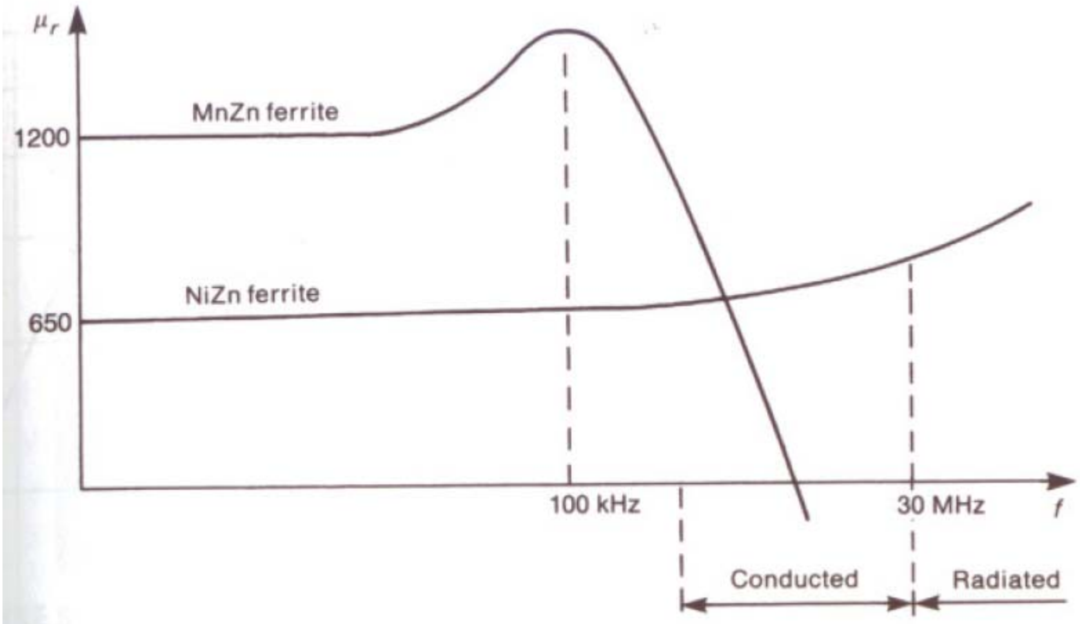
- where the reluctance is

$$\mathcal{R} = \frac{l}{\mu A}$$

Magnetic fields tend to concentrate in high-permeability materials. Larger μ → smaller R_{core} → larger Ψ_{core}

Ferromagnetic Materials

- Saturation and Frequency Response
  - Frequency Response
    - A large value of initial permeability may not be the best choice in the frequency of interest due to the frequency response.



Large μ is required for large inductance.

Ferrite Beads

- Characteristics
  - Ferrite materials are basically nonconductive ceramic materials (that differ from other ferromagnetic materials) such as iron in that they have low eddy-current losses at frequencies up to hundreds of megahertz.
  - Thus they can be used to attenuate the high-frequency noises that we wish to suppress and not affect the more important lower-frequency components of the functional signal.
  - It can be inserted in series with a wire or land to provide a high-frequency impedance in that conductor.

Ferrite Beads

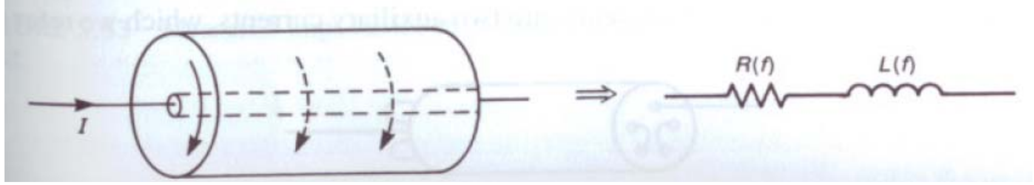
- Lossy Ferrite
  - Equivalent Circuit
    - The inductance is proportional to the permeability of the bead material $L_{\text{bead}} = \mu_0 \mu_r K$
    - Thus the impedance of the bead inductance is

$$
\begin{aligned}
j\omega L_{\text{bead}} &= j\omega \mu_0 \mu_r K \\
&= j\omega \mu_0 (\mu_r' - j\mu_r'') K \\
&= \underbrace{\omega \mu_r''(f) \mu_0 K}_{R(f)} + \underbrace{j\omega \mu_r'(f) \mu_0 K}_{L(f)}
\end{aligned}
$$

    - where $\mu_r = \mu_r'(f) - j\mu_r''(f)$

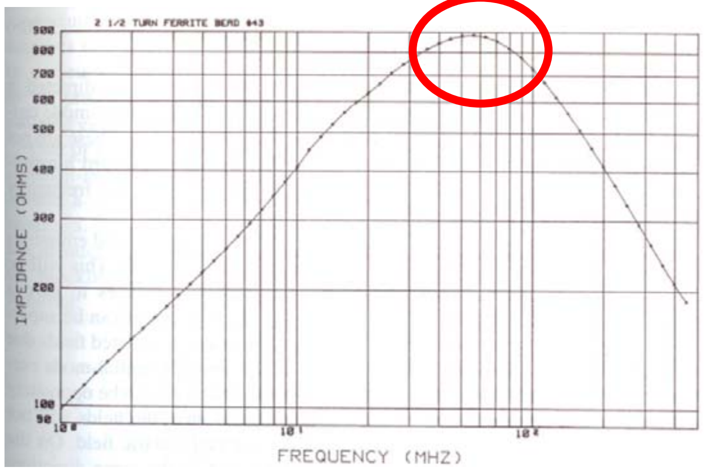
Losses in bead material

Stored magnetic energy



Ferrite Beads

- Lossy Ferrite
  - Equivalent Circuit
    - Multiple-hole ferrite beads can be used to increase the inductance, thus increasing the high-frequency impedance.
    - Ferrite beads are no different than other uses of ferrites in that they are susceptible to saturation when used in circuit that pass high-level, low-frequency currents.



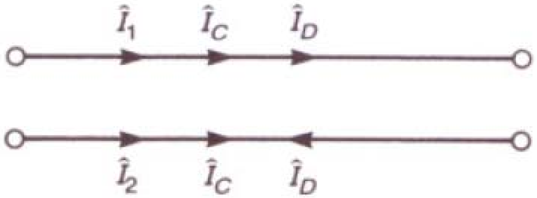
Resonance caused by the capacitance between adjacent wires.

Common-Mode Chokes

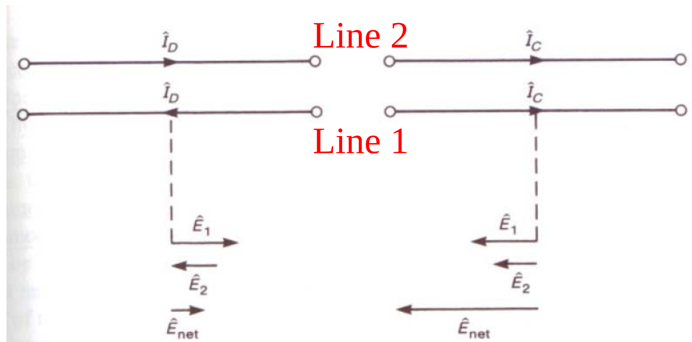
- Parallel Wires
  - Effects of Common- and Differential- Modes
    - The currents I_1 and I_2 could be decomposed of a combination of common- and differential-mode currents.

$$\hat{I}_1 = \hat{I}_C + \hat{I}_D \qquad \hat{I}_D = \tfrac{1}{2}(\hat{I}_1 - \hat{I}_2)$$

$$\hat{I}_2 = \hat{I}_C - \hat{I}_D \qquad \hat{I}_C = \tfrac{1}{2}(\hat{I}_1 + \hat{I}_2)$$



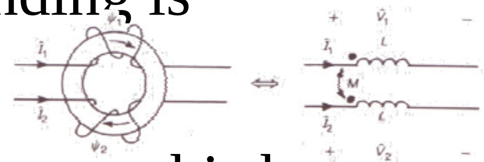
    - Common-mode currents have a much higher potential for producing radiated emissions than do differential-mode currents.



Common-Mode Chokes

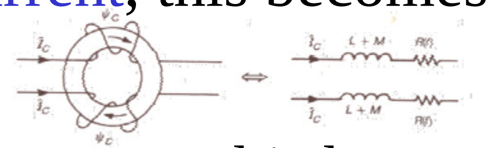
- Parallel Wires
  - Theory of Common-Mode Chokes
    - The impedance of one winding is

$$\hat{Z}_1 = \frac{\hat{V}_1}{\hat{I}_1} = \frac{pL\hat{I}_1 + pM\hat{I}_2}{\hat{I}_1} \qquad p = j\omega$$



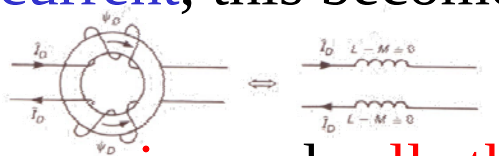
    - For the common-mode current, this becomes

$$\hat{Z}_{CM} = p(L+M)$$



    - For the differential-mode current, this becomes

$$\hat{Z}_{DM} = p(L-M)$$



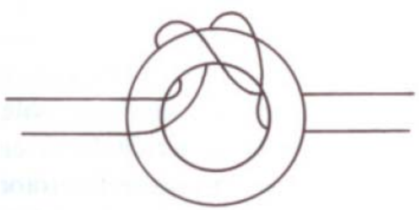
    - If the winding are symmetric and all the flux remains in the core, i.e., the flux of one winding completely links the other winding, then $L=M$ and $Z_{DM}=0$.

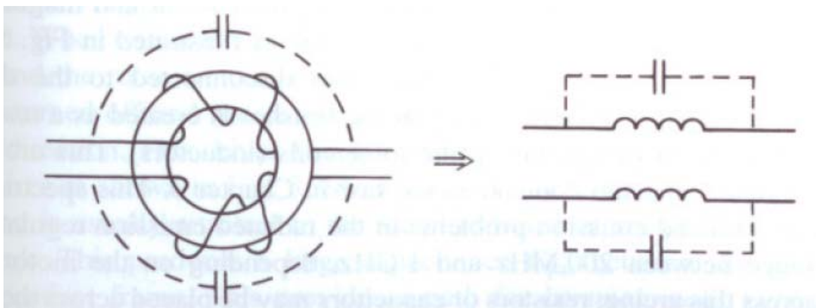
Common-Mode Chokes

- Parallel Wires
  - Theory of Common-Mode Chokes
    - Thus, in the ideal case where $L=M$, a common-mode choke has no effect on differential-mode currents, but selectively places an inductance $2L$ in series with the two conductors to common-mode currents.
    - Use of ferrite cores places a frequency-dependent resistance, $R(f)$, in series with the common-mode currents as well. Hence common-mode currents not only are blocked but also have their energy dissipated in the $R(f)$.

Common-Mode Chokes

- Parallel Wires
  - Theory of Common-Mode Chokes
    - The wires must be wound around the core such that the fluxes due to the two common-mode currents add in the core whereas the fluxes due to the two differential-mode currents subtract in the core.
    - One should ensure that the wires entering the winding and those exiting the winding are separated from each other on the core such that the parasitic capacitance between them is small.



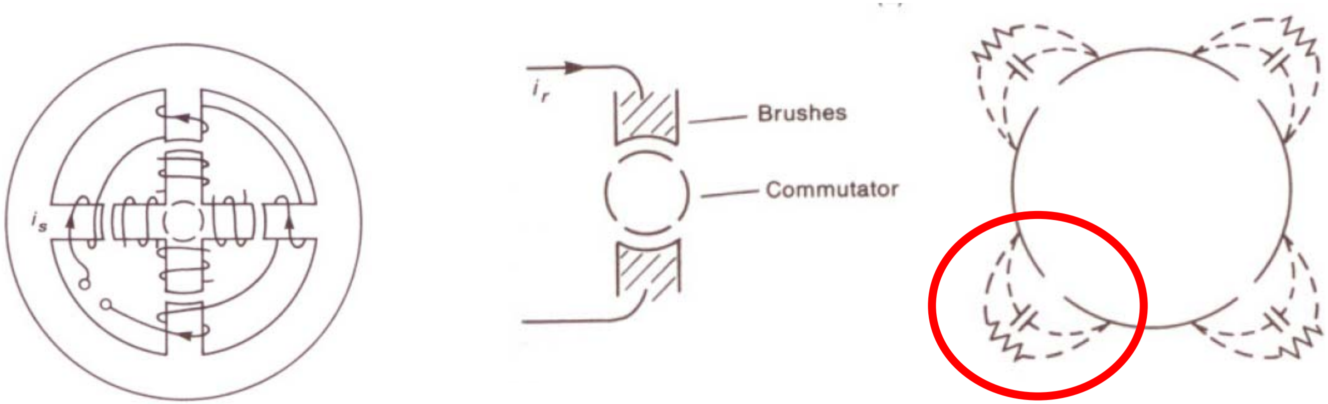


Common-Mode Chokes

- Parallel Wires
  - Theory of Common-Mode Chokes
    - Since fluxes due to the differential-mode currents cancel in the core and do not saturate it, the differential-mode currents (functional) could be as large as desired.
    - The common-mode noise is usually small and would not suffer from the saturation, thus a large blocking inductance is obtained.
    - The functional signals (differential-mode current) are not (ideally) affected by the presence of the choke, and also do not affect the performance of the choke.

Electromechanical Devices

- DC Motors
  - Arc Suppression
    - As the current to the rotor coils is connected and disconnected to the dc source through the commutator segments, arcing at the brushes is created as a result of the periodic interruption of the current in the rotor coils (inductors). $\boxed{\Phi = Li \rightarrow v = -L(\delta i / \delta t)}$

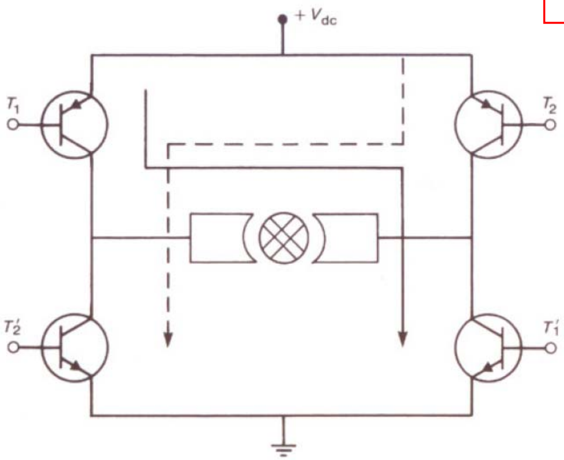


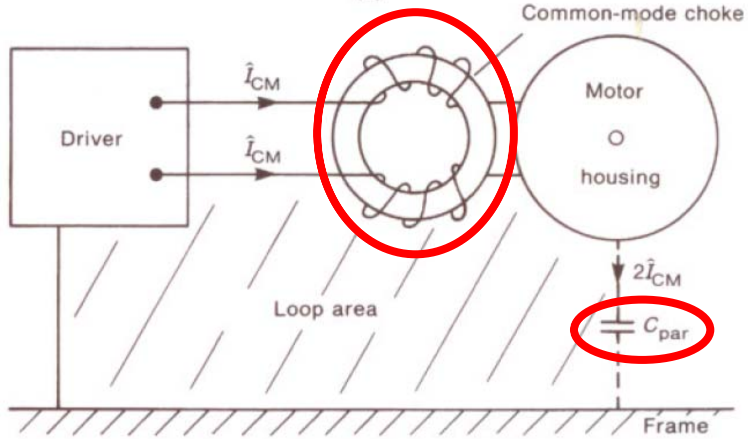
Resistors or capacitors used to suppress this arcing.

Electromechanical Devices

- DC Motors
  - Driver Circuit
    - The driver circuits are used to change the direction of rotation to provide precise position control of the motor.

The loop area should be as small as possible to reduce radiated emission.





Noise is generated while changing from T_1-T_1' path to T_2-T_2' path.

A common-mode choke is used to reduce the common-mode noise.

Electromechanical Devices

- Other Devices
  - Stepper Motors
    - The stator and the rotor are segmented into a large number of poles around their peripheries in order to provide fine positioning.
  - AC Motors
    - This motor are used to provide constant speed and drive small cooling fans.
  - Solenoids
    - This is composed of a coil of wire with a ferromagnetic slug at its center.
  - All these devices need a common-mode choke to suppress the common-mode currents.

Digital Circuit Devices

- Important Effects
  - Speed of Digital Data
    - The requirement for increased speeds of data transmission and processing will no doubt cause these EMC concerns to increase in digital products in the future.
  - Buffer Gates
    - Buffer gates are frequently provided to interface between low-current logic signal and high-current outputs. These have the effect of "squaring up" the signals, which in turn reduce the rise/falltimes, thus increasing its high-frequency spectral contents.

Digital Circuit Devices

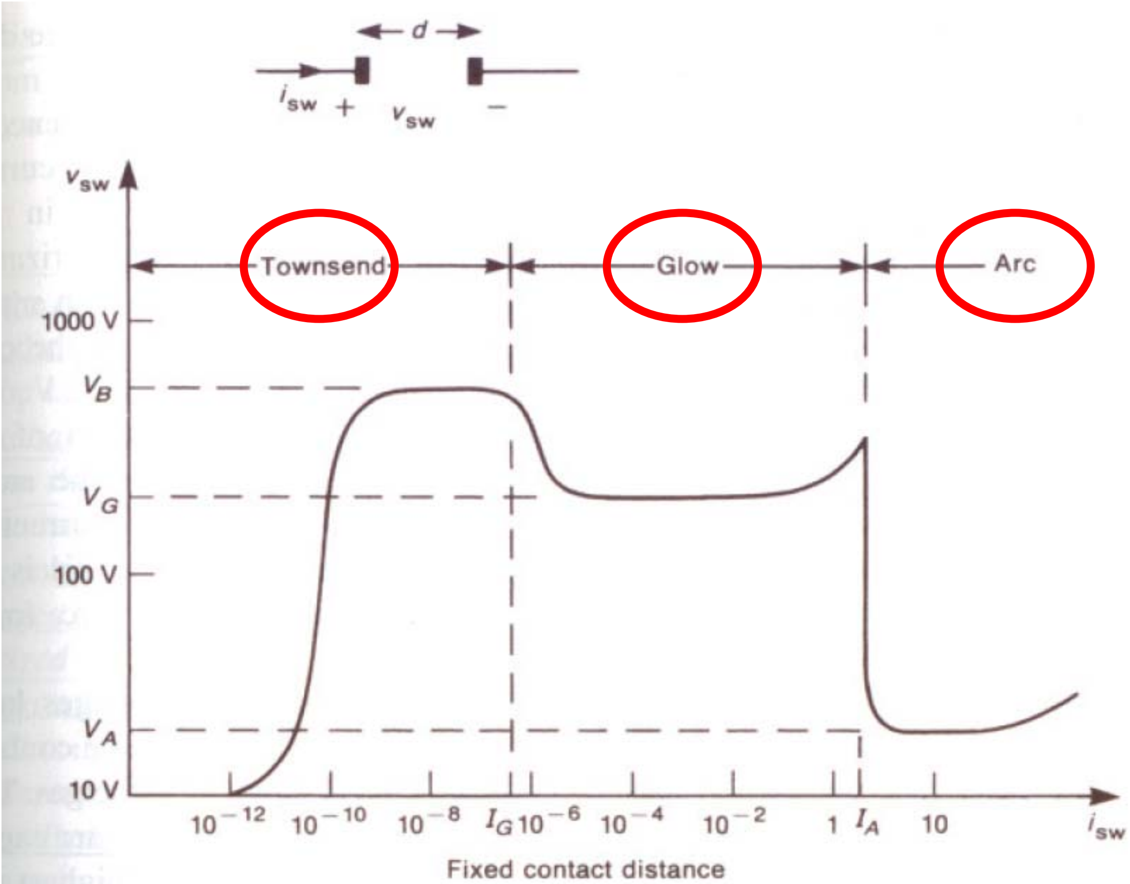
- Important Effects
  - Rare Event Conductors
    - Conductors used in “rare events” such as reset should be taken care. Although they are not intended to carry high-frequency signals, they may have these present as a result of inadvertent coupling to these lines.
    - The most effective method of reducing radiated and conducted emissions is to affect the source of these emissions.
  - Semiconductor Junction Capacitances
    - This would provide a direct connection at high frequencies from the input of the device to its outputs.

Effect of Component Variability

- Conflicts Between Goal of EMC and Goal of Functional Performance
  - Important Points
    - One must realize that the functional performance goals and the EMC performance goals are often in conflict.
    - For example, the functional performance goals need a shorter rise/falltimes, whereas EMC performance goals need a longer rise/falltimes.
    - Changing parts vendors to reduce cost at some point in the production cycle of the product can create compliance problems.

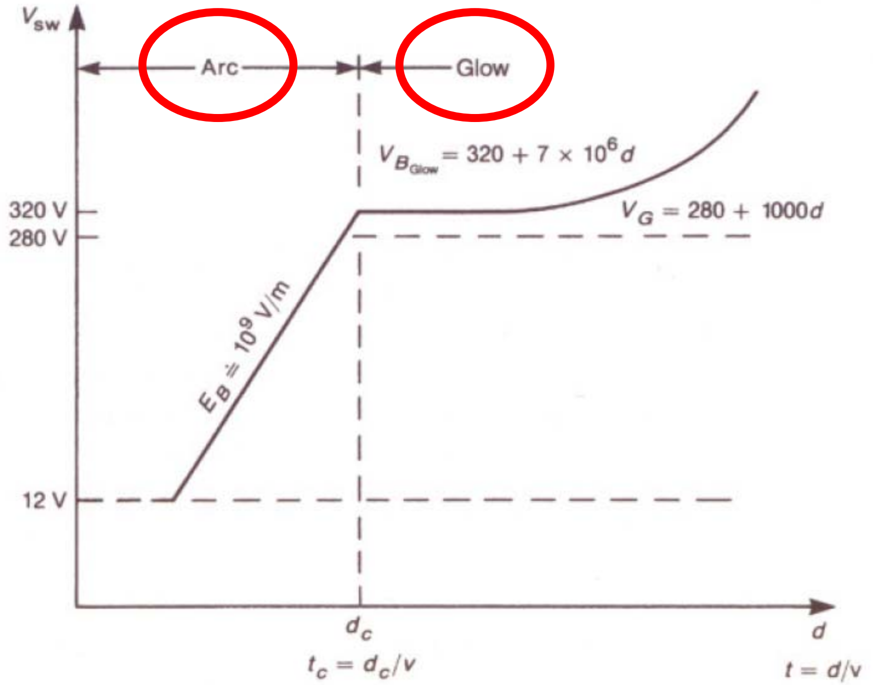
Mechanical Switches

- Arcing at Switch Contacts
  - Arcing at Mechanical Contacts—Fixed Contact Distance



Mechanical Switches

- Arcing at Switch Contacts
  - Arcing at Mechanical Contacts—Variable Contact Distance
    - This figure is formed when the contact is opened with a constant speed *v*.

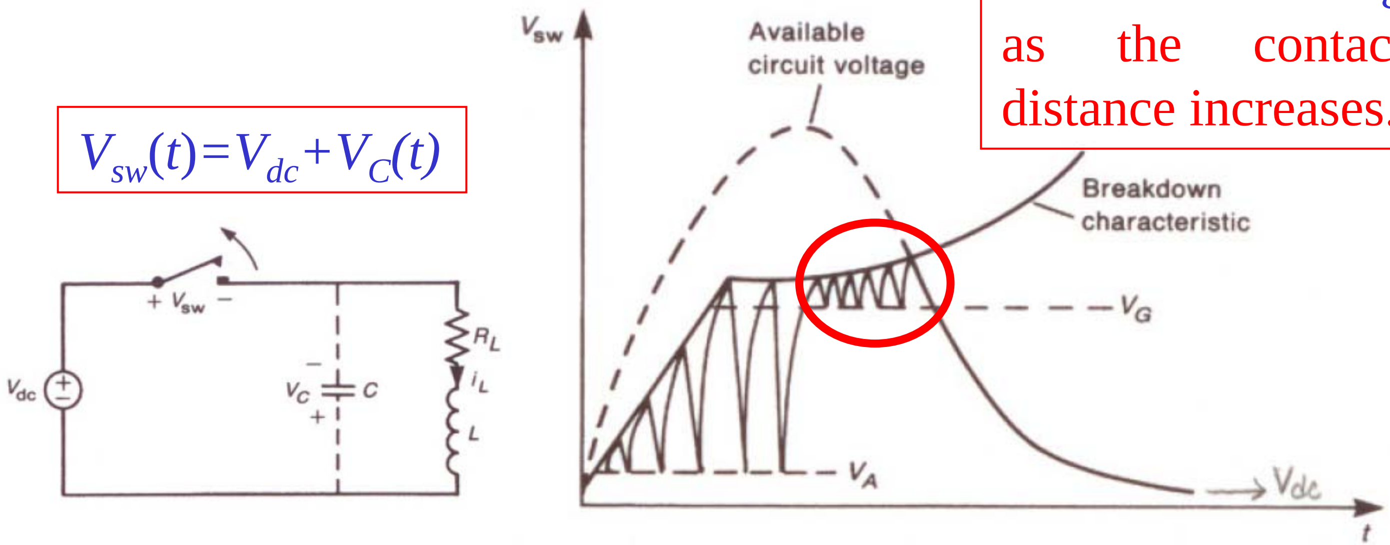


Mechanical Switches

- The Showering Arc
  - – Switches Used on Inductive Loads
    - Switches used to interrupt inductive loads such as solenoids or motors, would cause the showering arc.
    - This figure is plotted for the shower arc after the switch is opened.

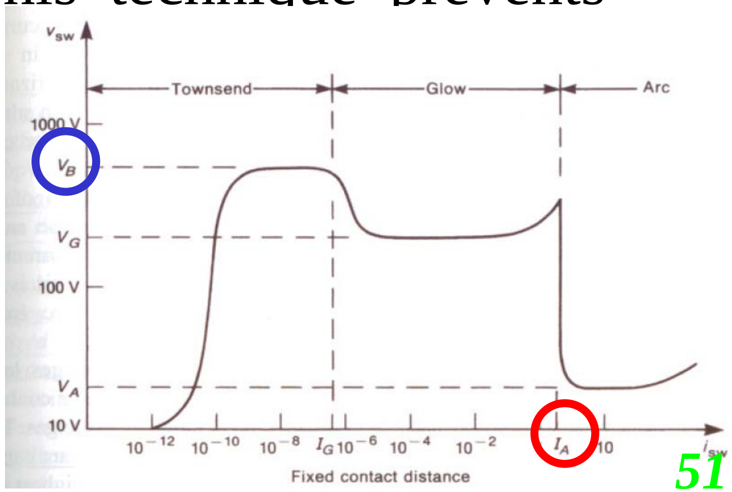
Glow Showering as the contact distance increases.

$V_{sw}(t)=V_{dc}+V_C(t)$



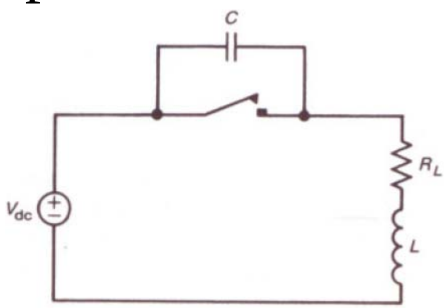
Mechanical Switches

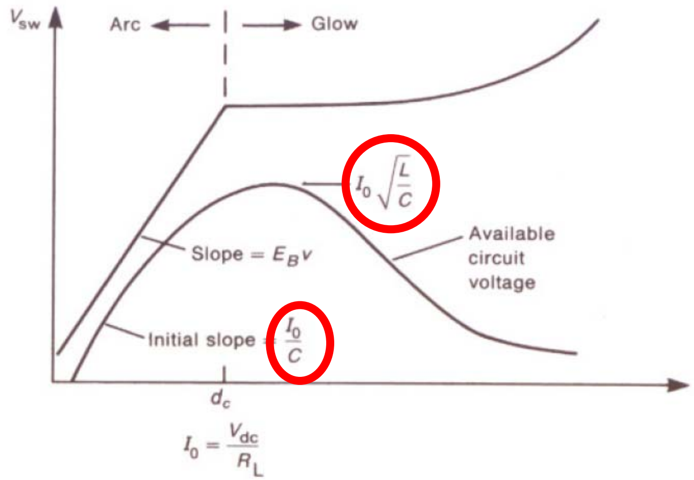
- Arc Suppression
  - Two Types of Methods
    - Preventing the switch voltage from exceeding the glow breakdown voltage of the switch (which is approximately 320V). → This technique prevents the arc from forming.
    - Ensuring that the arc current is below the minimum arc-sustaining current. → This technique prevents the arc from being sustained.



Mechanical Switches

- Arc Suppression
  - Capacitance in Parallel with Contact or Inductor L
    - Contact damage during switch closure may be significant if a rather large value of capacitor is adopted since the capacitor charging current is large.





$$\text{(a)} \quad E_B v > \frac{V_{dc}}{R_L C} \qquad I_0$$

$$\text{(b)} \quad \frac{V_{dc}}{R_L}\sqrt{\frac{L}{C}} < V_{B,\,gas} \cong 320 \text{ V}$$

Mechanical Switches

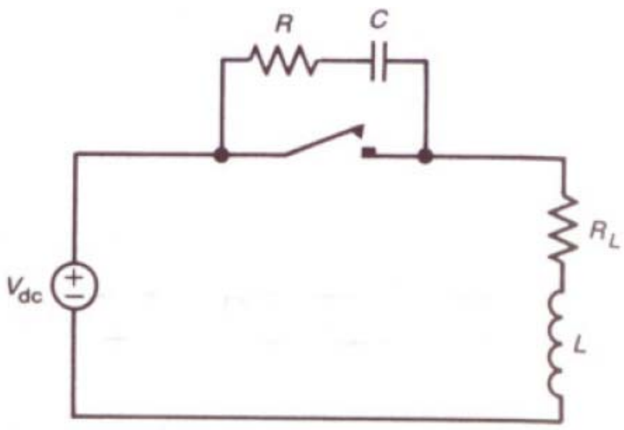
- Arc Suppression
  - RC Solution
    - A resistor is placed in series with the capacitor to limit the discharge current that occurs on contact closure.
    - The resistor R is chosen such that the discharge current on switch closure is below I_A and the contact voltage equal to at most the supply voltage.

$$\frac{V_{\mathrm{dc}}}{I_{A,\min}} < R < R_L$$

The values of the capacitances are derived from (a) and (b):

$$(1) \quad C \geq \left(\frac{1}{320} I_0\right)^2 L$$

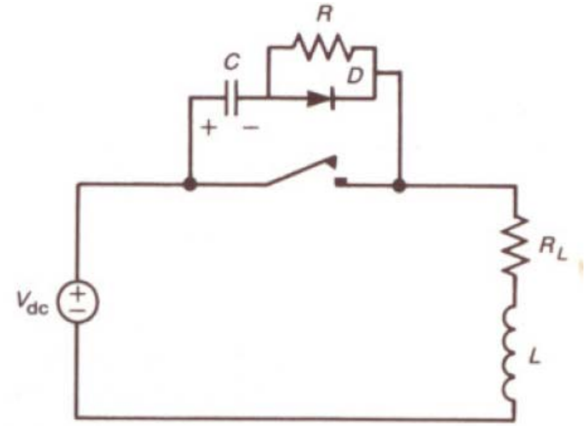
$$(2) \quad C \geq I_0 \times 10^{-6}$$



Mechanical Switches

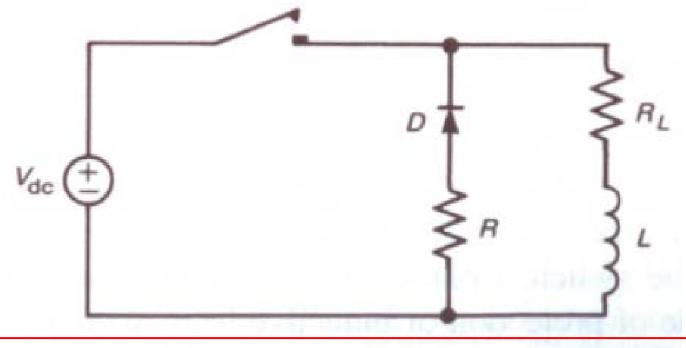
- Arc Suppression
  - RC and Diode Solution
    - A more sophisticated circuit uses a diode to discharge the charges on the capacitor while the contact is opened.
    - The capacitor value is chosen as above, but the resistor value is chosen to limit the current on closure to be less than the minimum arcing current:

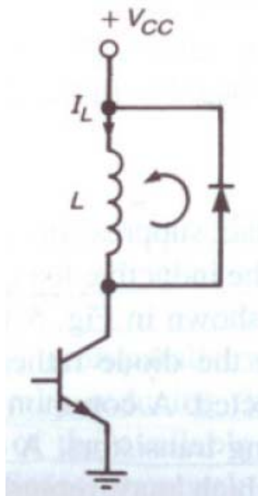
$$R \geq V_{dc}/I_{A,\min}$$



Mechanical Switches

- Arc Suppression
  - Diode Protection for an Inductive Load
    - The capacitor value is chosen as above, but the resistor value is chosen to limit the current on closure to be less than the minimum arcing current:





Since $\Phi = Li \rightarrow v = -L(\delta i/\delta t)$, we should use a diode to prevent a large voltage from arcing the contact.

The diode should be placed as close as possible to the inductor in order to reduce the loop area.