Digital measurement of Impedance

Impedance - basics (remember)

• the total opposition of a device or circuit to the flow of an alternating current at given frequency;

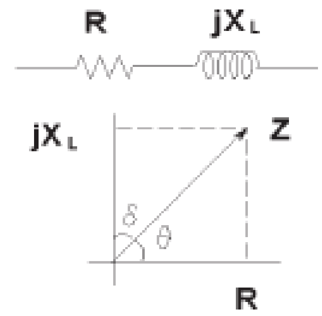
$$Z = \frac{\underline{U}}{\underline{I}} = R_S + jX_S = |Z| e^{j\varphi_Z} = \frac{|\underline{U}|}{|\underline{I}|} e^{j(\phi_U - \phi_I)}$$

$$|Z| = \sqrt{R_S^2 + X_S^2} \quad ; \quad \varphi_Z = \operatorname{arctg}\frac{X_S}{R_S}$$

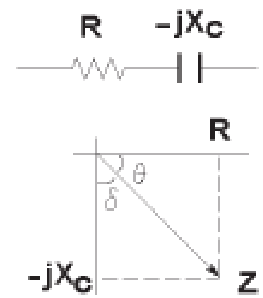
$$Y = \frac{\underline{I}}{\underline{U}} = \frac{1}{Z} = G_P + jB_P = |Y| e^{j\varphi_Y}$$

$$G_P = \frac{R_S}{R_S^2 + X_S^2} \quad ; \quad B_P = \frac{-X_S}{R_S^2 + X_S^2}$$

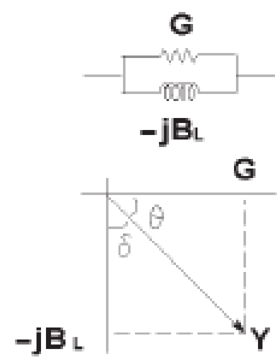
$$Q = \frac{1}{D} = \frac{1}{\operatorname{tg}\delta} = \frac{|P_r|}{P_a} = \frac{|X_S|}{R_S} = \frac{|B_p|}{G_P}$$



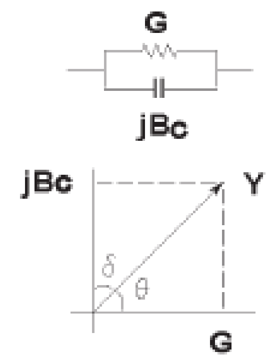
(a) Inductive vector



(b) Capacitive vector



(c) Inductive vector



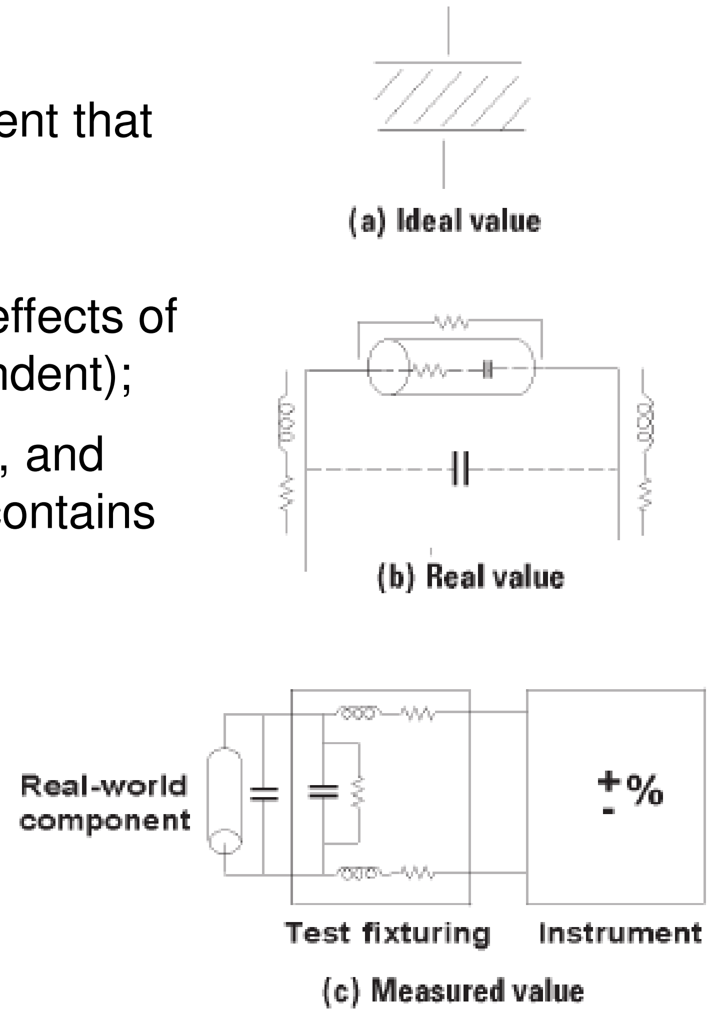
(d) Capacitive vector

Impedance value type

• An *ideal* value - the value of a circuit component that excludes the effects of its parasitics; (it has no frequency dependence);

• The *real* value - takes into consideration the effects of a component's parasitics (it is frequency dependent);

•The *measured* value - the value obtained with, and displayed by, the measurement instrument. It contains errors when compared to real value;



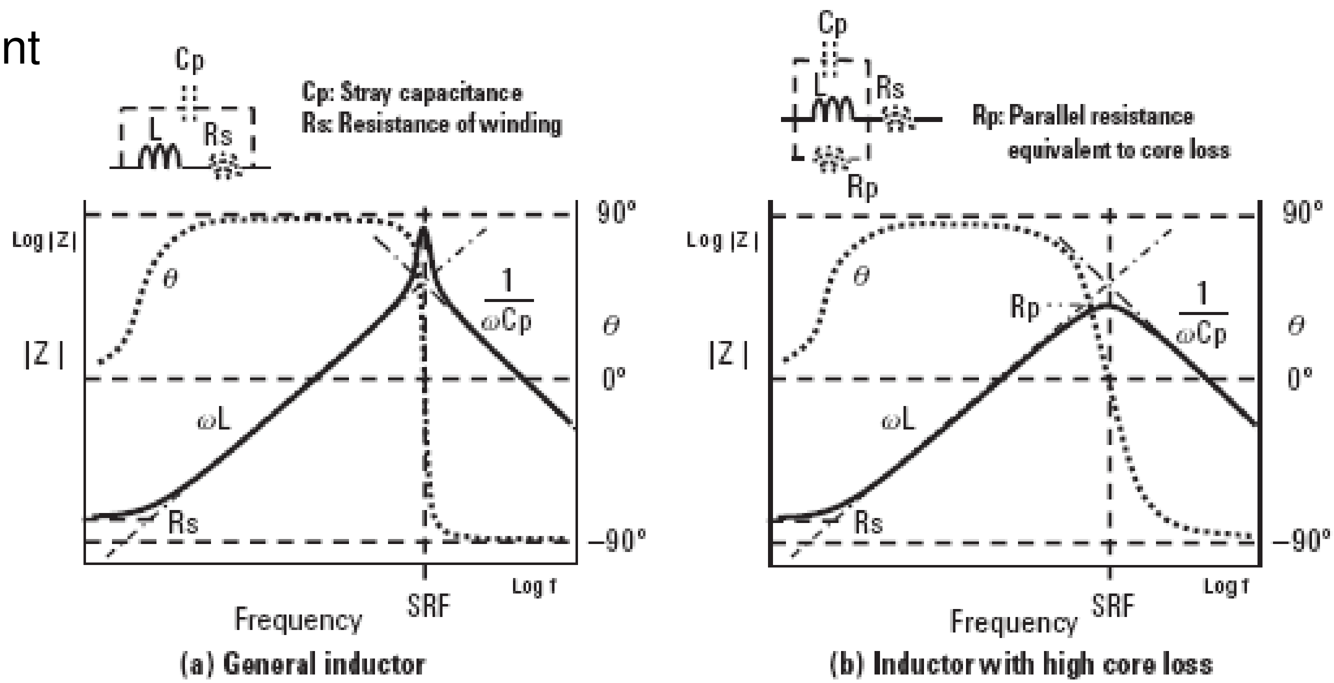
Component dependency factor (remember)

- frequency of test signal;
- level of test signal;
- temperature, etc.

- Frequency dependency of inductor

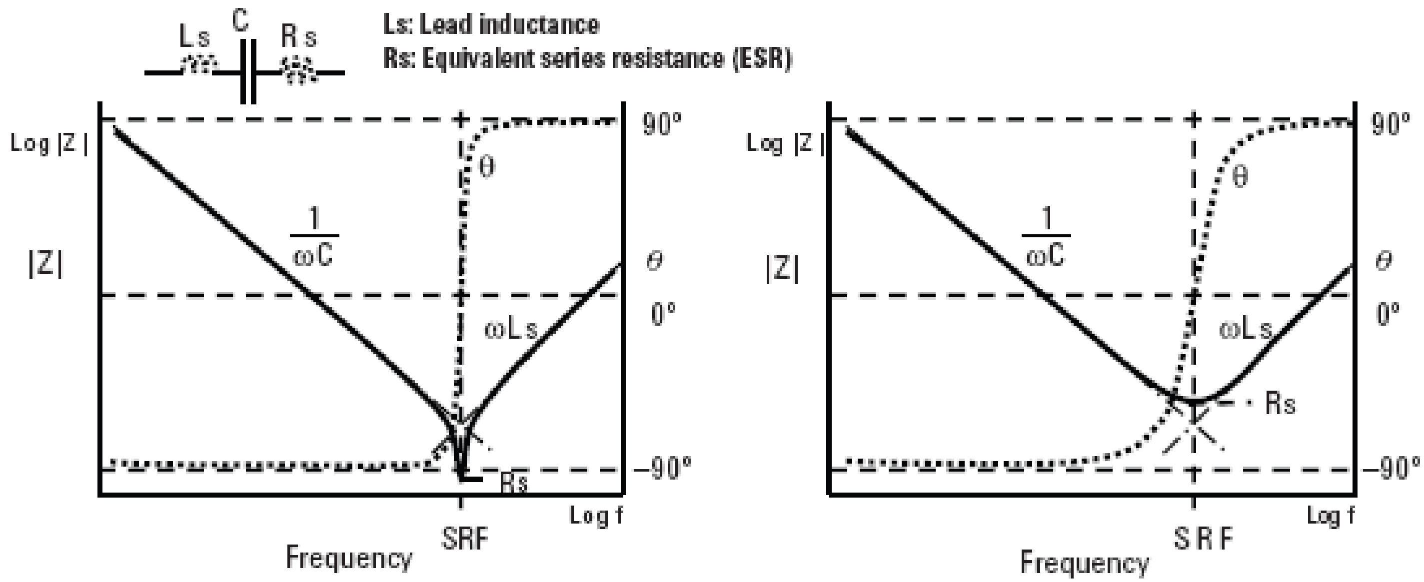
- SRF – serial resonant frequency

SRF> frequency of interest



Component dependency factor (cont'd)

•Frequency dependency of capacitor



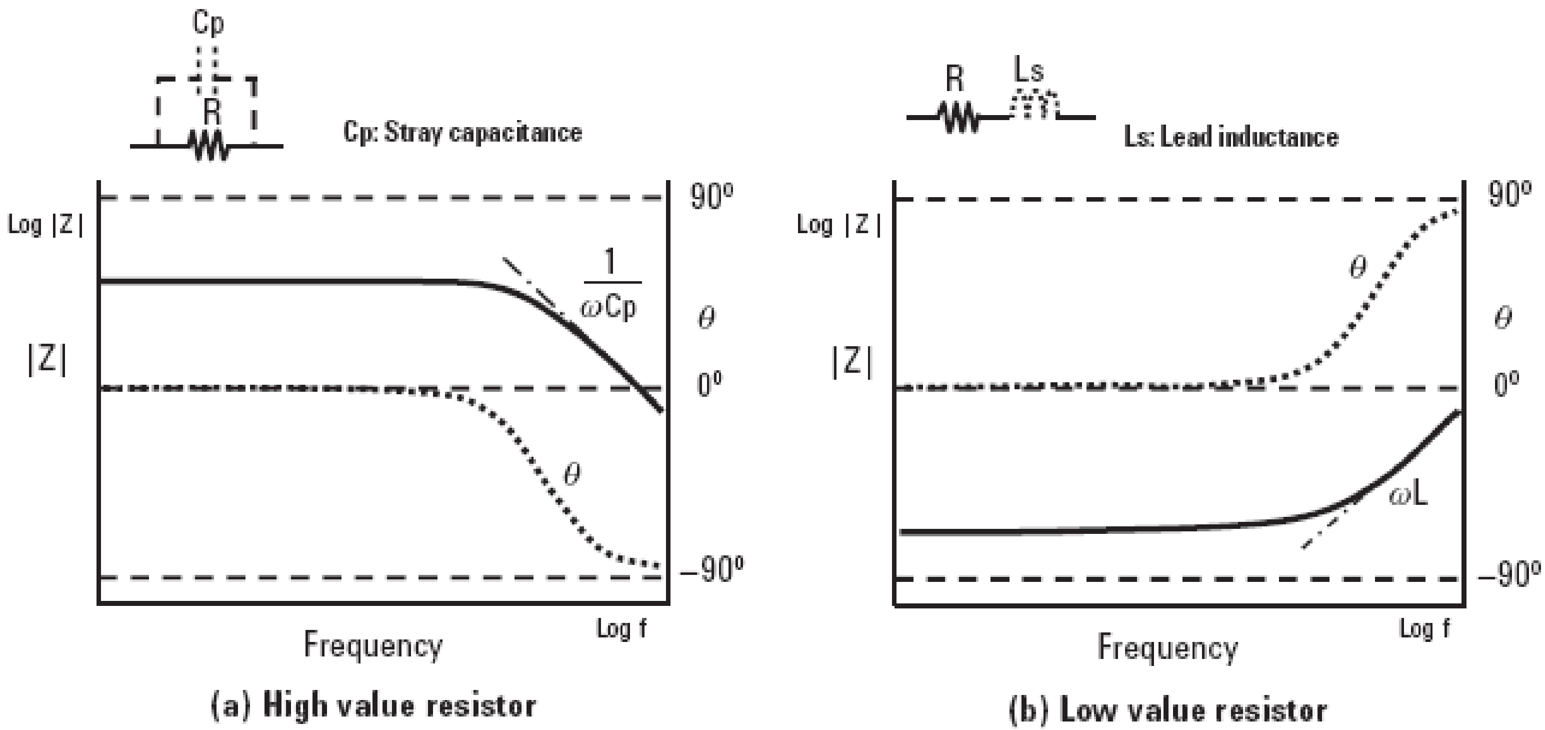
(a) General capacitor

(b) Capacitor with large ESR
(Equivalent Series Resistance)

SRF > frequency of interest

Component dependency factor (cont'd)

•Frequency dependency

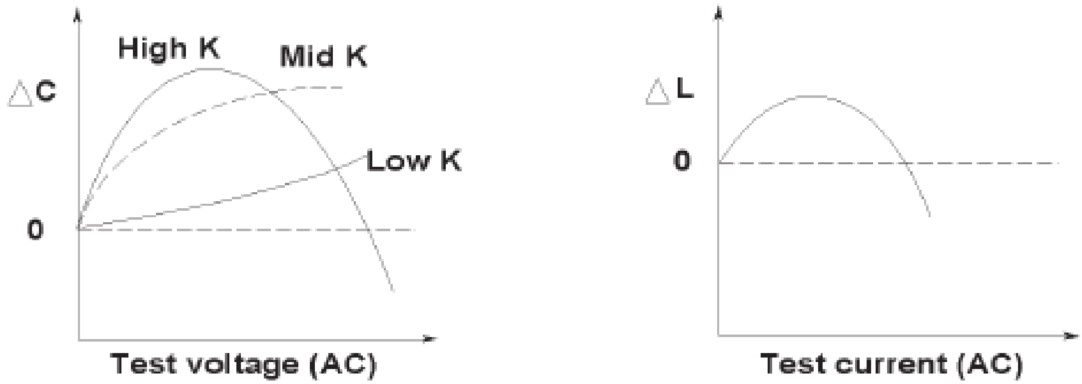


Component dependency factor (cont'd)

- Test signal level

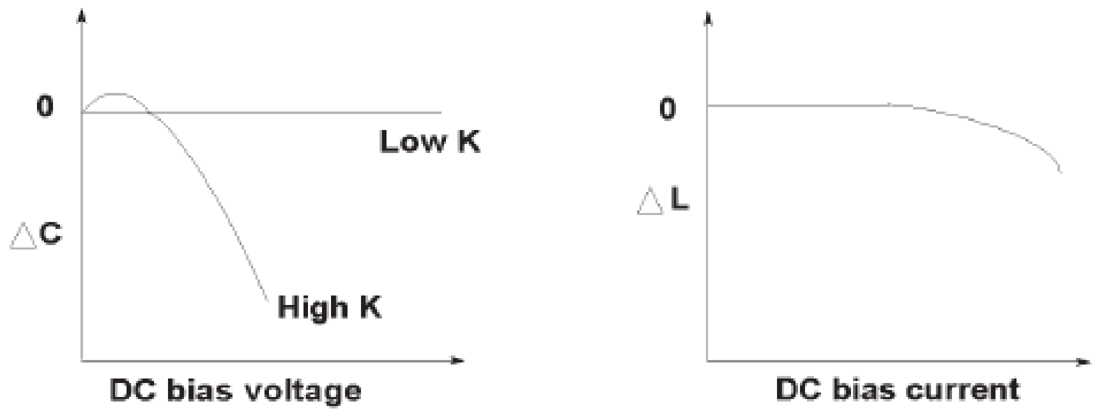
$$C = K\varepsilon_0 \frac{S}{d}$$

$$L = \mu_r \mu_0 \frac{N^2 S}{L}$$



(a) Ceramic capacitor - AC voltage dependency

(b) Cored-inductor - AC current dependency



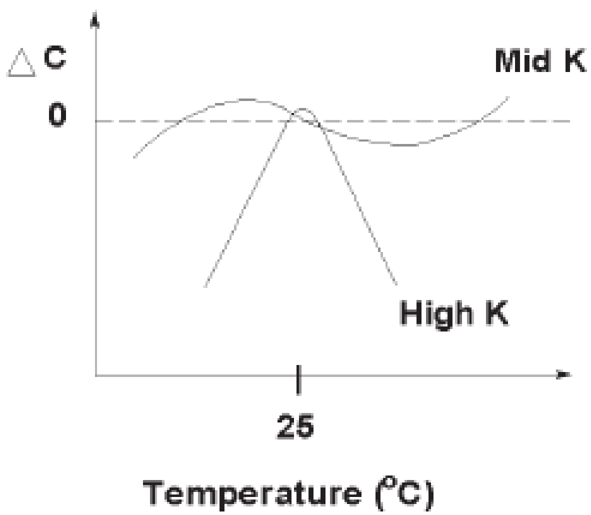
(a) Ceramic capacitor - DC bias voltage dependency

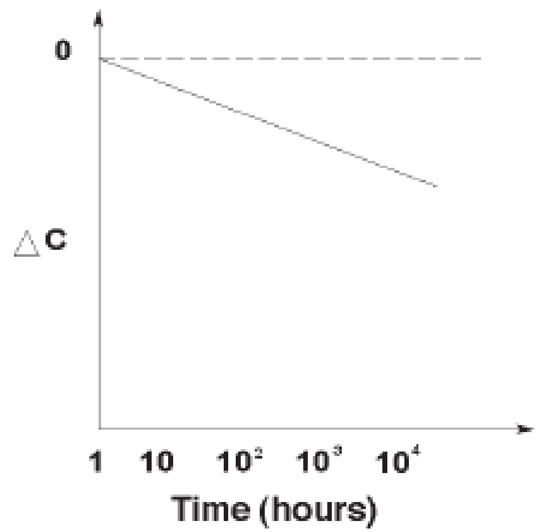
(b) Cored-inductor - DC bias current dependency

Component dependency factor (cont'd)

- Other dependency factors

Example: capacitor



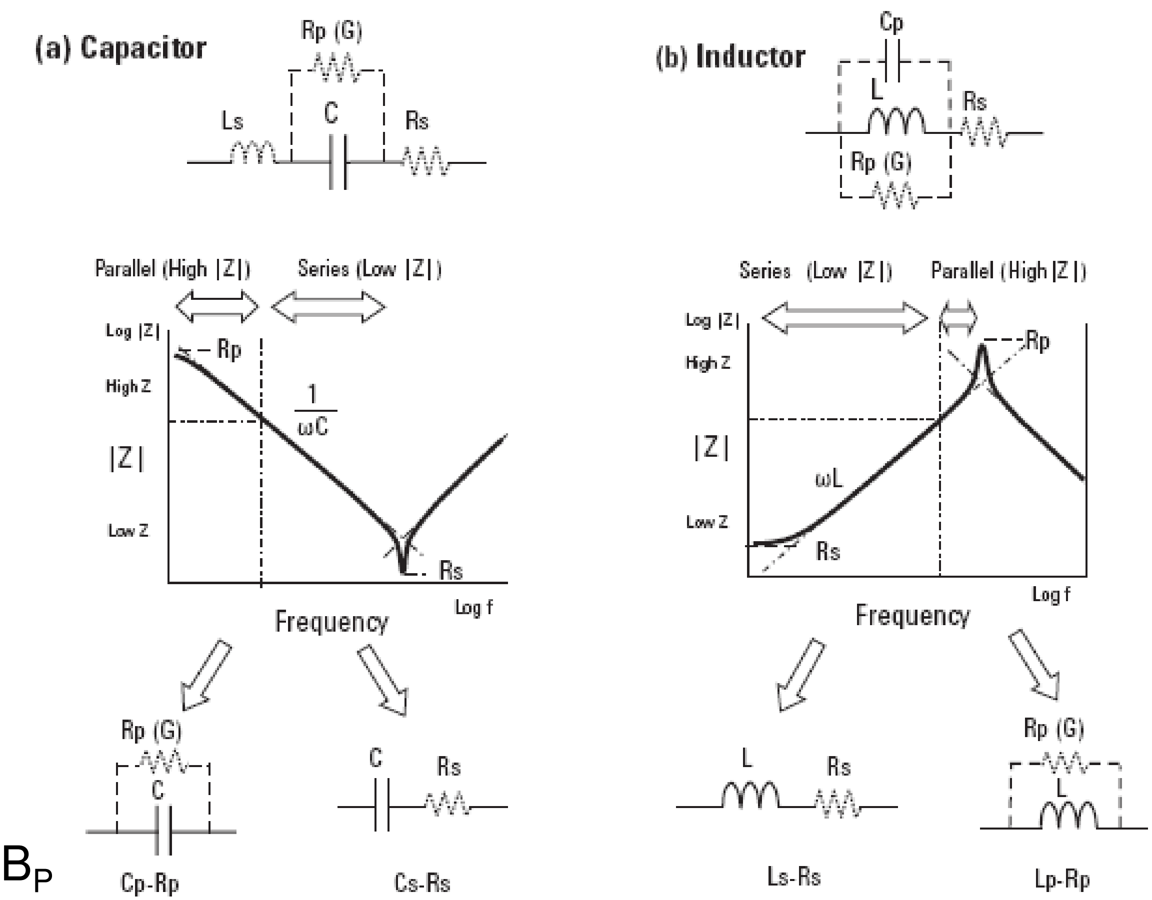


Equivalent circuit models (two elements)

$$R_P = R_S\left(1+Q^2\right)$$

$$X_P = X_S\left(1+\frac{1}{Q^2}\right)$$

$$\begin{cases} L_P = L_S\left(1+\dfrac{1}{Q^2}\right) \\ C_S = C_P\left(1+\dfrac{1}{Q^2}\right) \end{cases}$$

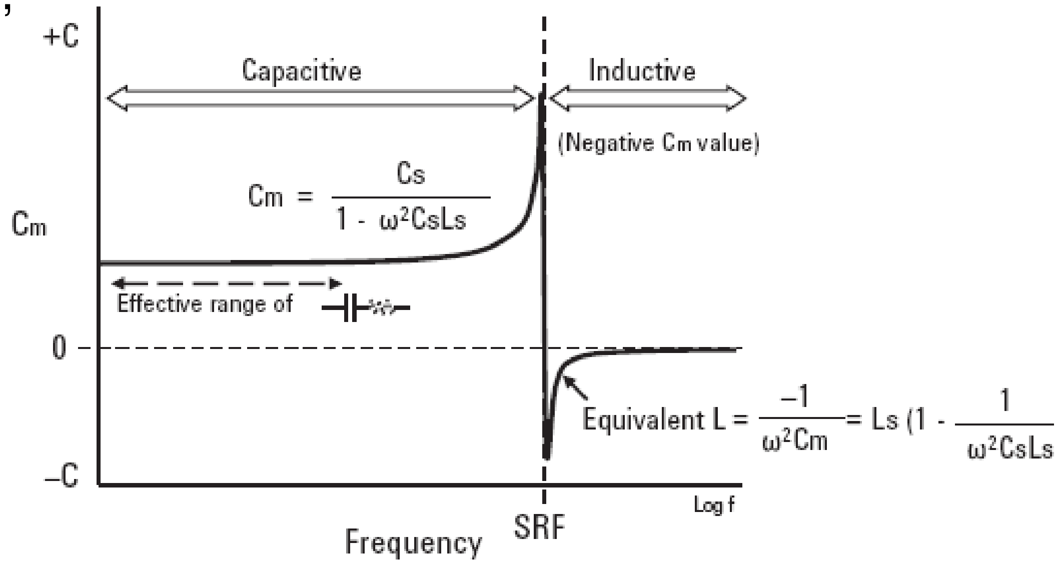


Measurement parameters:

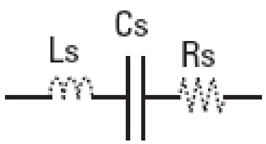
- serial: C_S , R_S , L_S , X_S
- parallel: C_P , R_P , L_P , X_P , B_P

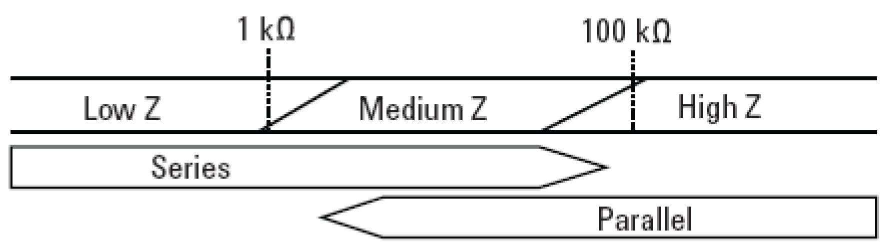
Three-element equivalent circuit *

For high frequency (RF) measuring;



• capacitor serial equivalent circuit (Influence of parasitic inductance on capacitor);





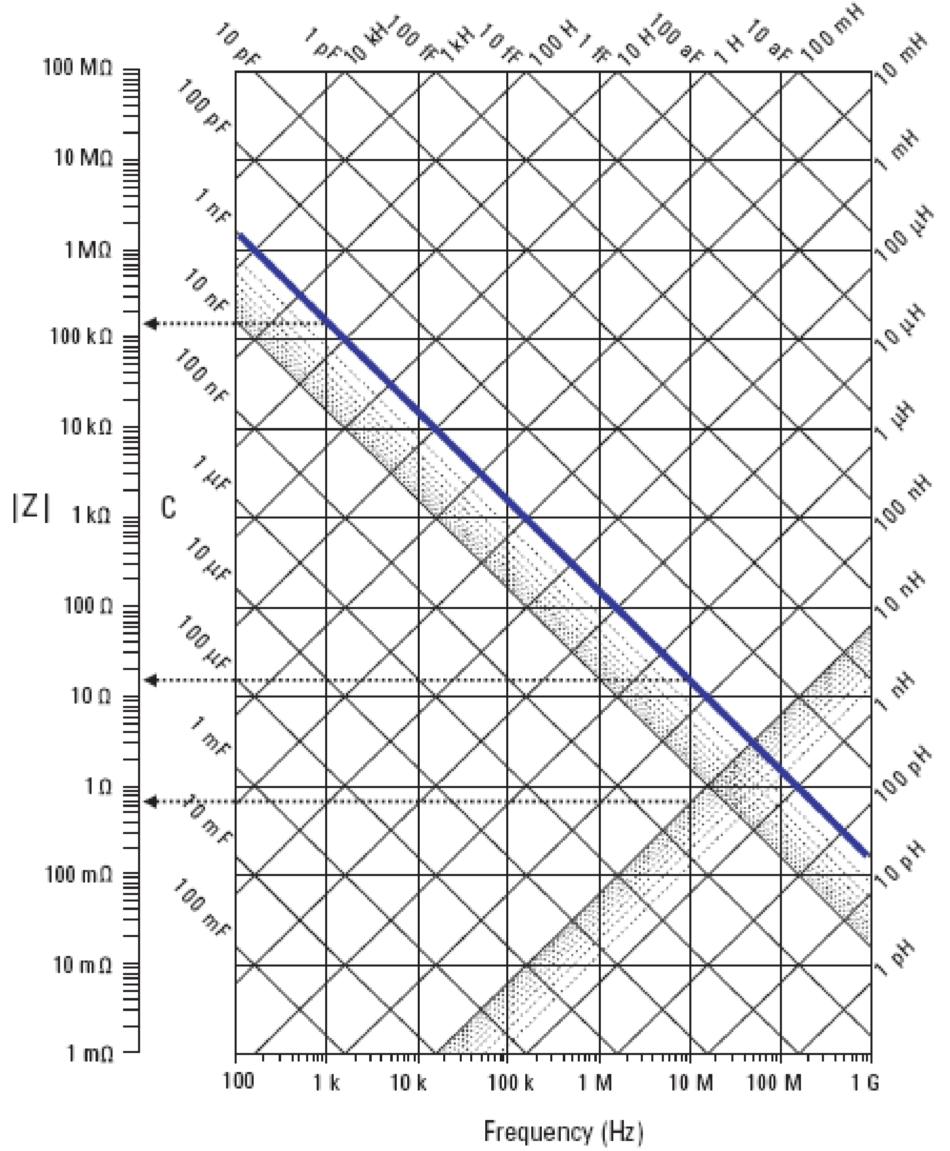
• High and low impedance criteria

Reactance chart

• shows the impedance and admittance values of pure reactance at arbitrary frequencies.

Example: reactance of a 1nF capacitor is 160kΩ at 1kHz and 16Ω at 10MHz.
- A parasitic series resistance of 0.1Ω can be ignored at 1kHz, but it yields a dissipation factor D=0.0063 at 10 MHz.
- a parasitic inductance of 10nH can be ignored at 1 kHz and decreases measured capacitance by 4% at 10MHz .

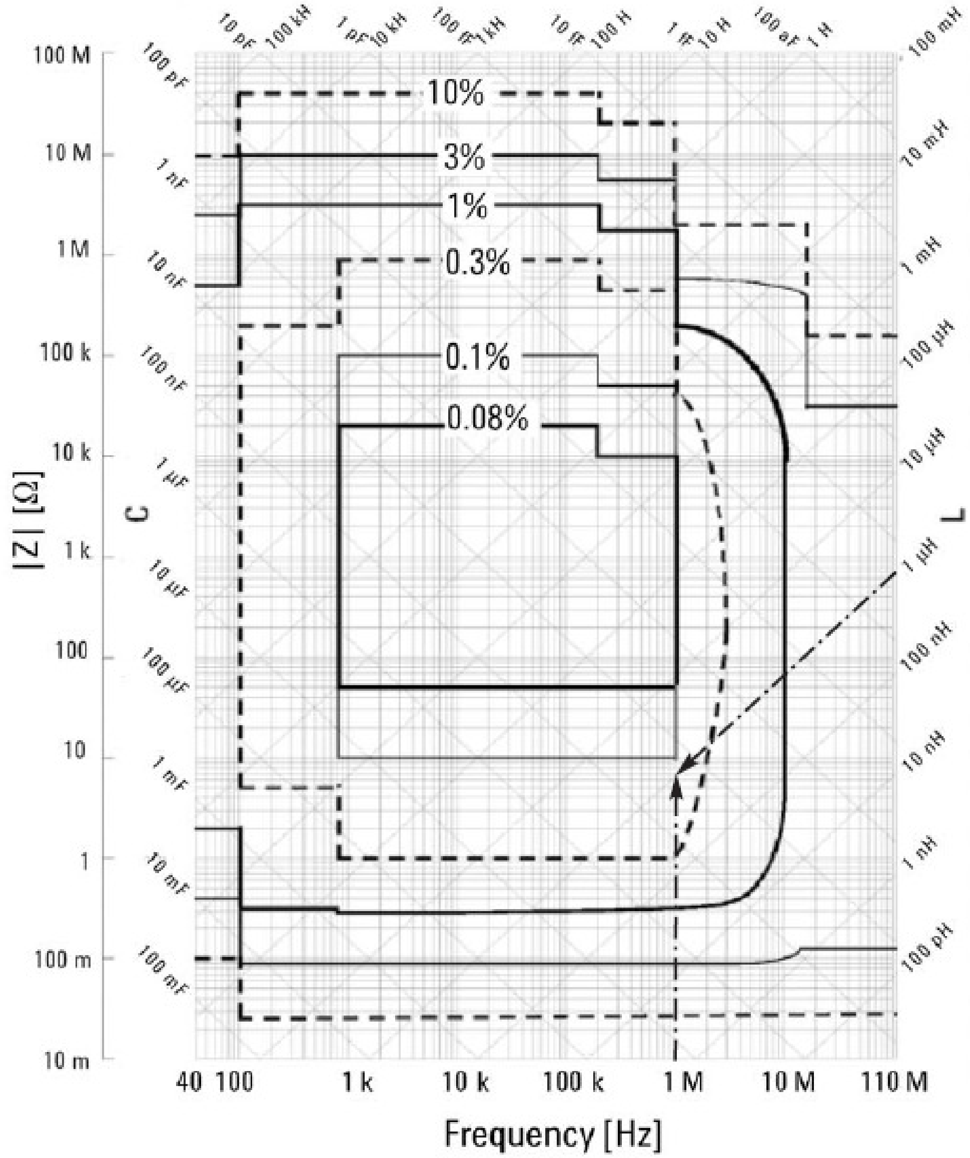
At the intersection of 1nF line capacitor and the 10nH inductance line is self resonant frequency (SRF).



- **Reactance chart**

 - useful to estimate measurement accuracy for capacitance and inductance at given frequency.

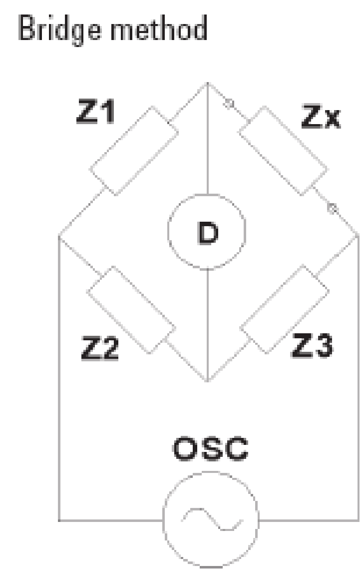
- impedance measuring instruments measure Z=R + jX or Y=G + jB and then compute C_s, C_p, L_s, L_p, D, Q, |Z|, |Y|, etc.
- range and accuracy for the capacitance and inductance vary depending on frequency.



Measurement methods (ac)

- Bridge methods
  - classic bridge
  - Auto-balancing bridge
- I-V methods
  - classic method
  - RF method for low impedance
  - RF method for high impedance
- Network analysis methods
- Resonant methods
  - analog Q - meter
  - digital Q - meter
- methods of conversion $Z_X \rightarrow T_X$ or $Z_x \rightarrow f_X$

Bridge classic method



$$I_D = 0 \Rightarrow Z_x = \frac{Z_1 \cdot Z_3}{Z_2}$$

Advantages
- High accuracy
- Wide frequency coverage by using different types of bridges [0-300MHz]
- Low cost

Disadvantages
- Needs to be manually
- Narrow frequency coverage with a single instrument

Applications
- Standard laboratories

I-V classic methods

- in practice low loss transformer replace R (to prevent the effects of low value resistor in the circuit);

Advantages

• Grounded device measurement

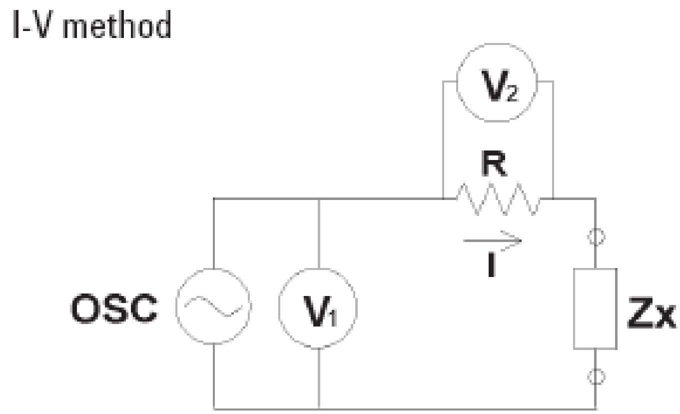
• Suitable to probe-type test needs

Disadvantages

• Operating frequency range is limited by transformer 10kHz – 100MHz

Applications

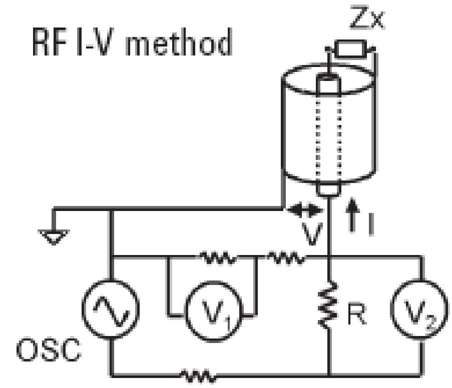
• Grounded devices measurement



$$Z_X = \frac{\underline{V}_1}{\underline{I}} = \frac{\underline{V}_1}{\underline{V}_2} R_X$$

RF I-V method

- are based on the same principle as the I-V method;
- uses an impedance-matched measurement circuit (50 Ω) and a precision coaxial test port
- R is known



Low impedance type

$$Z_X = \frac{V}{I} = \frac{2R}{\frac{V_2}{V_1} - 1}$$

Advantages

- High accuracy
- Wide impedance range
- High frequencies [1MHz – 3GHz]

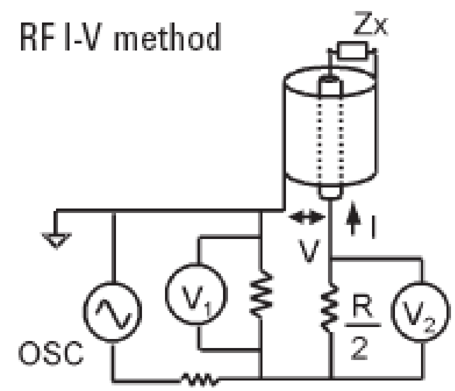
Disadvantages

- Operating frequency range is limited by transformer of probes

Applications

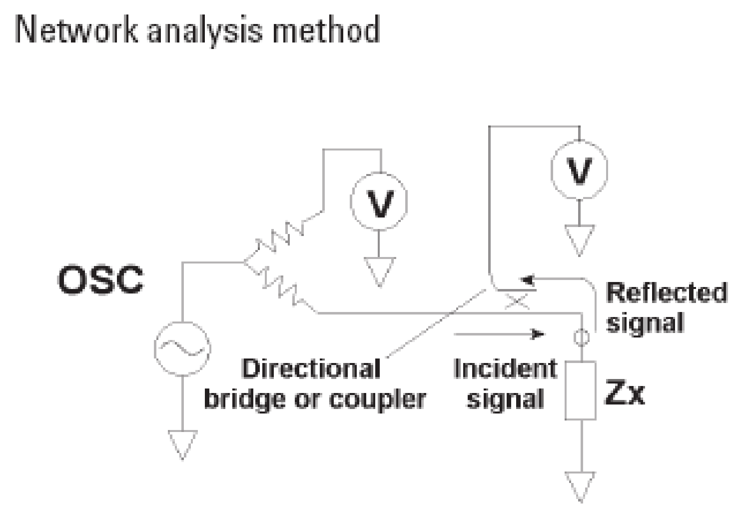
- RF component measurement

$$Z_X = \frac{V}{I} = \frac{R}{2} \cdot \left(\frac{V_1}{V_2} - 1 \right)$$



High impedance type

Network analysis method



• measures reflection coefficient (ratio of an incident signal to the reflected signal);
• uses directional coupler or bridge to detect the reflected signal;
• it is usable in the higher frequency range;

Advantages

• High accuracy for Z_X closed to the characteristic impedance
• High frequency range [300kHz – 500MHz]

Disadvantages

• requiring calibration at frequency changing
• Narrow impedance measurement range

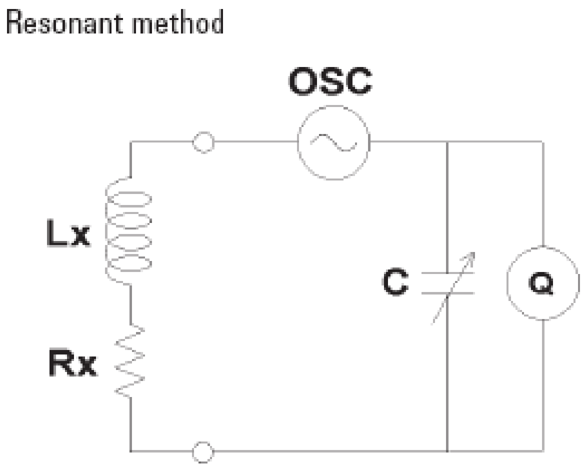
Applications

• RF component measurement

Resonant method (analog Q-meter)

- the circuit is adjusted to resonance using a tuning capacitor (C)
- Q is measured directly using a voltmeter placed across the tuning capacitor
- L_X can be measured directly
- C_X and extended L_X can be measured indirectly using serial or parallel connections

$$\begin{cases} C = C_V + C_X \\ L = L_{adj} + L_X \end{cases}$$



$$L_X = \frac{1}{\omega^2 C}$$

$$Q_X = \frac{U_C}{E} = \frac{1}{R_X \omega^2 C}$$

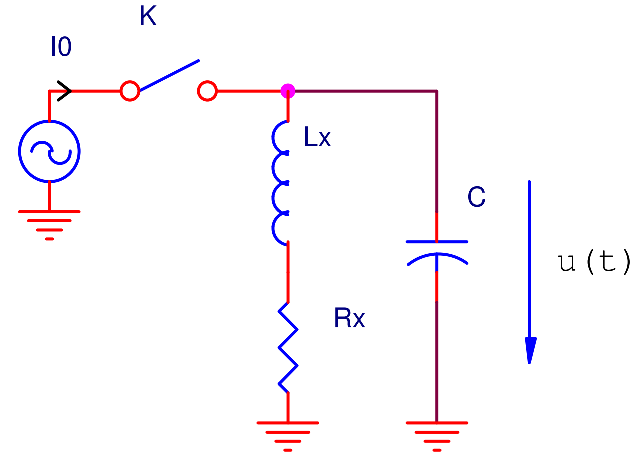
Advantages
- Good Q accuracy
- High frequency range [70kHz – 50MHz]

Disadvantages
- requiring tuning to resonance
- Low impedance measurement accuracy

Applications
- High Q devices measurement

Resonant method (digital Q-meter)

- digital Q-meter uses resonance of parallel circuit;
- Theoretical consideration



$$L\frac{d^2 i(t)}{dt^2} + r\frac{di(t)}{dt} + \frac{i}{C} = 0$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad \xi = \frac{r}{2}\sqrt{\frac{C}{L}} = \frac{r}{2\omega_0 L} = \frac{1}{2Q}$$

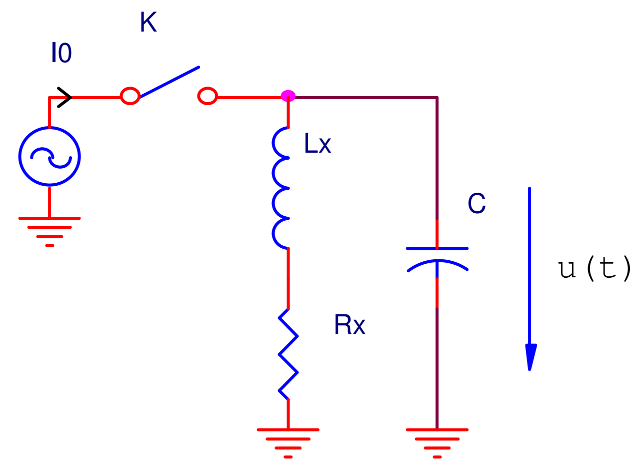
$$i(t) = I_0 \exp\left(-\frac{r}{2L}t\right)\cos\left(\omega_0\sqrt{1-\xi^2}\cdot t + \phi\right)$$

$$\frac{I(t_2)}{I(t_1)} = \frac{I_0 \exp\left(-\frac{r}{2L}t_2\right)}{I_0 \exp\left(-\frac{r}{2L}t_1\right)} = \frac{1}{K} \Rightarrow t_2 - t_1 = \frac{2L}{r}\ln K = \frac{2Q}{\omega_0}\ln K = nT_0 = n\cdot\frac{2\pi}{\omega_0}$$

$$\text{if } Q > 3 \Rightarrow \xi < 1/6 \Rightarrow \omega \approx \omega_0\left(1 - \frac{1}{2}\xi^2\right) \approx \omega_0 \Rightarrow n = \frac{Q}{\pi}\ln K$$

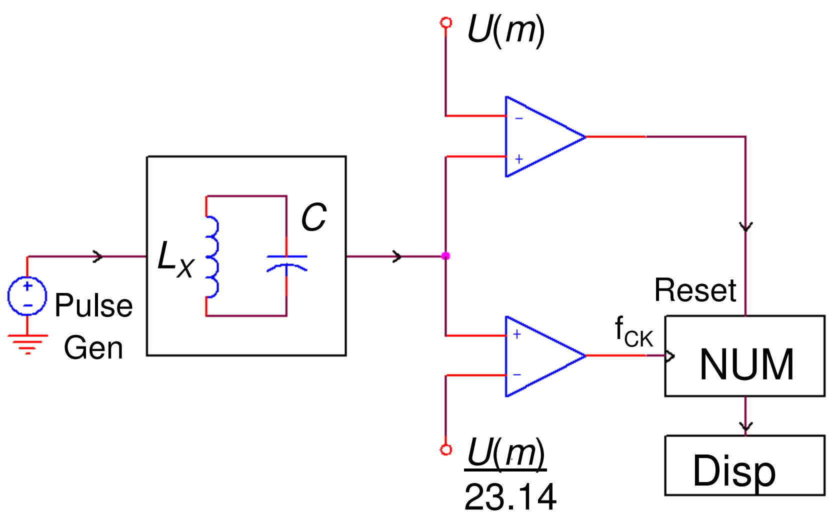
Resonant method (digital Q-meter)

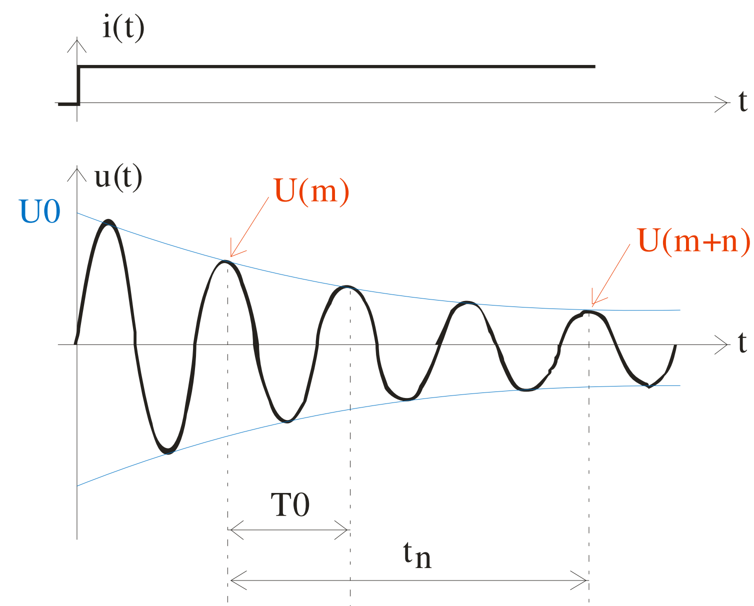
- practical consideration



$$u(t)=\frac{I_n}{\omega_n C}\exp\left(-\frac{R\cdot t}{2L}\right)\sin\omega_n t \quad , \quad \omega_n\approx\omega_0\ (Q_x\geq 3)$$

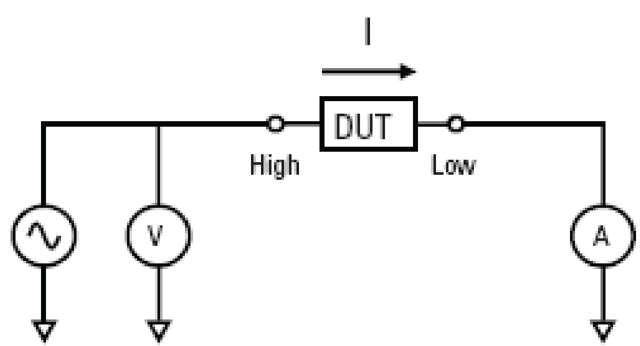
$$Q_X=n=\frac{t_n}{T_0}=\frac{Q}{\pi}\ln K\Rightarrow\ K=\frac{U(mT_0)}{U((m+n)T_0)}=\mathrm{e}^{\pi}=23.14$$





Auto-balancing bridge method

- DUT = device under test
- uses a signal source, a voltmeter, and an ammeter that measure vectors (magnitude and phase angle)
- The input impedance of ammeter (virtually zero) does not affect measurements
- Distributed capacitance of the test cables does not affect measurements
- Guarding technique can be used to remove stray capacitance effects



$$Z_X = \frac{\underline{V}}{\underline{I}}$$

Advantages

• High accuracy, wide ranges of impedance
• Wide frequency ranges [20Hz-110MHz]
• Grounded device measurement

Disadvantages

• Higher frequency ranges not available

Applications

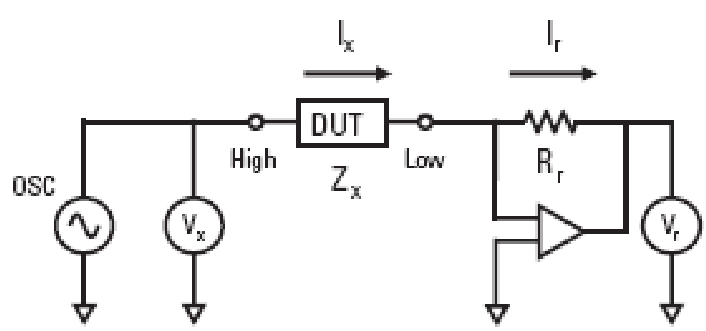
• Generic component measurement
• Grounded device measurement (RLC-meter)

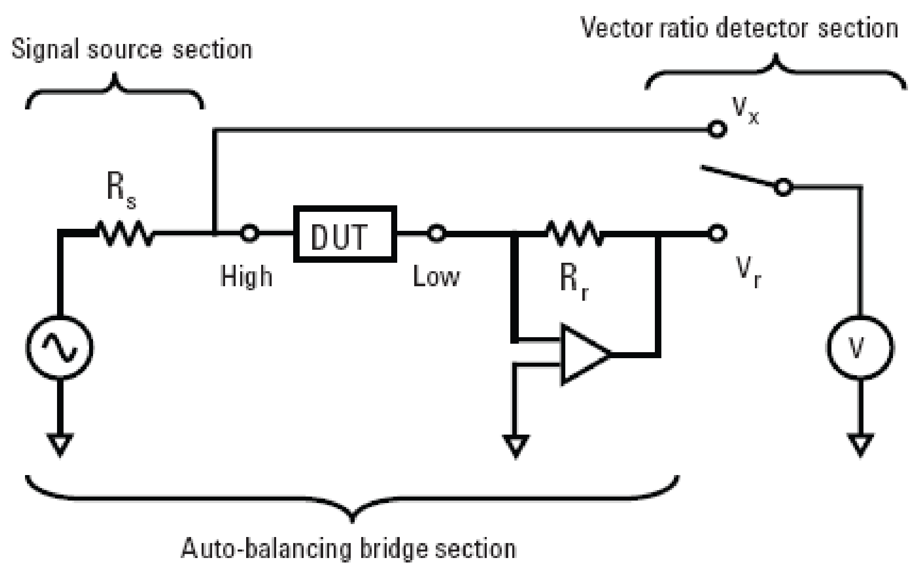
Auto-balancing bridge method (cont'd)

- for low frequency employs I-V converter (<100kHz) circuit and V-I converter with operational amplifier
- uses two vector voltmeters
- R_r , the range resistor, determines impedance measurement range;
- V_x and V_r can be measured with the same vector voltmeter (ratio detector);
- R_r has known value;

$$\frac{\underline{V}_X}{\underline{Z}_X} = \underline{I}_X = \underline{I}_r = \frac{\underline{V}_r}{R_r} \Rightarrow \underline{Z}_X = \frac{\underline{V}_X}{\underline{I}_X} = R_r \frac{\underline{V}_r}{\underline{I}_r}$$

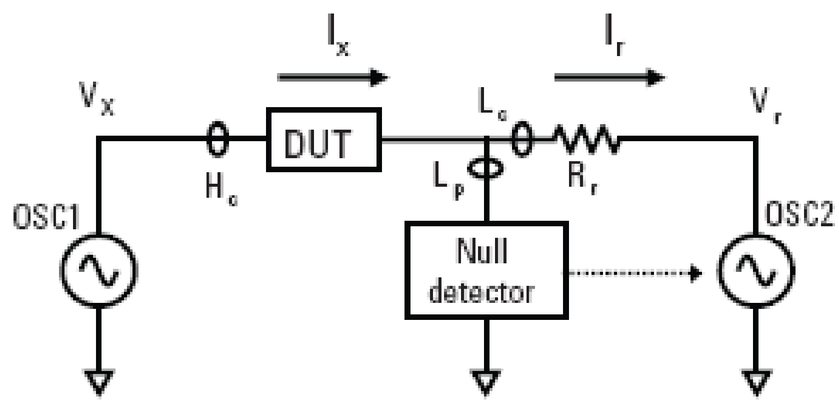
Auto-balancing bridge method





Auto-balancing bridge method (cont'd)

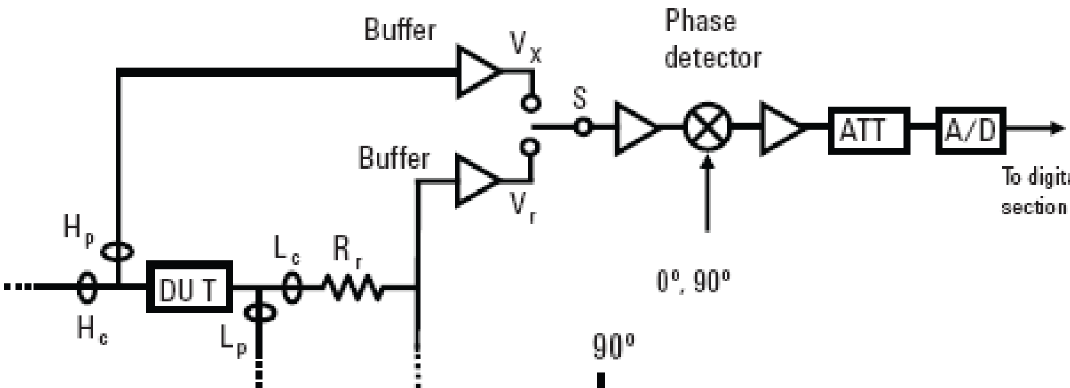
• the auto-balancing bridge section balances the range resistor current with the DUT current while maintaining a zero potential at the Low terminal;
• the null detector detects the unbalance current I_X-I_r and controls both the magnitude and phase angle of the OSC_2 output so that goes current to zero;
• circuit configuration cannot be used for high frequency >100kHz;
• to cover frequencies above 100 kHz the bridge employs null detector, 0°/90° phase detectors, and a vector Modulator;



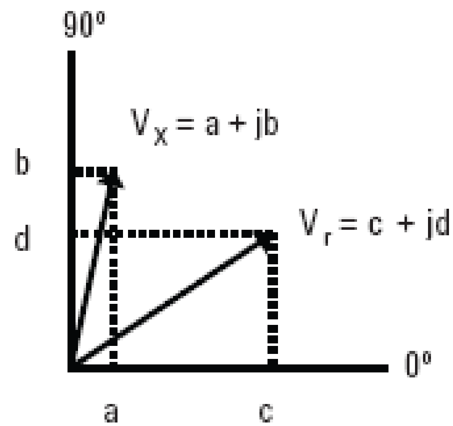
Operation image of the auto-balancing bridge

Auto-balancing bridge method (cont'd)

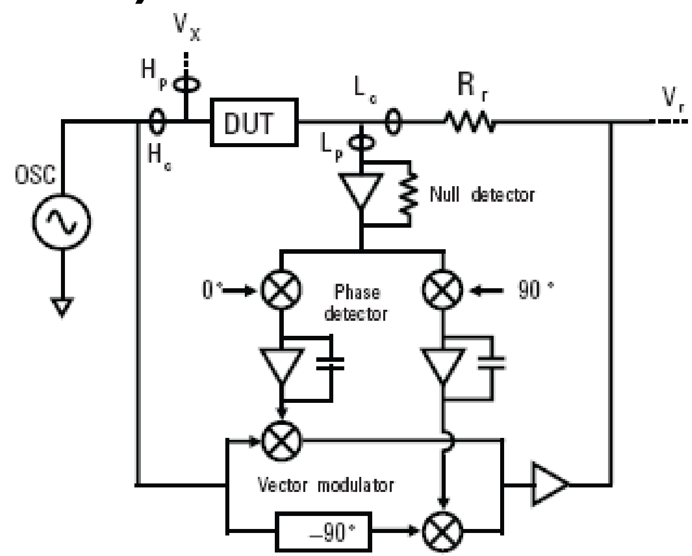
- the auto-balancing bridge section for high frequency measurement
- Vector ratio detector section



Block diagram



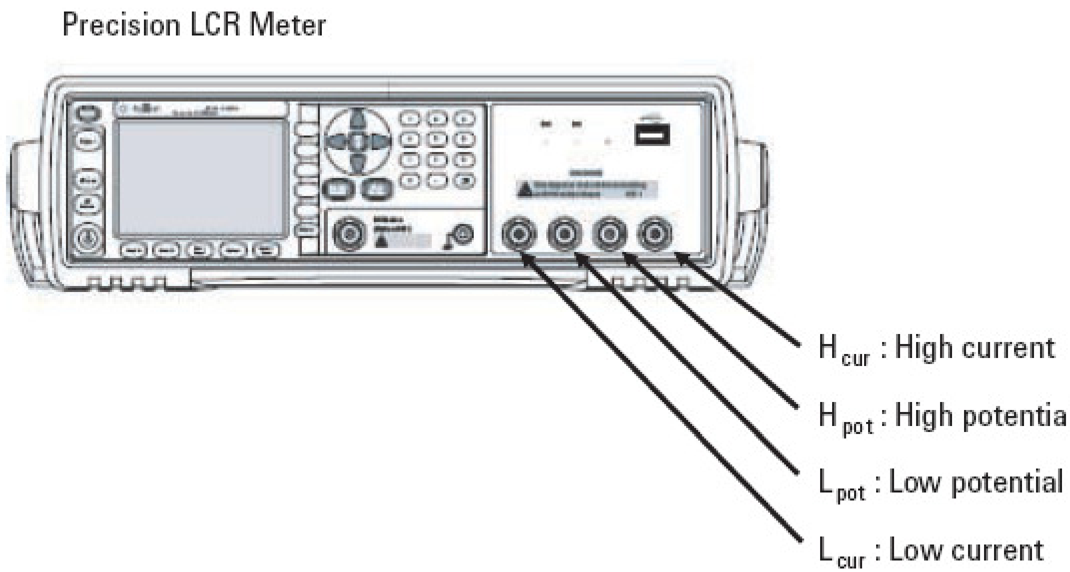
Vector diagram of V_x and V_r



Auto-balancing bridge for frequency above 100 kHz

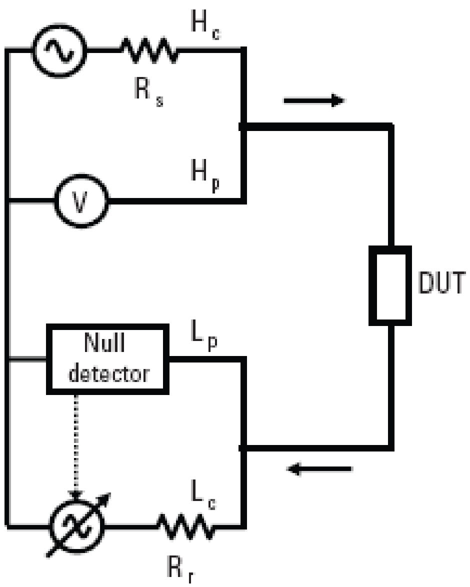
Fixturing and Cabling

• auto-balancing bridge instrument is generally equipped with four BNC connectors, H_{cur}, H_{pot}, L_{pot}, and L_{cur} ;

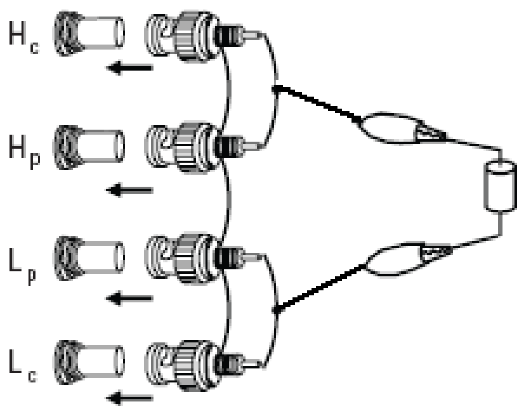


Two-terminal configuration (2T)

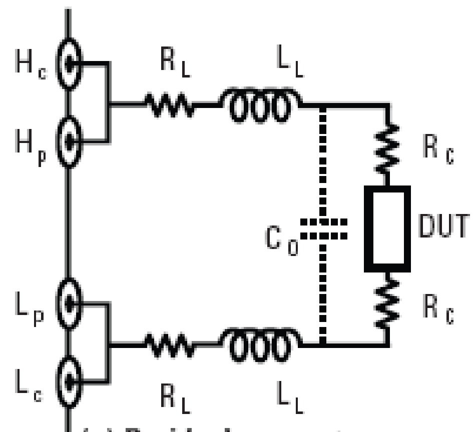
• is the simplest method of connecting a DUT
• contains error sources: lead inductances (L_L), lead resistances (R_L), stray capacitance (C_o) between two leads and contact resistances (R_C) between the test fixture's electrodes and the DUT;
• measurement ranges 100Ω - 10KΩ



(a) Schematic diagram



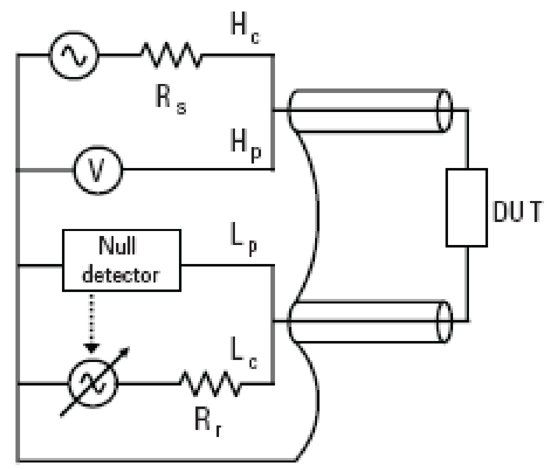
(b) Connection image



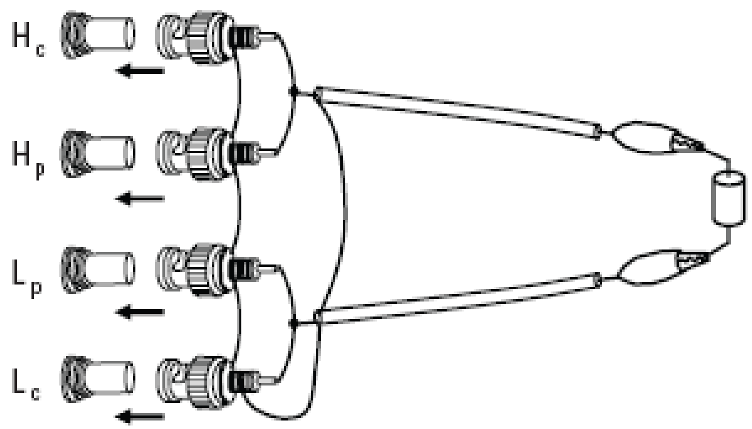
(c) Residual parameters

Three-terminal configuration (3T)

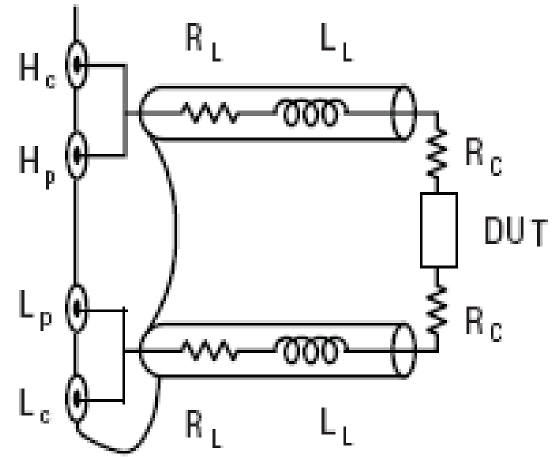
- employs coaxial cables to reduce the effects of stray capacitance;
- accuracy is improved for the higher impedance values;
- measurement ranges 100Ω - 10MΩ;



(a) Schematic diagram



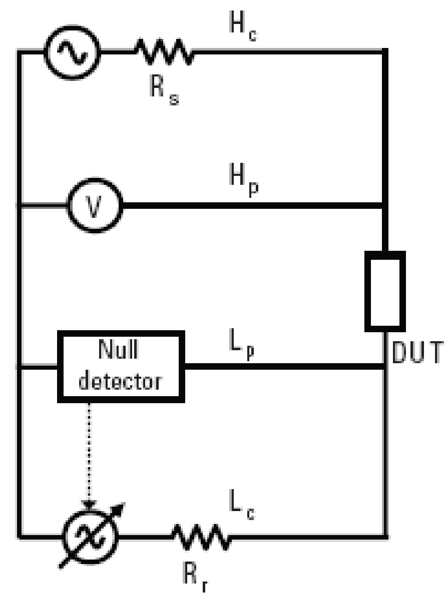
(b) Connection image



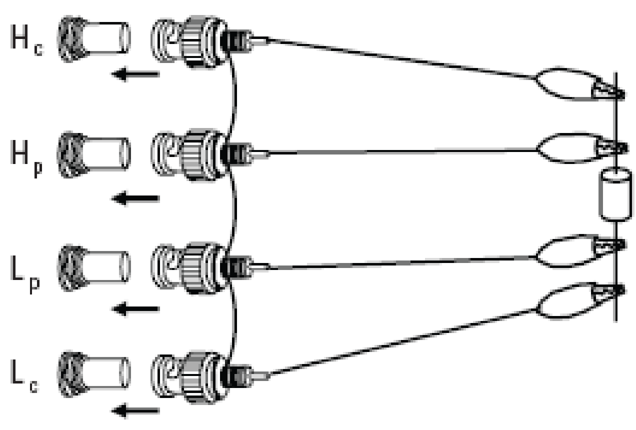
(c) Residual parameters

Four-terminal configuration (4T)

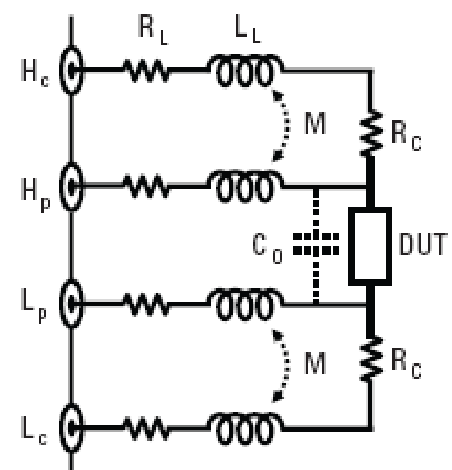
- the signal current path and the voltage sensing leads are independents;
- reduce the effects of lead impedances (ωL_L and R_L) and contact resistances (R_c);
- introduces error at low impedance measurement due mutual coupling between the leading wires
- measurement ranges 10mΩ - 10kΩ;



(a) Schematic diagram



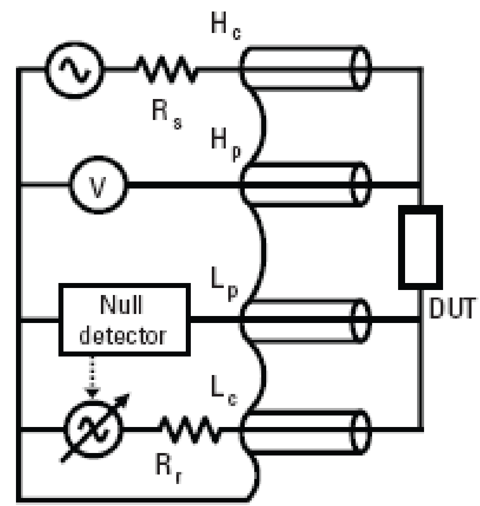
(b) Connection image



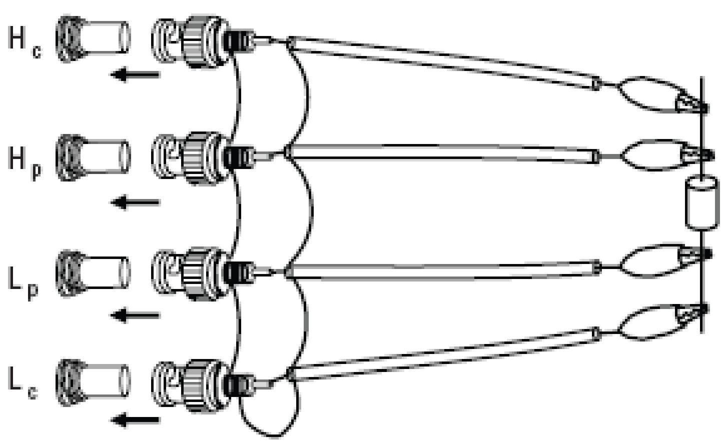
(c) Residual parameters

Five-terminal configuration (5T)

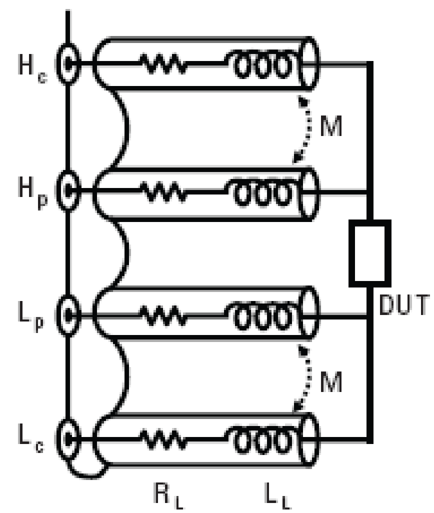
• employs four coaxial cables and all of the outer shielding conductors of the four cables are connected to the guard terminal
• does not resolve mutual coupling problem;
• measurement ranges 10mΩ - 10MΩ;



(a) Schematic diagram



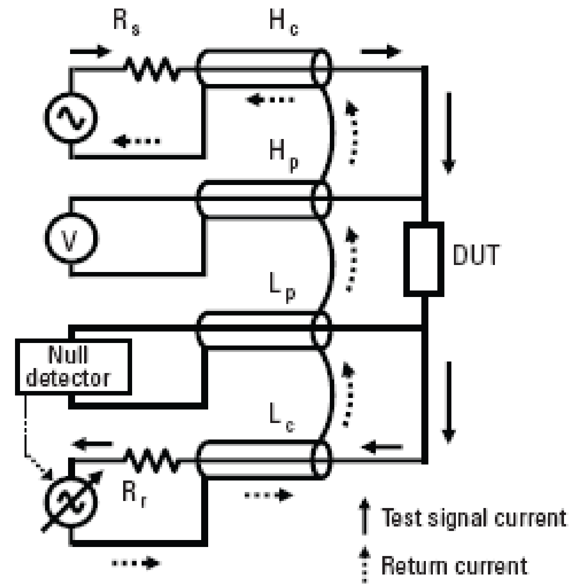
(b) Connection image



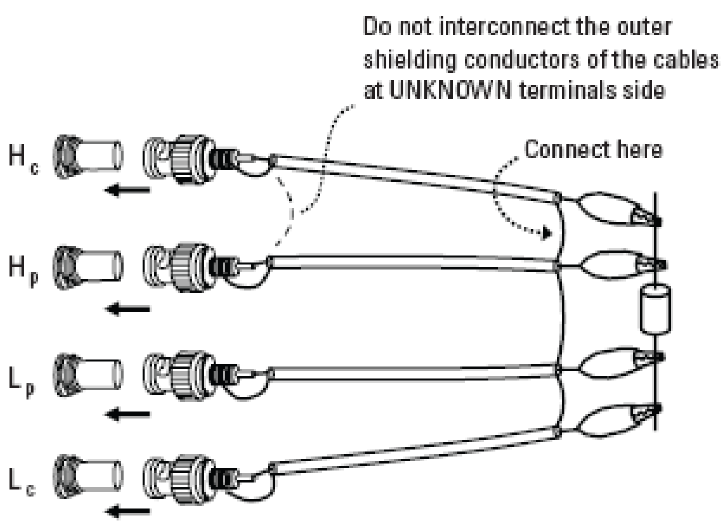
(c) Residual parameters

Four-terminal pair configuration (8T)

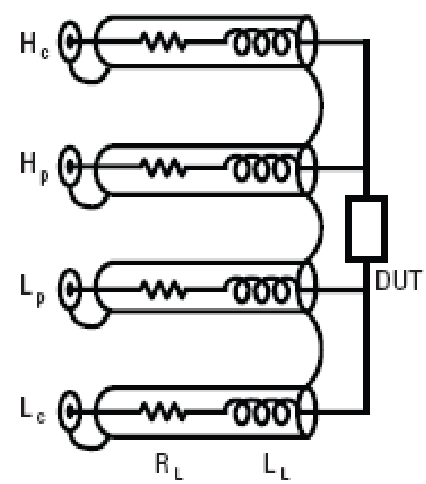
- employs four coaxial cables to reduce the effects of stray capacitance;
- connects the outer shielding conductors to each other at the ends of the coaxial cables,
- isolate outer conductors at H_c, H_p, L_p, and L_c terminals
- solves the mutual coupling between the leads
- measurement ranges 1mΩ - 10MΩ;



(a) Schematic diagram



(b) Connection image



(c) Residual parameters

Bibliography

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• S. Ciochina, *Masurari electrice si electronice*, 1999;