Electronic Components

Real-world components, network elements, and network models

Real-world electronic components

Show intended electrical behavior over a limited operating range:

- Temperature
- Voltage
- Current
- Frequency
- Time
- Force
- Illumination
- E-field
- H-field
- etc.

- Non-ideal electrical properties of used materials that determine the intended electrical behavior
  - Temperature, time, and frequency dependency of conductivity, permeability and permittivity
- Undesired physical side effects
  - Charge storage and generation of / susceptibility to E-fields
  - Magnetic flux storage and generation of / susceptibility to H-fields
  - Power dissipation, heat capacity and self heating
  - Generation of / susceptibility to mechanical forces
  - Distibuted character of vector fields: E, H, F, v, T, etc.

}

Elaborate component models that sufficiently accurate describe the behavior over the desired operating range

Use different models for:
- Nonlinear and non-stationary behavior
- Small-signal dynamic behavior
- Noise behavior

Use lumped element models for (quasi) static vector fields and distributed element models for dynamic vector fields

Einstein:
"Models should be as simple as possible, but not simpler"

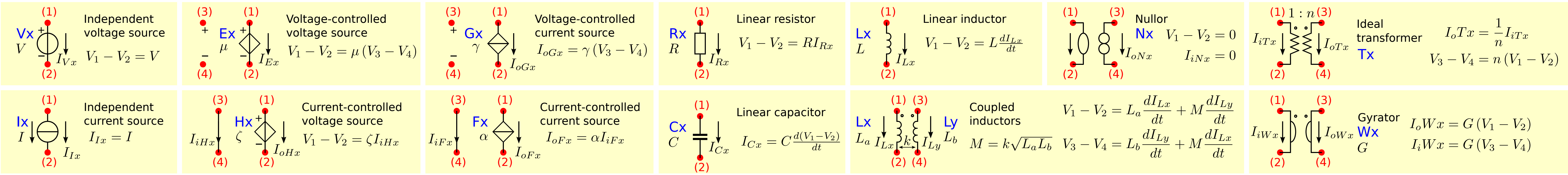
Box:
"All models are wrong, but some are useful"

SPICE B-sources

Controlled voltage or current sources that can have
- Laplace expressions
- Nonlinear expressions
- Logical expressions

Network elements (linear, time-invariant: SLiCAP)

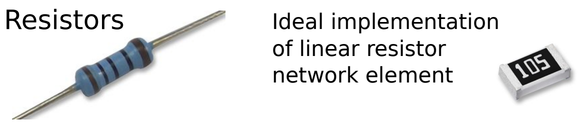
Abstractions that model specific electrical behavior



Network models of electronic components

Component | **Intended** | **Other aspects** | **Example**

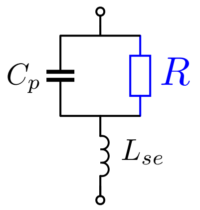
Resistors



Ideal implementation of linear resistor network element

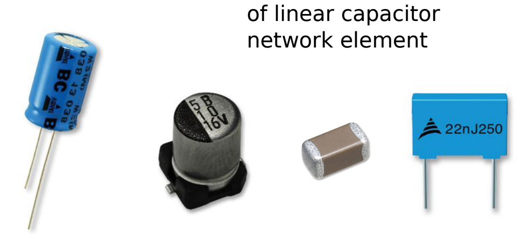
- Nonlinearity
- Voltage breakdown
- Noise generation
- Power failure
- Self heating
- Ageing
- Temperature sensitivity
- Self / mutual capacitance
- Self / mutual inductance
- Frequency dependency

Example: modeling small-signal dynamic behavior



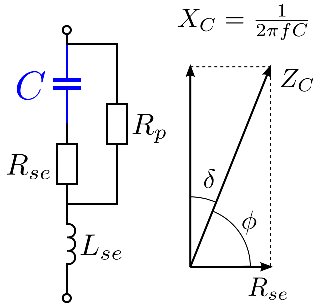
Nonideal behavior depends on technology used:
- Metail foil: low-noise, high accuracy, high stability
- Thick film: low-cost
- Wire wound: high power

Capacitors



Ideal implementation of linear capacitor network element

- Nonlinearity
- Voltage breakdown
- Inrush current breakdown
- Charge leakage
- Power dissipation
- Noise generation
- Self heating
- Ageing
- Temperature sensitivity
- Mutual capacitance
- Self / mutual inductance
- Frequency dependency
- Acoustic noise generation



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

$Z_C = \sqrt{\frac{1}{4\pi^2 f^2 C^2} + R_{se}^2}$

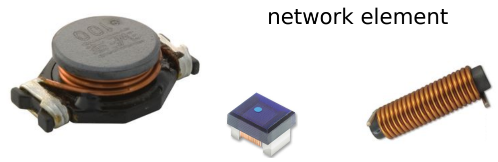
$\tan\delta = 2\pi fCR_{se}$

$f_{res} = \frac{1}{2\pi\sqrt{L_{se}C}}$

$Q = \frac{2\pi fC}{\frac{1}{R_p} + \frac{R_{se}}{4\pi^2 f^2 C^2}}$

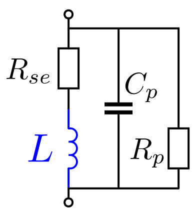
Nonideal behavior depends on the dielectric used:
- Electrolitic: Polarized, high capacitance values
- Ceramic: NP0, GOG, high temperature stability
- Film: High current, high stability, high accuracy

Inductors



Ideal implementation of linear inductor network element

- Nonlinearity
- Voltage breakdown
- Saturation
- Power dissipation
- Noise generation
- Self heating
- Ageing
- Temperature sensitivity
- Self / mutual capacitance
- Mutual inductance
- Frequency dependency
- Acoustic noise generation

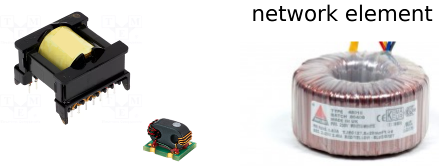


$f_{res} = \frac{1}{2\pi\sqrt{LC_p}}$

$Q = \frac{2\pi fL}{R_{se} + \frac{4\pi^2 f^2 L^2}{R_p}}$

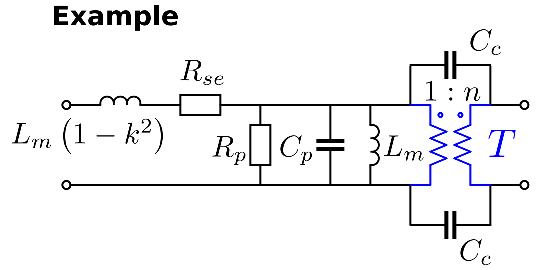
Nonideal behavior depends on core material, wire type, and winding method:
- Air coil, silvered copper: high frequencies, high Q
- Iron powder core: soft saturation
- Litze wire: low skin effect
- Low capacitive winding methods: high self-resonance

Transformers

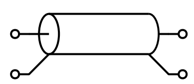


Ideal implementation of ideal transformer network element

- Magnetisation inductance
- Leakage inductance
- Voltage breakdown
- Saturation
- Resistive losses
- Core losses
- Self heating
- Self resonance
- Capacitive coupling



Interconnections



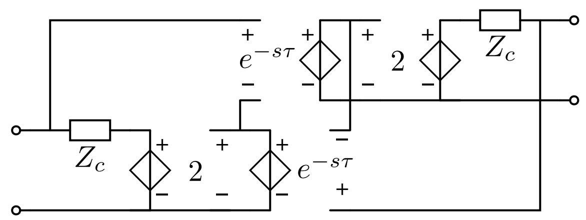
Z_c Characteristic impedance

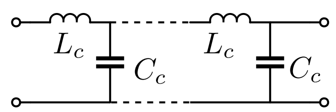
L_c Inductance per unit of length

C_c Capacitance per unit of length

τ Delay per unit of length

Unbalanced lossless transmission line model





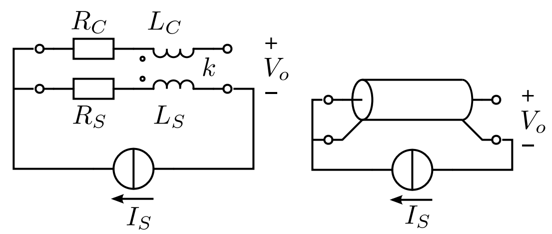
$Z_c = \sqrt{\frac{L_c}{C_c}}$

$\tau = \sqrt{L_c C_c}$

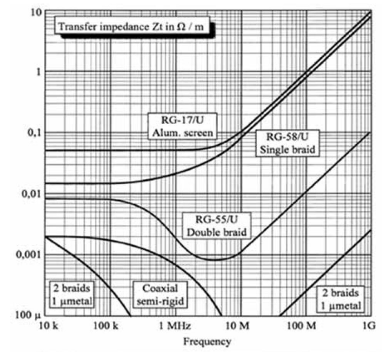
$L_c = Z_c\tau$

$C_c = \frac{\tau}{Z_c}$

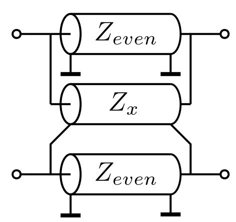
- Losses
- Transfer impedance Z_T

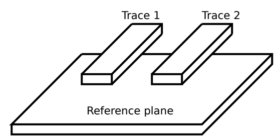


$Z_T = \frac{V_o}{I_S} = R_S + sL_S\left(1 - k\sqrt{\frac{L_C}{L_S}}\right)$



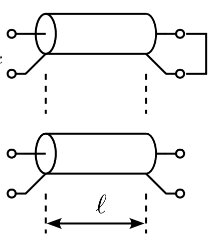
Balanced transmission line model





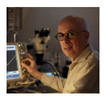
$\frac{1}{Z_x} = \frac{1}{2Z_{odd}} - \frac{1}{2Z_{even}}$

Low-frequency approximations: $f \ll \frac{1}{2\pi\ell\tau}$



$Z_i = 2j\pi f\ell L_c$

$Z_i = \frac{1}{2j\pi f\ell C_c}$



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