Electrical and Electronic Measurements:

LCR Meter

1

Measurement Discrepancy

- All of us have experienced the situation where measurement results did not match our expectations or did not correlate.

- Have you ever experienced one of these two situations;
Measuring the same DUT with two different instruments and getting completely different results,
or even measuring the same DUT, with the same instrument, within the same week and getting two different results?

2

Measurement Discrepancy (Cont'd)

Which value is correct?
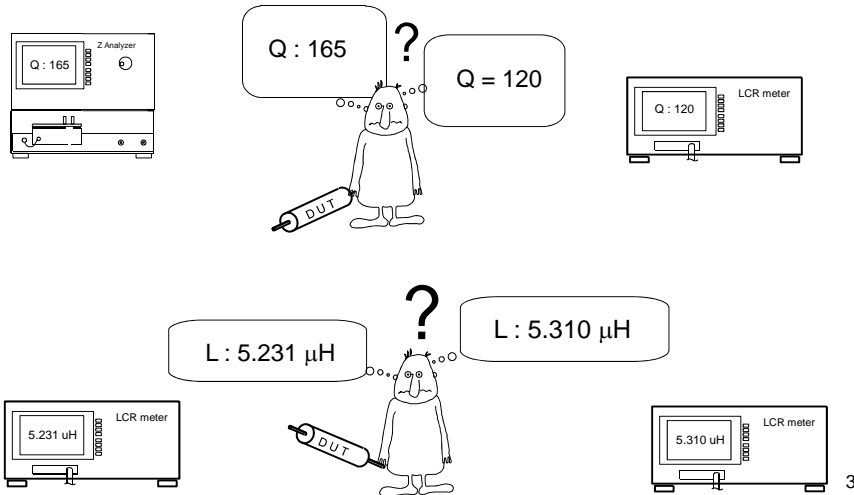
Measurement Discrepancy (Cont'd)

Accurate impedance measurements are dependent upon many factors.

- The testing conditions or component dependency factors affect the component behavior and the measured values.

- It is important to realize that the value we measure is not necessarily the one we want.
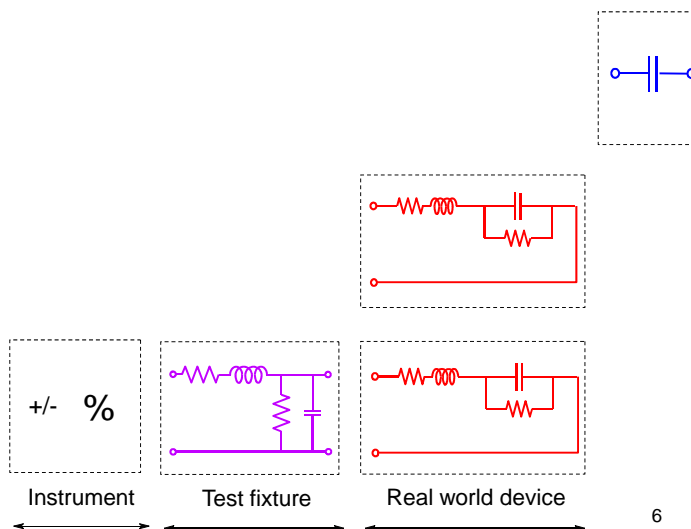
Measurement Discrepancy Factors

- True, Effective, and Indicated Values
  Which value do instruments measure?

- Measurement Errors
  Because of the instrument technique and
  the accessories we use, we introduce
  additional errors or measurement errors.

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True/Effective/Indicated Values

- True

- Effective

- Indicated

+/- %

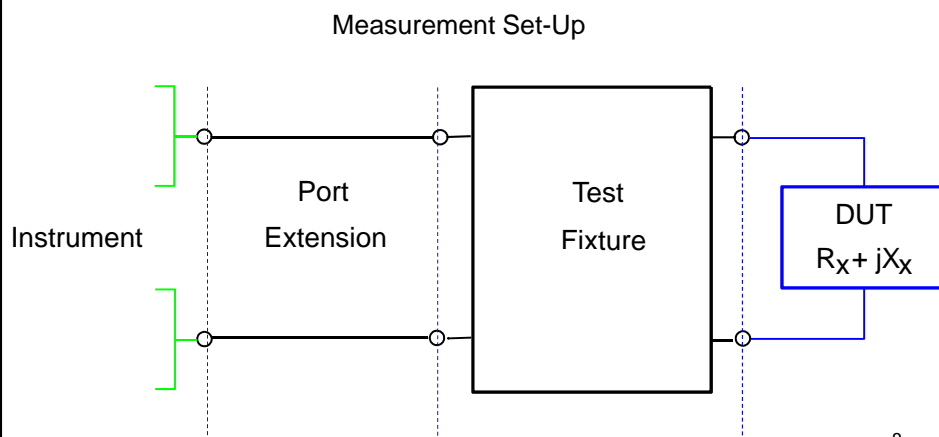Instrument   Test fixture   Real world device

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True/Effective/Indicated Values (Cont'd)

- The true value excludes all parasitics and is given by a math relationship involving the component's physical composition.

- The effective value is what we generally want to measure because it takes into consideration the parasitics and dependency factors.

  When designing and simulating circuits, only effective values should be used to reflect the actual circuit behavior.

- The indicated value given by the instrument takes into account not only the real world device, but also the test fixture and accessories as well as the instrument inaccuracies and losses.
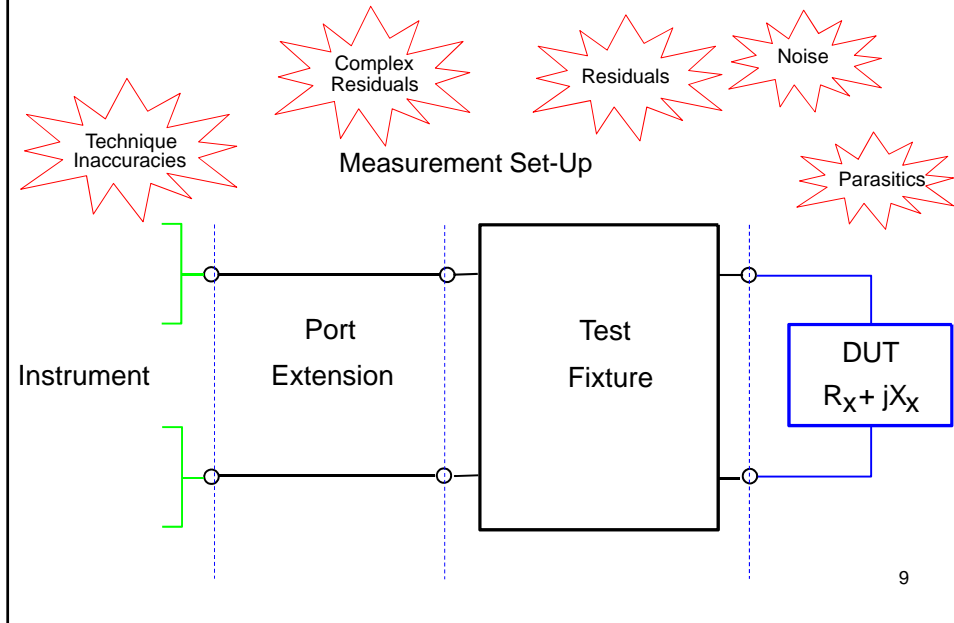
7

True/Effective/Indicated Values (Cont'd)

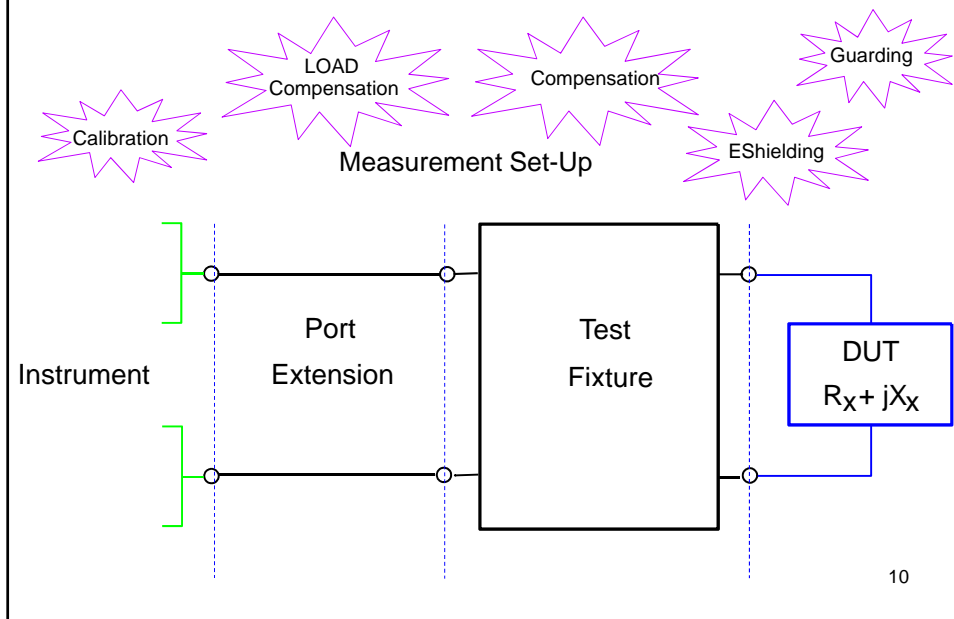- Our goal is to make the indicated value as close as possible to the effective value.

Measurement Set-Up

Instrument

Port Extension

Test Fixture

DUT
$R_X + jX_X$

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True/Effective/Indicated Values (Cont'd)

Complex Residuals

Residuals

Noise

Technique Inaccuracies

Measurement Set-Up

Parasitics

Instrument

Port Extension

Test Fixture

DUT $R_X + jX_X$

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True/Effective/Indicated Values (Cont'd)

LOAD Compensation

Compensation

Guarding

Calibration

Measurement Set-Up

EShielding

Instrument

Port Extension

Test Fixture

DUT $R_X + jX_X$

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True/Effective/Indicated Values (Cont'd)

- Guarding helps minimizing parasitics and ground loops or common mode currents in the case of floating measurements.

  The guard terminal is usually what we can consider a zero-potential of the instrument, and it is often simply a "ground" terminal (but not always).

Note: In floating measurements, neither point of the measurement is at ground potential.

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True/Effective/Indicated Values (Cont'd)

- Shielding minimizes the amount of interference induced in the measurement circuits.
  The exposed leads of leaded components catch interference and noise.

Note: The common-mode current is the unbalanced current (current not returned) on the cable. The radiation from a cable is directly proportional to the common-mode current on that cable. If this current is not returned on the cable, where does it go? Into radiation, that's where!

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True/Effective/Indicated Values (Cont'd)

- Charges or charged particles are point sources of an electrostatic field (E-field) storing energy.
- The error current coupled into measurement conductors is directly proportional to the strength of the field.
- For example, people carry static charges with them wherever they go. AC line potentials in and around the laboratory can elicit AC E-fields, which, in turn, generate error currents.
- Shields work by both reflection and absorption of field energy.

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True/Effective/Indicated Values (Cont'd)

- Test fixture residuals are minimized by proper design, but always exist.
  They are also measured together with the DUT and therefore must be removed by compensation.
- Port extension generally adds complex errors because of its non-negligible electrical length and its complex electrical path, i.e. switches.

  Load compensation or electrical delay minimizes these errors.

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True/Effective/Indicated Values (Cont'd)

- Technique inaccuracies reflect the errors of an instrument technique. They can be removed by calibration and this is done when the instrument is manufactured or serviced.

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Component Discrepancy Factors

- Component parasitics
- Test signal frequency
- Test signal level
- DC bias, voltage and current
- Environment (temperature, humidity, etc.)
- Component's current state
- Aging

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Component Parasitics

- The choice of a given model complicates the measurements and necessarily implies errors.
- All components have parasitics determined by the quality of component material and design.
- For example, in real world capacitor, there are unwanted series wire inductance and resistance and unwanted resistance and capacitance across the dielectric.

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Component Parasitics (Cont'd)

- However, we can quantify these parasitics by its model and the quality factor Q representing the component's non-ideal characteristics.
- The higher the Q, the better or more ideal the component.

Intrinsic C

Unwanted R and L of leads

Unwanted R and C of dielectric
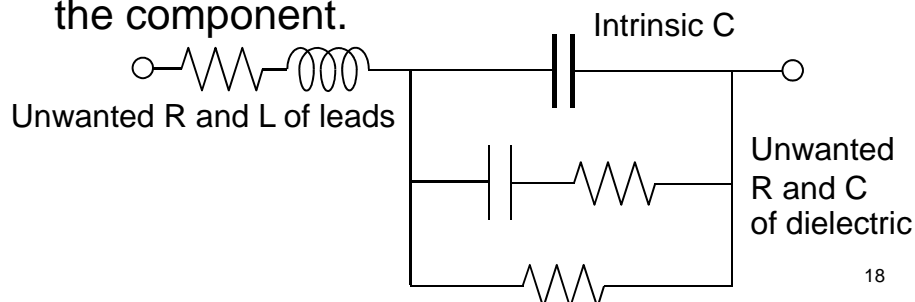
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Test Signal Frequency

- All components have frequency limitations and it is the most significant dependency factor.
- For example, this capacitor looks like a capacitor in the lower frequency region.
- The point where the capacitive and inductive reactance are equal is the resonant frequency and the component behaves like a resistor.
- At higher frequencies, this capacitor behaves like an inductor!
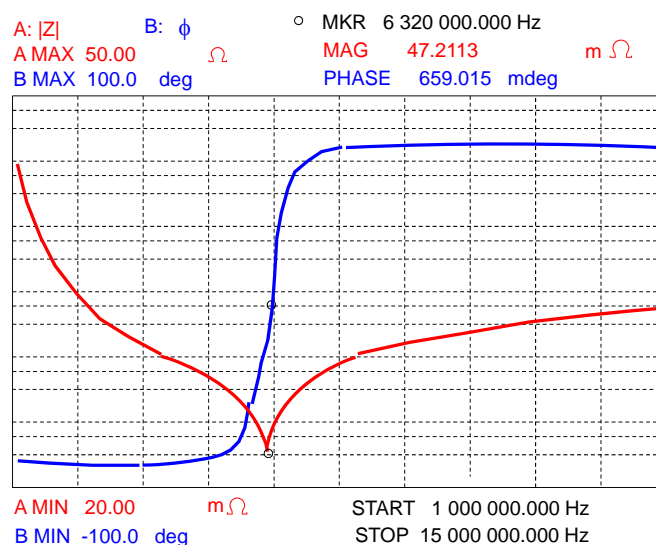
19

Test Signal Frequency (Cont'd)

Capacitor Model

$|X|$

$X_C = \dfrac{1}{\omega C}$

$X_L = \omega L$
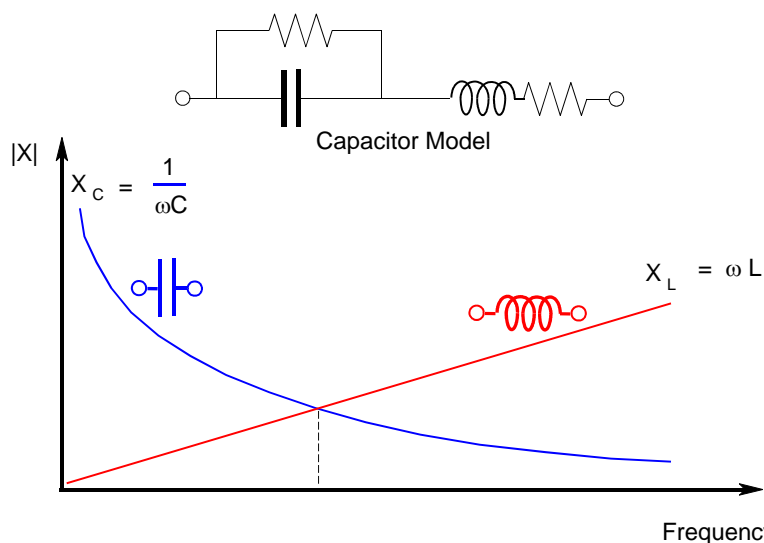
Frequency

20

Test Signal Frequency (Cont'd)

- This display shows |Z| and ϕ of a capacitor between 1 MHz and 15 MHz.
- Before resonance, the phase is around -90 degrees and the component effectively looks like a capacitor.
- The impedance decreases with the frequency until the resonance point, due to the inductive elements of the component. Note that at resonance, the phase is 0 degrees for purely resistive.
- After resonance the phase angle changes to +90 degrees so the inductive elements dominate.
- Remember, when you buy a capacitor, you get 3 components!

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Test Signal Frequency (Cont'd)

A: |Z|	B: ϕ	$\circ$ MKR 6 320 000.000 Hz	
A MAX 50.00	Ω	MAG 47.2113	m Ω
B MAX 100.0 deg		PHASE 659.015 mdeg	

A MIN 20.00	mΩ	START 1 000 000.000 Hz	
B MIN -100.0 deg		STOP 15 000 000.000 Hz	22

Test Signal Level

- For instance, the test signal level is a very important dependency factor for SMD (surface mounted device) becoming more and more popular.


SMDs on
USB flash drive

Note: Surface-mount technology (SMT) is a method for producing electronic circuits in which the components are mounted or placed directly onto the surface of printed circuit boards.

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Test Signal Level (Cont'd)

- For example, have a look into a typical chip capacitor performance

- The electrical properties of the dielectric material of ceramic capacitors cause the capacitance to vary with the applied AC test signal.

C Vs. AC Test Signal Level
SMD Capacitors with
Various dielectric constants K

C

High K

Mid K

Low K

Vac

- Capacitors with high value dielectric constant (K) exhibit an important dependency.
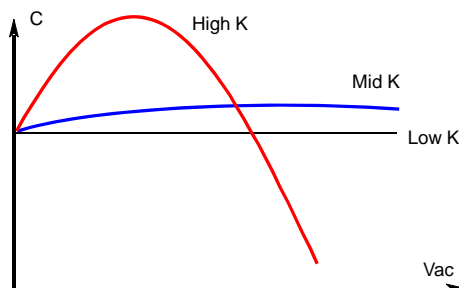
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Test Signal Level (Cont'd)

Note: The dielectric constant is the ratio of the permittivity of a substance to the permittivity of free space. It is an expression of the extent to which a material concentrates electric flux.

DC Bias

- DC bias voltage is a crucial parameter to insure the right performance.

- Type II SMD capacitors are more and more popular because of their high dielectric constant material which allows larger capacitance per unit volume.

C Vs. DC Voltage Bias

$\triangle$ C / %   Type I and II SMD Capacitors

- But their capacitance varies more with DC biasing than for Type I SMD capacitors.
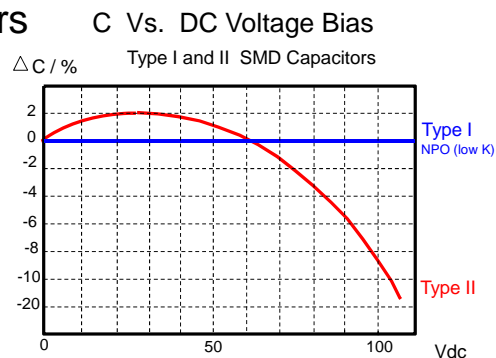
DC Bias (Cont'd)

- Switching power supplies are very common today.

- They use power inductors for filtering RFI and noise produced by high currents.

L Vs. DC Current Bias Level
Power Inductors

$\triangle$ L / %

2
0
-2
-4
-6
-8
-10
-20

0   50   100   Idc

- To maintain good filtering and ripple at high current levels, power inductors must be tested at operating conditions to ensure that the inductance roll-off does not affect the performance.
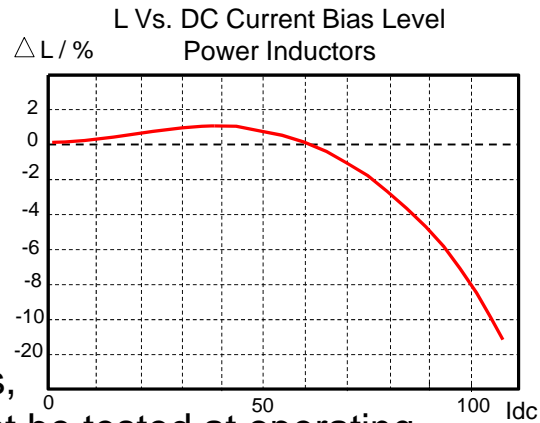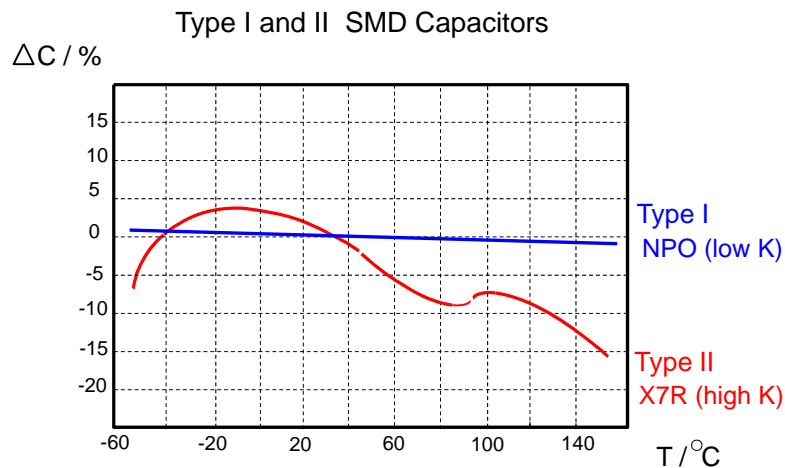
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Temperature

- Another drawback of Type II SMD capacitors is their behavior as a function of temperature.

- They are a lot less stable than Type I capacitors.

- This factor must be taken into account in the design process.

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Temperature (Cont'd)

Type I and II SMD Capacitors

$\triangle C$ / %

15
10
5
0
-5
-10
-15
-20

Type I
NPO (low K)

Type II
X7R (high K)

-60   -20   20   60   100   140

T / $^{\circ}$C

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Impedance Measurement

- Since all real world components have parasitics, we must lump all the resistive and reactive elements of the component together into an equivalent set of series or parallel elements.

- These two circuit modes allow the instrument to interpret the measurement data and translate it into indicated value according to the user's information (model choice).

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Impedance Measurement (Cont'd)

- Impedance cannot be directly measured like voltage, for instance.
- The fundamental parameter measured by the instrument depends upon the instrument technique.
- Then the internal processor makes a direct calculation to compute Z. But usually users ask for parameters like L, C, R, Q or D, which can be derived from simple two element models (series and parallel ones).
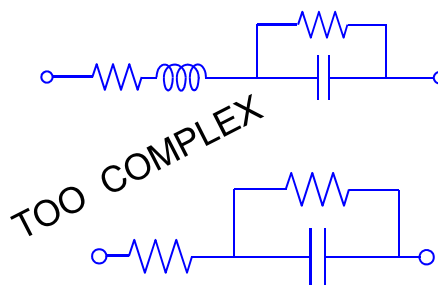- These are approximate models used to describe the component's behavior.

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Impedance Measurement (Cont'd)

Requires Simplified Models

Complete Capacitor Model
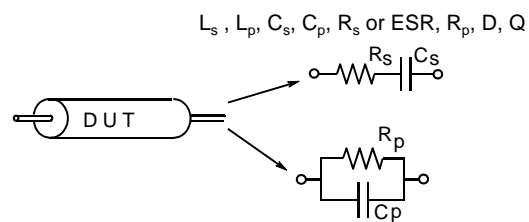R_s, L_s, R_p, C_p ?

No L Capacitor Model

TOO COMPLEX

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Impedance Measurement (Cont'd)

	I-V Method	Bridge Method
Measured	I, V	Known Z_1, Z_2 and Z_3
Direct Calculations	$Z = \dfrac{V}{I}$	$Z_4 = Z_2 Z_3 / Z_1$
Model based Approximations		L_s, L_p, C_s, C_p, R_s or ESR, R_p, D, Q

DUT

R_s C_s

R_p

C_p

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Model Simplification

R_s Vs. R_p , which one is the best approximation

No L Capacitor Model

R_p

R_s

C

Series model

R_s C_s

Large C

Small L

R_p

C_p

Parallel model

Small C

Large L

SMD
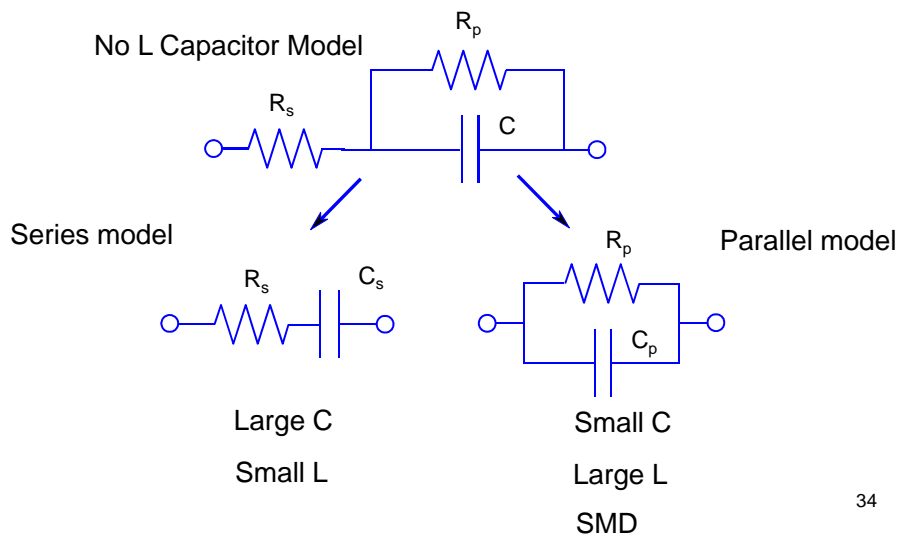
34

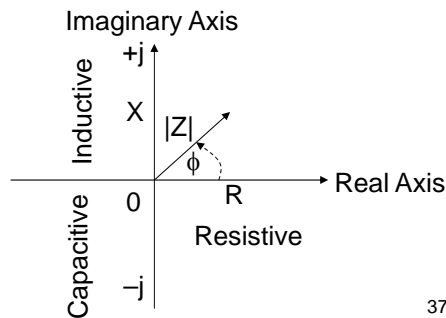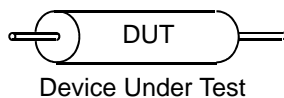# Model Simplification (Cont'd)

- Usually R_s is in Ω or mΩ while R_p is in MΩ or greater.

- For large C or low impedance devices, the loss due to the series resistance R_s is more significant than the leakage loss due to the parallel resistor R_p.

- Therefore series model is convenient for large capacitors (typically > 100 μF), while the parallel model fits the small capacitors (< 10 μF).

- However, for SMD capacitors, the parallel model is always better because of very low contact resistance, R_s, and inductance, L_s.

- On the other hand, we will use the parallel model for large inductors and the series model for small ones. [35]

Model Simplification (Cont'd)

- Since the user tells the instrument which model to use, this is another source of measurement discrepancy.

- Fortunately, both models are always correct and related to each other through this math formula.

- For low quality devices, one model is always a better approximation, while high quality or low dissipation DUTs exhibit identical series or parallel values (D <<1). [36]
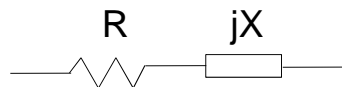
Impedance Measurement Plane

- Ideal components would lie on an axis.
- The more ideal an inductor or a capacitor, the less resistive it will be, therefore the angle ϕ will be close to to +90 degrees (inductor) or –90 degrees (capacitor).
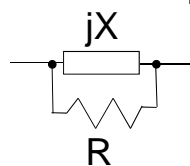
Imaginary Axis

$+j$

$-j$

Inductive

Capacitive

X

0

|Z|

ϕ

R

Real Axis

Resistive

DUT

Device Under Test

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Series and Parallel Model

- Series: $Z = R + jX$ and $Q = X/R$

  R   jX

- Parallel: $Z = \dfrac{jRX}{R + jX} = \dfrac{RX^2}{R^2+X^2} + \dfrac{j\,R^2X}{R^2+X^2}$
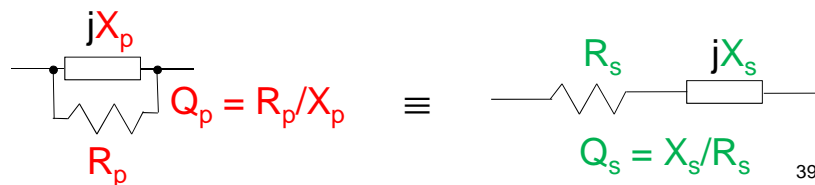
  jX

  and $Q = R/X$

  R

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Parallel-to-Series RX Equivalence

- $R_s = \dfrac{R_p X_p^2}{R_p^2 + X_p^2} = \dfrac{R_p}{(R_p/X_p)^2 + 1} = \dfrac{R_p}{1 + Q_p^2}$

- $X_s = \dfrac{R_p^2 X_p}{R_p^2 + X_p^2} = \dfrac{X_p}{1 + (X_p/R_p)^2} = \dfrac{X_p}{1 + 1/Q_p^2}$

jX_p

R_p

$Q_p = R_p/X_p$ $\equiv$

R_s jX_s

$Q_s = X_s/R_s$

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Parallel-to-Series RX Equivalence (Cont'd)

- $Q_s = X_s/R_s = \dfrac{X_p}{R_p} \dfrac{1 + Q_p^2}{1 + 1/Q_p^2} = \dfrac{X_p}{R_p} Q_p^2 = Q_p$

- At frequencies where $Q_{p,s} > 0$

$$R_p > R_s$$

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Series-to-Parallel RX Equivalence
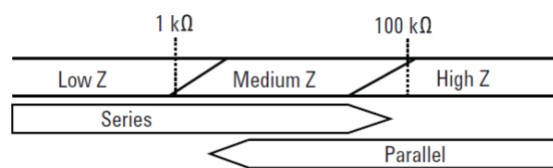
- $Q_s = Q_p$ or $Q_p = Q_s$
- $R_s = \dfrac{R_p}{1 + Q_p^2}$ or $R_p = (1 + Q_s^2)R_s$
- $X_s = \dfrac{X_p}{1 + 1/Q_p^2}$ or $X_p = (1 + 1/Q_s^2)X_s$

- When $Q_{p,s} \gg 1$

$$R_p \approx Q_s^2 R_s$$
$$X_p \approx X_s$$

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Relationship between X_s nad X_p

	Series	Parallel	Dissipation factor
	$R_s \;\pm jX_s$	G_p	(Same value for series and parallel)
Capacitance	$C_s = C_p(1 + D^2)$	$C_p = C_s/(1 + D^2)$	$D = R_s/X_s = \omega C_s R_s$
			$D = G_p/B_p = G_p/(\omega C_p) = 1/(\omega C_p R_p)$
Inductance	$L_s = L_p/(1 + D^2)$	$L_p = L_s(1 + D^2)$	$D = R_s/X_s = R_s/(\omega L_s)$
			$D = G_p/B_p = \omega L_p G_p = \omega L_p/R_p$
Resistance	$R_s = R_p D^2/(1 + D^2)$	$R_p = R_s(1 + 1/D^2)$	——

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Measurement Techniques

Selecting the appropriate measurement technique is an important aspect in performing impedance measurements.

- Auto balancing bridge
- Resonant Q-meter
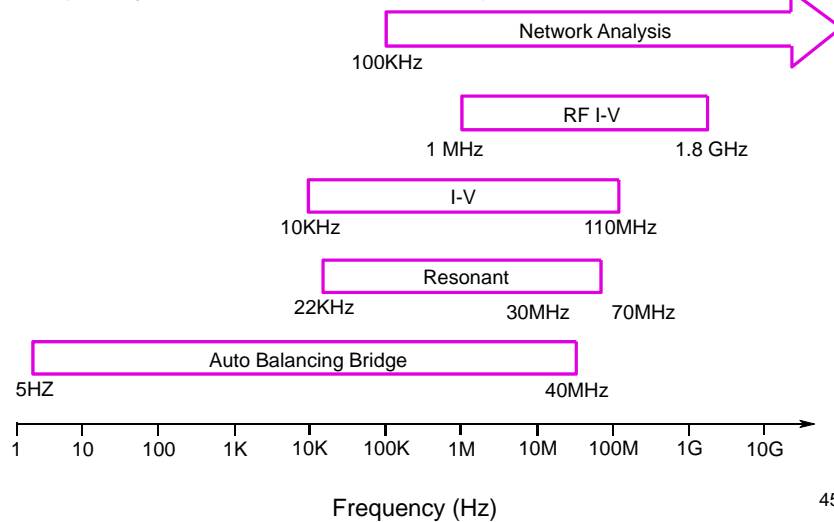- V-I probe
- RF I-V
- Network analysis

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Selection Criteria

- Given the measurement requirements and conditions of your application, you will choose the most appropriate measurement technique considering such factors as frequency coverage, measurement range, measurement accuracy, and ease of operation.

- However your choice will always require you to make tradeoffs as there is no one measurement method which includes all measurement capabilities.

- The selection criteria are required measurement accuracy, measurement parameters, DUT impedance, physical characteristics of the DUT, electrical test conditions, and frequency.
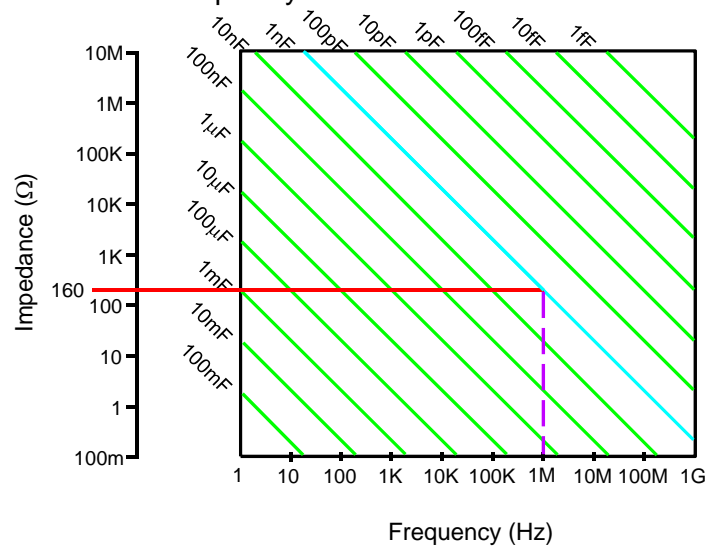
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Selection Criteria (Cont'd)
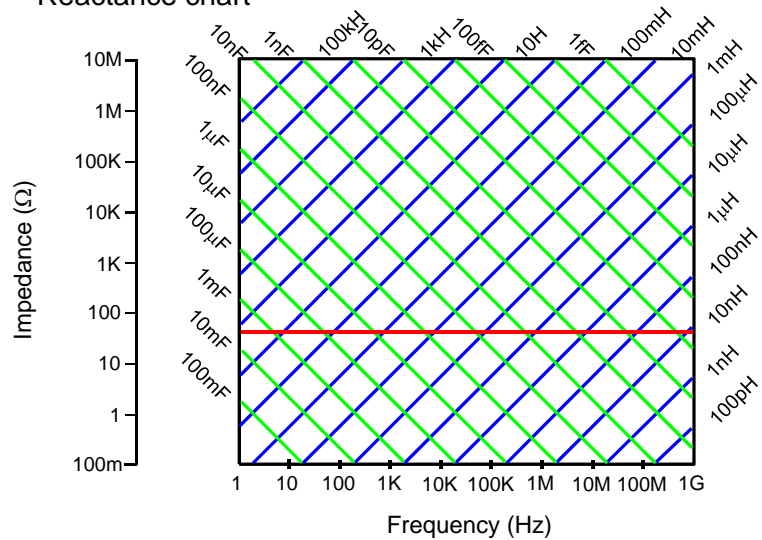
Frequency vs. Measurement techniques

Network Analysis

100KHz

RF I-V

1 MHz   1.8 GHz

I-V

10KHz   110MHz

Resonant

22KHz   30MHz   70MHz

Auto Balancing Bridge

5HZ   40MHz

1	10	100	1K	10K	100K	1M	10M	100M	1G	10G

Frequency (Hz)

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Selection Criteria (Cont'd)

Z and C vs. Frequency

Impedance (Ω)

10M
1M
100K
10K
1K
160
100
10
1
100m

10nF 1nF 100pF 10pF 1pF 100fF 10fF 1fF
100nF
1μF
10μF
100μF
1mF
10mF
100mF

1   10   100   1K   10K   100K   1M   10M   100M   1G

Frequency (Hz)
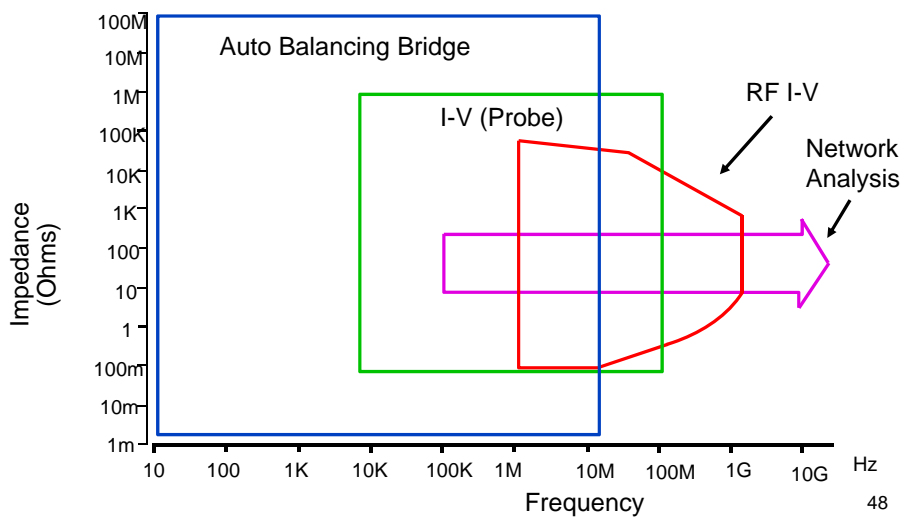
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Selection Criteria (Cont'd)

Reactance chart

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Selection Criteria (Cont'd)

Solution by frequency comparison


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Bridge Method

- Used in standard lab applications covering wide frequency range from DC to 300 MHz based on different bridge types.
- High accuracy
- Lower cost
- However, it needs to be manually balanced
- Narrower frequency coverage using single instrument

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Auto Balancing Bridge

Basically, in order to measure the complex impedance of the DUT it is necessary to measure the voltage of the test signal applied to the DUT and the current that flows through it.
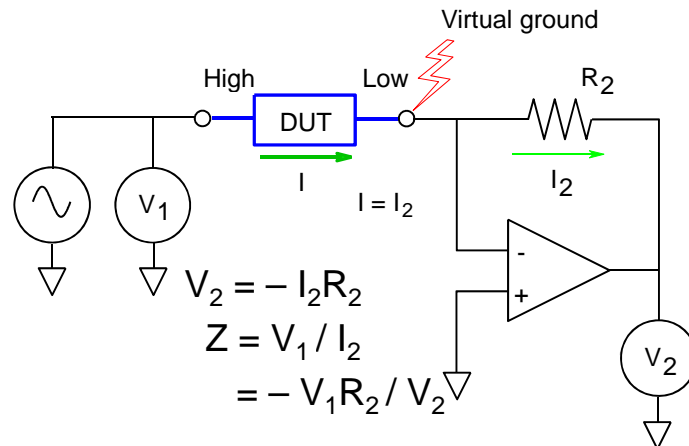
- The voltmeter and ammeter measure the vectors (magnitude and phase angle) of the signal voltage and current, respectively.

$$Z = V / I$$
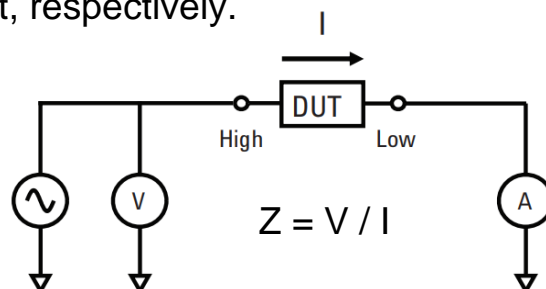
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Auto Balancing Bridge (Cont'd)

Using operational amplifier with a negative feedback loop

Virtual ground

High   Low

DUT

R_2

I

$I = I_2$

I_2

V_1

$V_2 = -I_2 R_2$

$Z = V_1 / I_2$

$= -V_1 R_2 / V_2$

V_2

Note: I-V converter is to produce a voltage proportional to the given current.

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Auto Balancing Bridge (Cont'd)

- The autobalancing bridge technique is by far the best technique for measurements below 40 MHz.

- It provides the most accurate measurements possible (basically 0.05%) and has the widest impedance measurement range.

- A wide range of AC and DC stimulus can be applied to the component. In addition, because this is a low frequency technique, it is the simplest measurement technique to use.
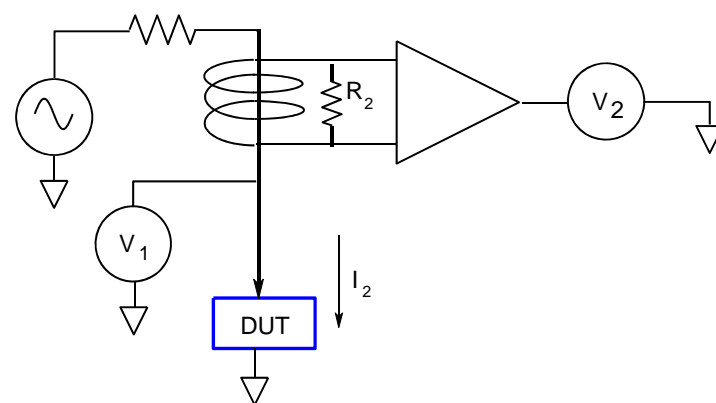
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Resonant Q-Meter

- Very good for high Q / low D measurements
- It is ideal for measurement for 10KHz to 70 MHz frequency range.
- However, it needs to be tuned to resonance
- Require reference coil for capacitors
- Limited L,C values accuracy
- Low accuracy for low impedance measurement

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V-I Probe Technique

$V_2 = I_2 R_2$

$Z = V_1 / I_2 = V_1 R_2 / V_2$

54

V-I Probe Technique (Cont'd)

- Medium frequency, 10k - 110 MHz
- Moderate accuracy and measurement range
- Floating measurement technique, thus grounded and in-circuit measurements are very easy.
- Simple-to-use
- Operating frequency is limited based on transformer used in the probe.

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References

- Component Industry Trends: Driven by New End-User Equipment, Agilent Technologies
- Challenges and solutions for Impedance measurements - Keysight
- http://www.rfwireless-world.com/test-and-measurement/impedance-measurement-basics-and-methods.html

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