BE1M13VES

Manufacturing of Electrical Components

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Overview

1 Frequency dependency of resistors

2 Frequency dependency of capacitors

3 Frequency dependency of inductors

4 Notes

TOPIC

1 Frequency dependency of resistors

2 Frequency dependency of capacitors

3 Frequency dependency of inductors

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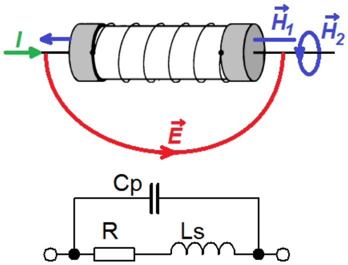
Equivalent Circuit

For AC circuits the parasitic serial inductance and parallel capacity must be taken into account. The frequency dependence of the resistors is caused especially by its construction.



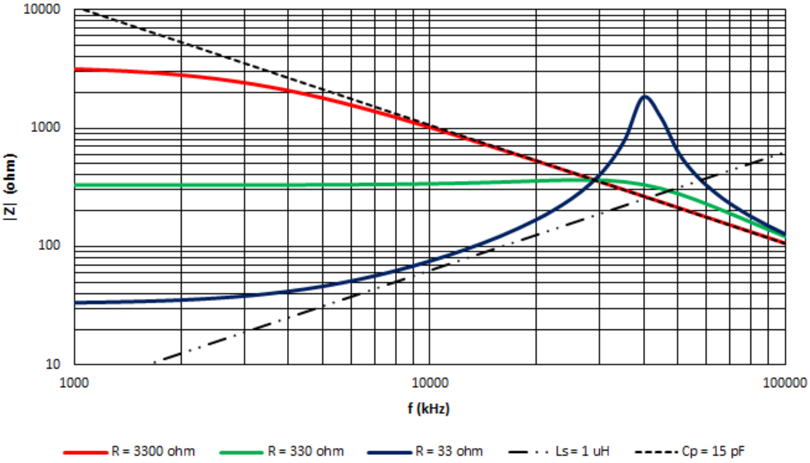
- H_1, H_2... magnetic field from resistive track and leads.
- E... electric field (capacitance) between opposite sides of package and leads.

Technology Overview

- Parasitic capacitance is dominant for higher values of resistance ($>$kΩ).
- Parasitic inductance is dominant only for small values of resistance ($<100\Omega$) and frequencies smaller than resonant frequency.
- Larger packages have larger parasitic inductance
  - power resistors (resistive wire) - worst
  - small smd thin film resistors - best



Impedance Plot Example



Equivalent Circuit Analysis

Impedance:

$$\hat{Z} = \frac{R - \frac{j}{\omega C_p} \cdot \left(\omega^2 L_s C_p \cdot (\omega^2 L_s C_p - 1) + (\omega C_p R)^2\right)}{(1 - \omega^2 L_s C_p)^2 + (\omega C_p R)^2}$$

Low frequencies ($\omega \to 0$): resistivity

$$\hat{Z} \approx R$$

High frequencies ($\omega >> \omega_{RES}$): parasitic capacitance effect

$$\hat{Z} \approx \frac{1}{j\omega C_p}$$

Equivalent Circuit Analysis - Resonance

Resonance frequency:

$$\omega_{RES} = \sqrt{\frac{1}{L_s C_p} - \left(\frac{R}{L_s}\right)^2}$$

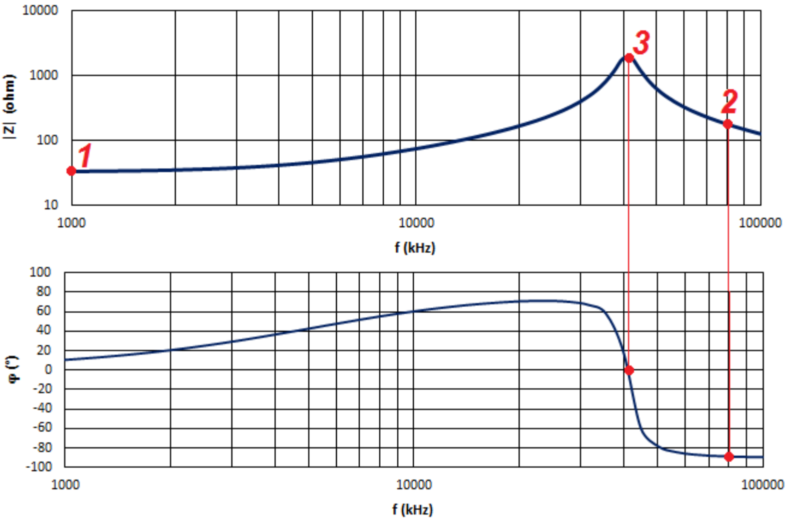
Impedance at ω_{RES}

$$\hat{Z}_{RES} = \frac{Z_0^2}{R}$$

Where Z_0 has the same definition as wave impedance:

$$Z_0 = \sqrt{\frac{L_s}{C_p}}$$

Analysis Example



Analysis Example

1. Resistance:

$$R = 33\Omega$$

2. Capacitance **(15 pF)**:

$$C_p \approx \frac{1}{\omega \cdot |Z|} = \frac{1}{503 \cdot 10^6 \cdot 180} = 11pF$$

3. Inductance **(1 μH)**:

$$L \approx Z_{RES} \cdot R \cdot C_p = 1900 \cdot 33 \cdot 15 \cdot 10^{-12} = 940nH$$

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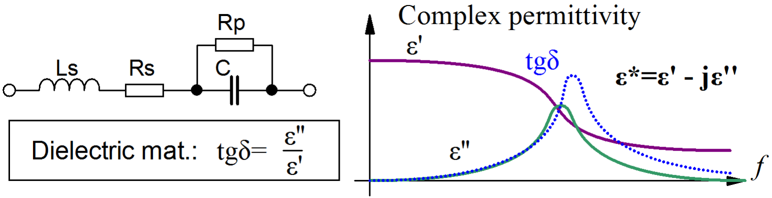
Equivalent Circuit



Frequency dependence due to package properties:

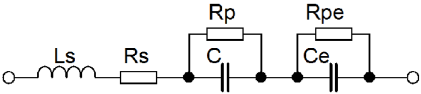
- Parasitic inductance of the leads and electrodes L_s.
- Parasitic resistance of the leads R_s.

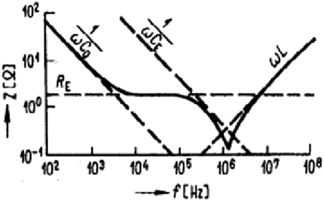
Frequency dependence due to material properties (complex permittivity):

- Change in dielectric power dissipation R_p (ϵ'') - dissip. factor (D).
- Change in capacity C (ϵ').

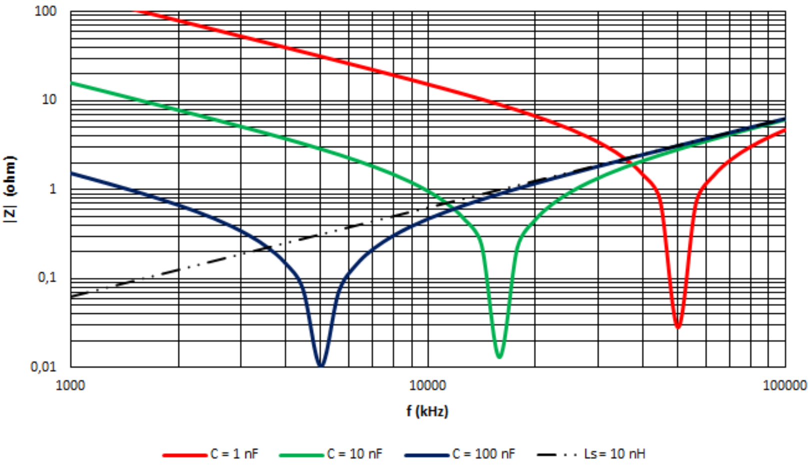
Technology Overview

- Capacitors with higher capacitance have lower resonant frequency.
- Foil capacitors have larger parasitic inductance L_s.
- Electrolytic capacitors have higher serial parasitic resistance R_s due to electrolyte presence.
- Equivalent scheme of electrolytic capacitor:





Impedance Plot Example



Equivalent Circuit Analysis

Impedance:

$$\hat{Z} = R_s + \frac{R_p}{(1 + (\omega C R_p)^2)} + j\left(\omega L_s - \frac{1}{\omega C} \cdot \frac{(\omega C R p)^2}{(1 + (\omega C R_p)^2)}\right)$$

Low frequencies ($\omega << \omega_{RES}$): capacitance

$$\hat{Z} \approx \frac{1}{j\omega C}$$

High frequencies ($\omega >> \omega_{RES}$): parasitic inductance

$$\hat{Z} \approx j\omega L_s$$

Equivalent Circuit Analysis - Resonance

Resonance frequency:

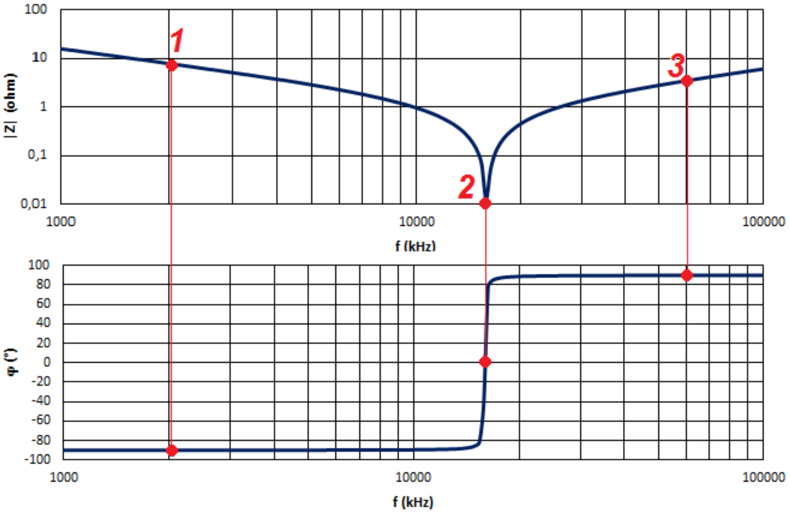
$$\omega_{RES} = \sqrt{\frac{1}{L_s C} - \left(\frac{1}{R_p Cp}\right)^2} \approx \sqrt{\frac{1}{L_s C}}$$

Impedance at ω_{RES}

$$\hat{Z}_{RES} = R_s + \frac{Z_0^2}{R_p} \approx R_s$$

- The approximation is made for capacitors with high resistance R_p and value of capacitance $C > 1\ nF$
- The higher resistance at the resonance is caused by the factor $\frac{Z_0^2}{R_p}$ or by **skin-effect**.
- The parasitic resistances can change due to frequency dependence of complex permittivity.

Analysis Example



Analysis Example

1. Capacitance **(10 nF)**:

$$C \approx \frac{1}{\omega \cdot |Z|} = \frac{1}{12.6 \cdot 10^6 \cdot 7.85} = 10.1nF$$

2. Serial resistance **0.01 Ω)**:

$$R_s \approx Z_{RES} = 0.01\Omega$$

3. Inductance **(10 nH)**:

$$L \approx \frac{|Z|}{\omega} = \frac{3.65}{376 \cdot 10^6} = 9.7nH$$

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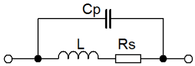
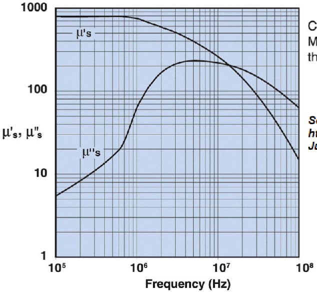
Equivalent Circuit



$$\mu^* = \mu' - j\mu''$$

Magnetic mat.: $\mathrm{tg}\delta = \dfrac{\mu''}{\mu'}$

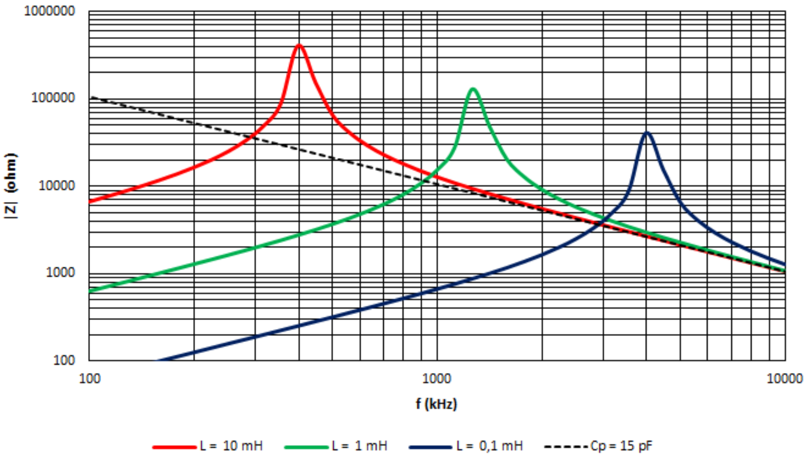


Complex Permeability vs. Frequency Measured on a 17/10/6mm toroid using the HP 4284A and the HP 4291A.

Source: http://www.nutsvolts.com/magazine/article/July2015_HamWorkbench

- The same equivalent circuit as in case of resistors.
- The frequency dependence strongly affected by core material properties and skin-effect.
- Coils with high impedance have lower resonant frequencies.

Impedance Plot Example



Equivalent Circuit Analysis

Very low frequencies ($\omega \to 0$): parasitic resistivity

$$\hat{Z} \approx R_s$$

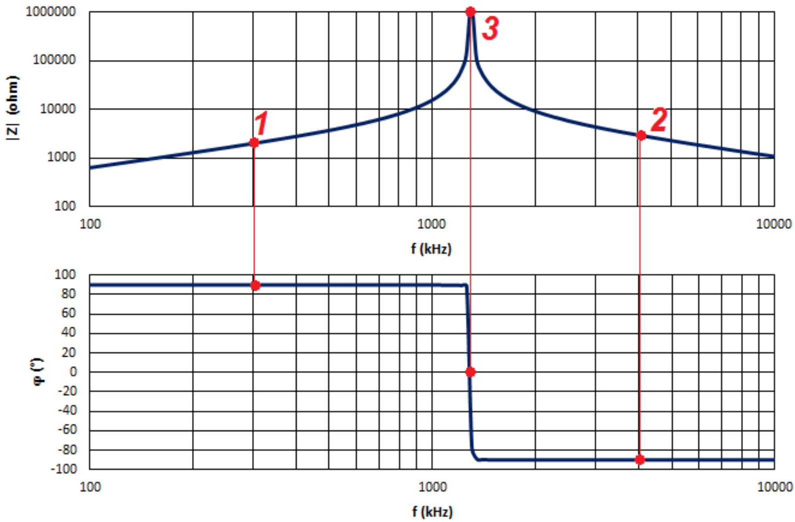
Low frequencies ($\omega << \omega_{RES}$): inductance

$$\hat{Z} \approx j\omega L$$

High frequencies ($\omega >> \omega_{RES}$): parasitic capacitance effect

$$\hat{Z} \approx \frac{1}{j\omega C_p}$$

Analysis Example



Analysis Example

1. Inductance **(1 mH)**:

$$L \approx \frac{|Z|}{\omega} = \frac{2050}{1885 \cdot 10^3} = 1.1mH$$

2. Parallel capacitance **(15 pF)**:

$$C \approx \frac{1}{\omega \cdot |Z|} = \frac{1}{25.1 \cdot 10^6 \cdot 2970} = 13pF$$

3. Serial resistance **10 Ω)**:

$$R_s \approx \frac{Z_0^2}{Z_{RES}} = \frac{10^{-3}}{15\dot{1}0^{-12} \cdot 10^6} = 6.67\Omega$$

- **NO!** ... better to find out the serial resistance from DC measurement.

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NOTES

- In case of impedance plot use logarithmic scale for both axis.
- In case of phase plot use logarithmic scale only for frequency.
- $$\hat{Z} = R + jX$$
- $$|Z| = \sqrt{R^2 + X^2}$$
- $$\varphi = arctg\frac{X}{R}$$
- resonance: $X = 0$, $\varphi = 0$, parallel $\Rightarrow$ high $|Z|$, serial $\Rightarrow$ low $|Z|$