

## WORKSHOP 5 - EMC OF ICs - THE FRENCH TOUCH

On the combined effect of environmental and service conditions on the EMC behavior of the passive component up to the circuit.

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(with Dr. Fahim HAMI & Dr. HDR. Moncef KADI)



# Outline

- Introduction
- Objectives
- Characterization and modelling of Frequency & Temperature-Dependent Behavior of CM capacitors
- Characterization and modelling of Frequency & Temperature-Dependent Behavior of coupled inductors
- Application to the EMI filter modelling
- Conclusion

# INTRODUCTION/context

□ Electrification of means of transport :

➤ Multi-constrained environment:

Electrical

Thermal

Mechanical

Vibratory

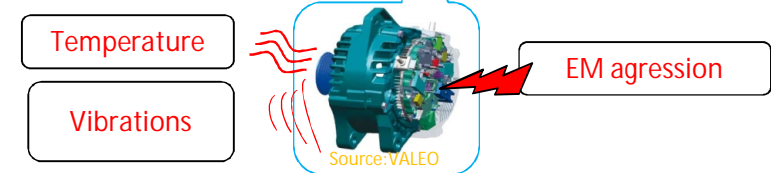
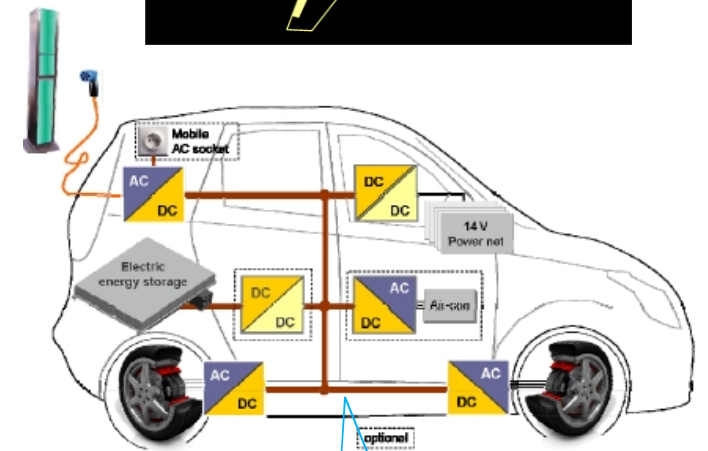
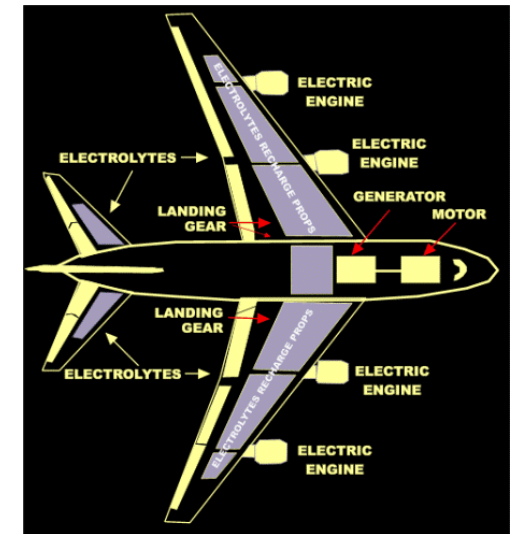
Economic!

➤ Standardization

EMC

Security

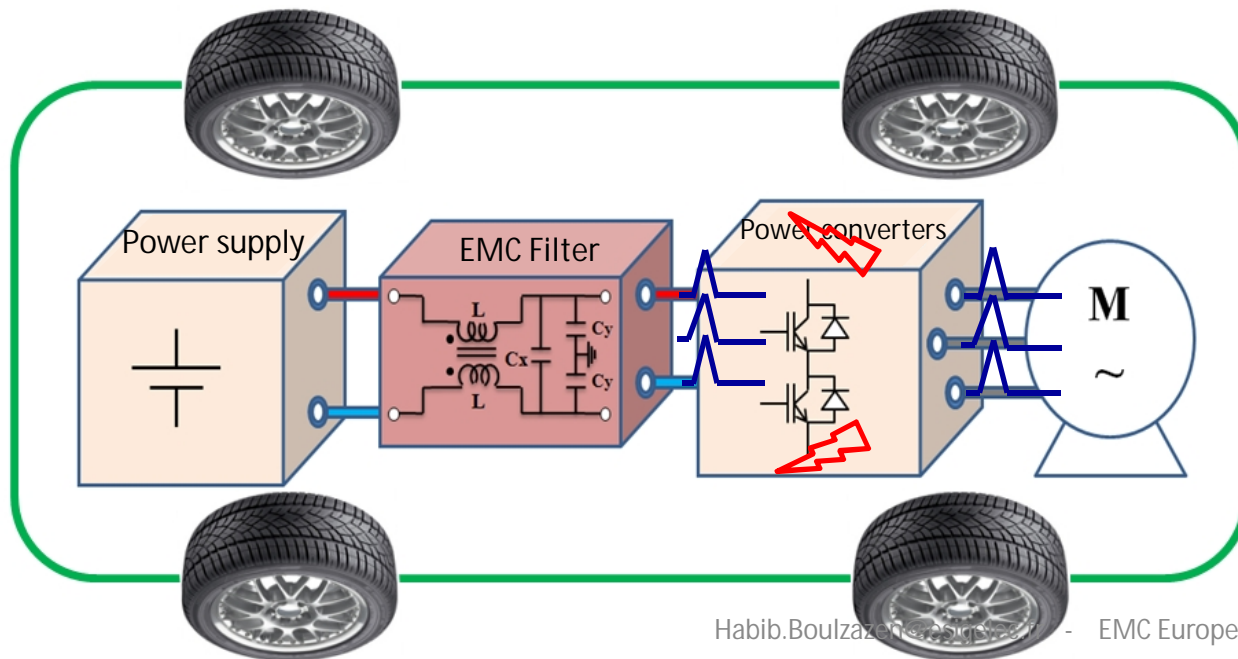
Reliability



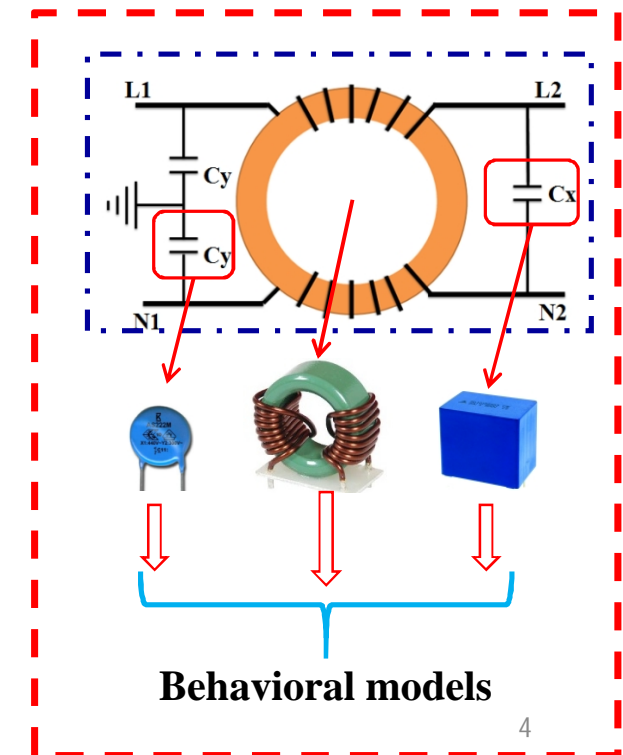
# INTRODUCTION/context

## □ EMC context

- Power electronic converters with high switching frequency become the main source of the conducted electromagnetic emissions, especially in automotive and aeronautical applications
- To attenuate the EM disturbances → EMI filtering (**passive filtering**)



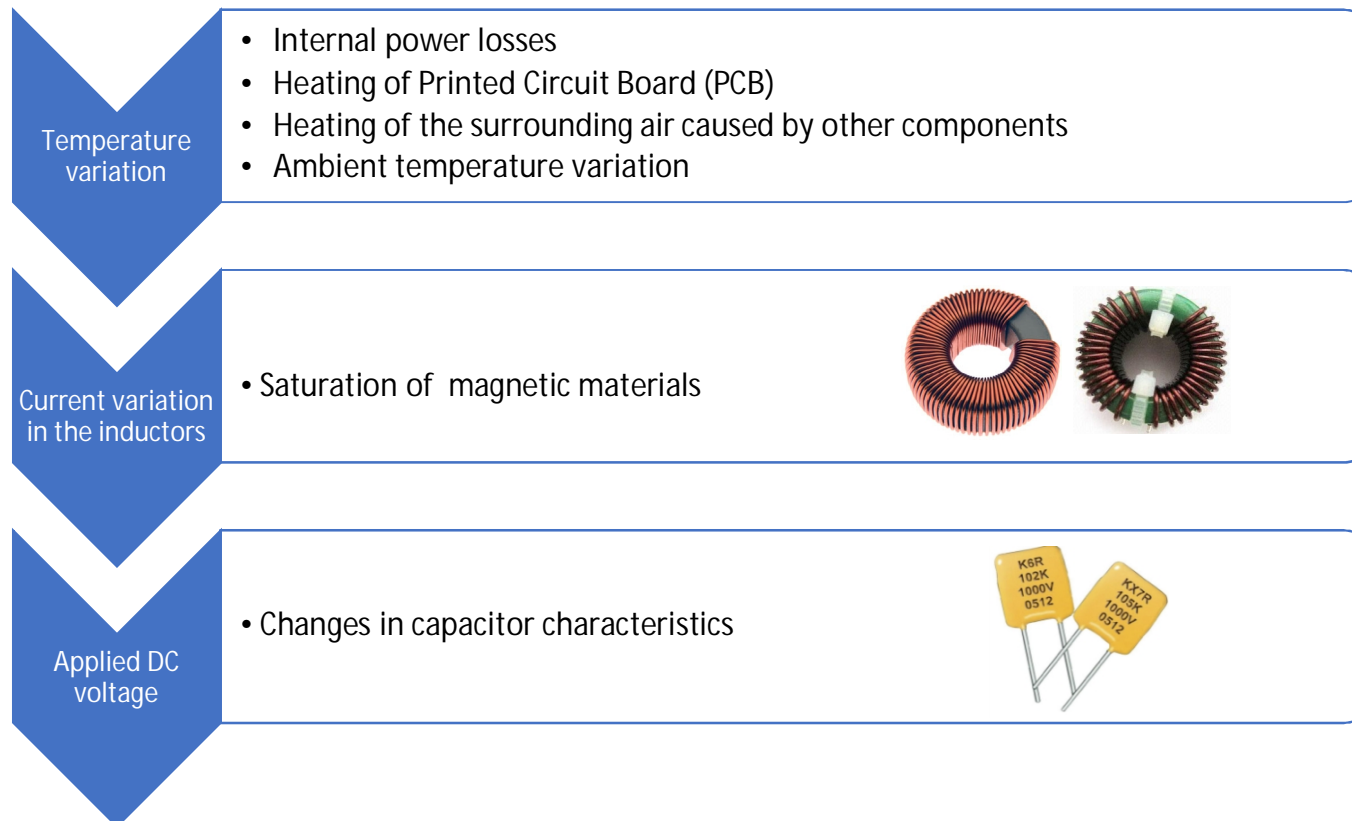
Habib.Boulzalen - EMC Europe 2017





# INTRODUCTION/problematic

- Sensitivity of passive components to the operating conditions context



Aspects that should be considered → by having a detailed behavior of these components in the simulations during the schematic design phase

# INTRODUCTION/problematic

- ❑ Why characterizing and modelling passive components respecting to operating conditions ?
- Real operation conditions may exceed the limits of nominal service profile of components
- Passive component manufacturers rarely provide the behavior of components beyond their service profile limits (datasheet)
- Questions :
  - How the frequency behavior of the components and the circuit comprising them with respect to the operating and environmental conditions evolves?
  - What's the effect on their EMC behavior? (ex: EMI filter)

**Automotive**

Source: A.Pergoot, Electronics'2007

ITRS 2010 (until 2024)  
-40°C up ~150°C (until 200°C)

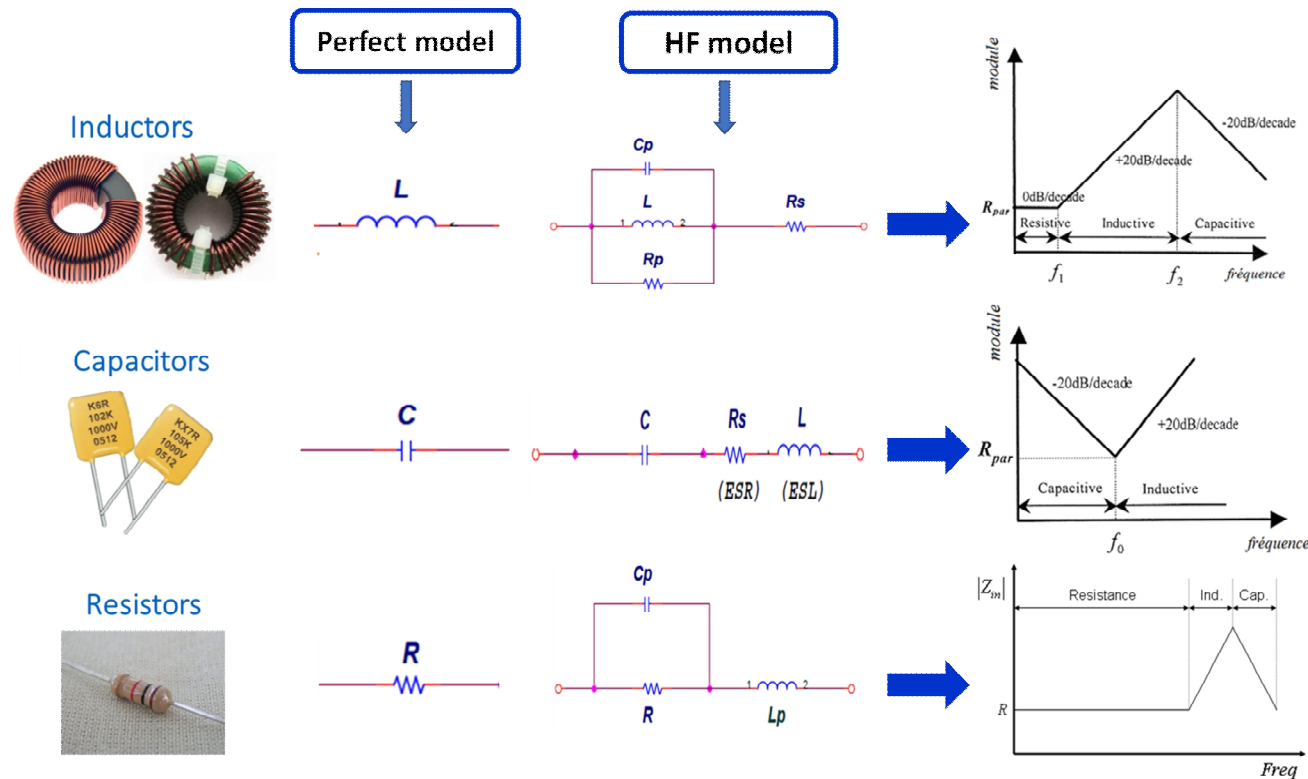
**Aeronautic**

Système électrique de commande d'inverseur (ETRAS) pour nacelle moteur de l'A380

Temperature :  
-60°C up to 250°C

# INTRODUCTION/problematic

- The frequency behavior and the parasitic elements of the passive components :
  - Relatively well known (use of VNA or Zmeter)
  - A profusion of works exists in the literature on this subject (ex: [1-3])
  - **Models proposed are independent of physical conditions such as the thermal aspects.**
  
- Few studies were made about the EMC modeling of passive circuits with the consideration of operating conditions :
  - Most of proposed models → dedicated to non-linear components (diodes and transistors).



1. M. Moreau & al. "Modeling of Conducted EMI in Adjustable Speed Drives," IEEE Trans. on EMC, Vol. 51, N° 3, pp.665-672, August, 2009.
2. J-L. Kotny & al. "High Frequency Modeling Method of EMI filters," IEEE Energy Conversion Congress and Exposition -ECCE09, pp. 1671-1678, 2009.
3. S. Wang & al. "Effects of Parasitic Parameters on EMI filter performance," IEEE Transactions on Power Electronics, Vol. 19, No. 3, pp.669-677, May 2004.

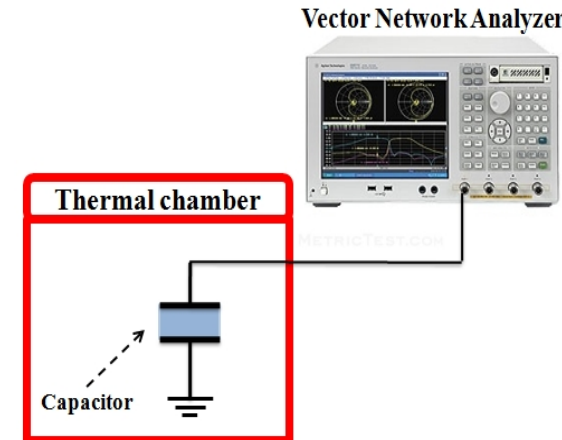
# OBJECTIVES

- Propose a behavioral models of coupled inductors and capacitors commonly used for EMI filters.
- Propose experimental methods, characterization techniques and analytical tools that can simplify and improve the design of these components by simulation with considering the influence of temperature on the frequency behavior of their impedances
- Present the experiment configurations used to identify parasitic elements and their temperature dependence
- Compare simulation to measurement results in order to test their effectiveness at high frequency and with regard to temperature variations
- Combine the developed models of capacitor and coupled inductors to simulate, in a wide range of frequencies (from 10 kHz to 100 MHz), the influence of temperature on CM filter attenuation

# Frequency & Temperature-Dependent Behavior of CM capacitors

## ➤ HF Characterization under temperature variation

- Different technologies of CM capacitors are characterized
- Test bench composed of VNA and thermal chamber
- Measurement results are recorded in the frequency range [10 kHz - 100 MHz]
- Temperature varied from -40 °C up to 140 °C.
- Teflon coaxial cables are used to resist to high and very low temperature.

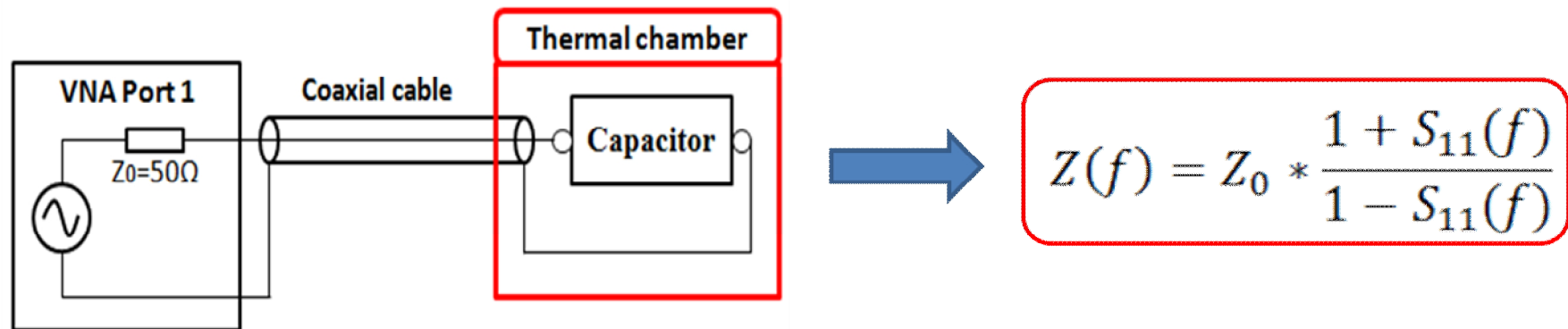


Capacitor	Nominal value C	Nominal temperature range	Maximum VDC voltage
Ceramic (X7R)	3700 pF	-40°C up to +85°C	750 AC
Ceramic (NPO)	1nF	-55°C up to +125°C	100V
Ceramic (Z5U)	200nF	-40°C up to +120°C	200V
Electrolytic Alu	1 μF	-40°C up to +85°C	350 AC
Tantale	0.22 μF	-55°C up to +125°C	35V AC
Film (PEN)	0.01μF	-40°C up to +80°C	100V AC
Film (PP)	0.22 μF	-40°C up to +120°C	1kV DC
Mica	100 pF	-55°C up to +125°C	500V DC

# Frequency & Temperature-Dependent Behavior of CM capacitors

## ➤ HF Characterization under temperature variation

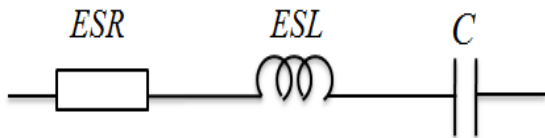
- The temperature is changed every twenty minutes.
- The S-parameters are measured and recorded for each temperature value
- the input complex impedance  $Z_{in}(f)$  is deduced from the input reflection coefficient  $S_{11}(f)$  by using the expression below



# Frequency & Temperature-Dependent Behavior of CM capacitors

## ➤ HF Characterization under temperature variation

☐ Measurement results on different technologies:

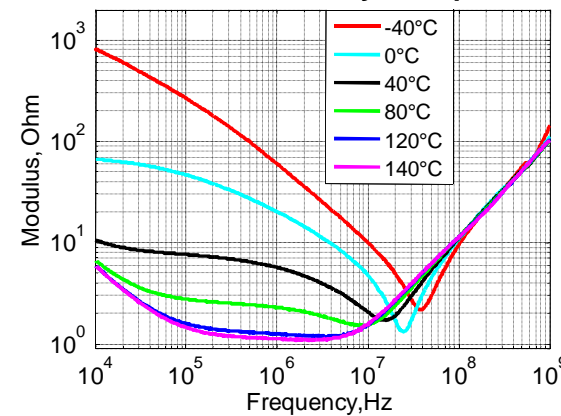


✓ ESR and C are temperature-dependent for certain capacitor types ( $f < f_r$ ).

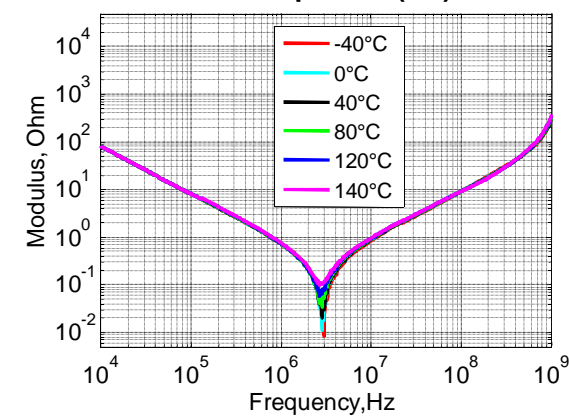
✓ The inductive part ESL is independent of the temperature ( $f > f_r$ ).

✓ Significant influence of temperature on X7R ceramic capacitors

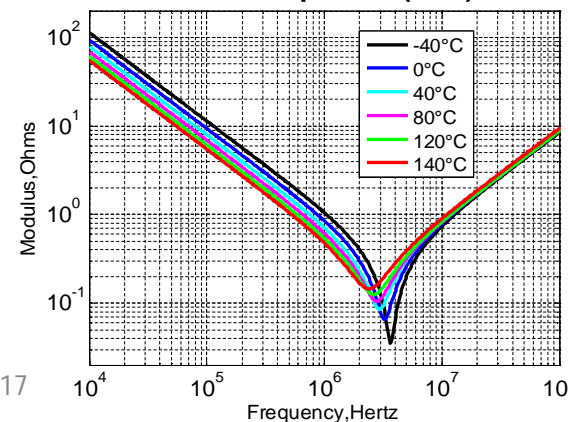
**Aluminum electrolytic Capacitor**



**Film Capacitor (PP)**



**Ceramic Capacitor (X7R)**



- ✓ Ceramic Capacitor (X7R)  
 $C_{nom}=3.7 \text{ nF}$ ,  $V_n=750 \text{ V}$   
 [-40°C up to +85°C]
- ✓ Film Capacitor (PP):  
 $C_{nom}=0.22 \text{ }\mu\text{F}$ ,  $V_n=1 \text{ Kv}$   
 [-40°C up to +120°C]
- ✓ Chemical Capacitor (Alu)  
 $C_{nom}=1 \text{ }\mu\text{F}$ ,  $V_n=350 \text{ V}$   
 [-40°C up to +85°C]

# Frequency & Voltage-Dependent Behavior of CM capacitors

## ➤ HF Characterization under bias-voltage variation

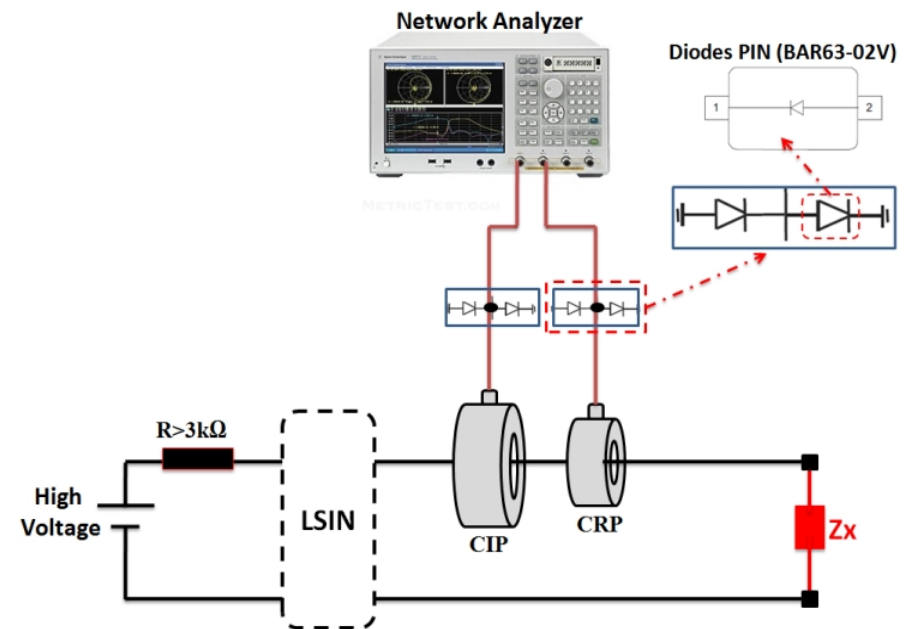
### ☐ Test bench & methodology:

✓ Two current probe method

✓ Galvanic isolation between the measurement device and the DC power supply.

✓ The error is less than 5% between [100 kHz-10 MHz]

✓ The method precision depends on the impedance of the LSIN, the accuracy of the two current probes and the RF quality of the connection wires.



$$Z_x(f) = K(f) * \frac{1+S_{11}(f)}{S_{12}(f)} - Z_{setup}(f)$$



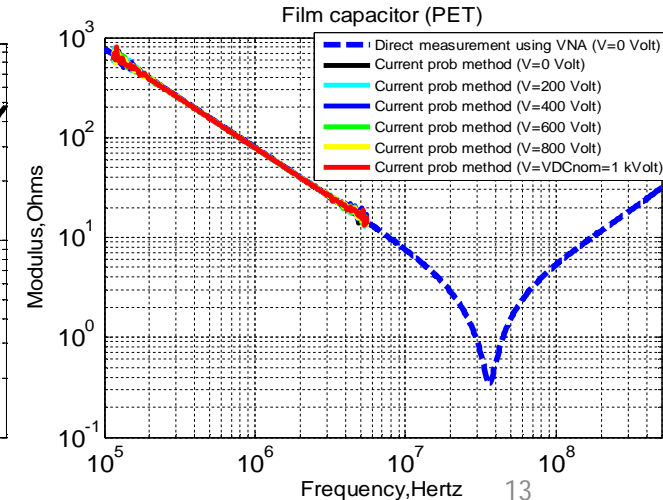
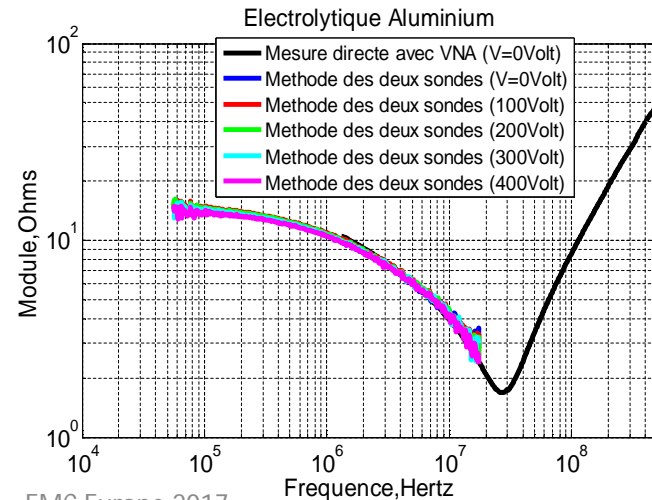
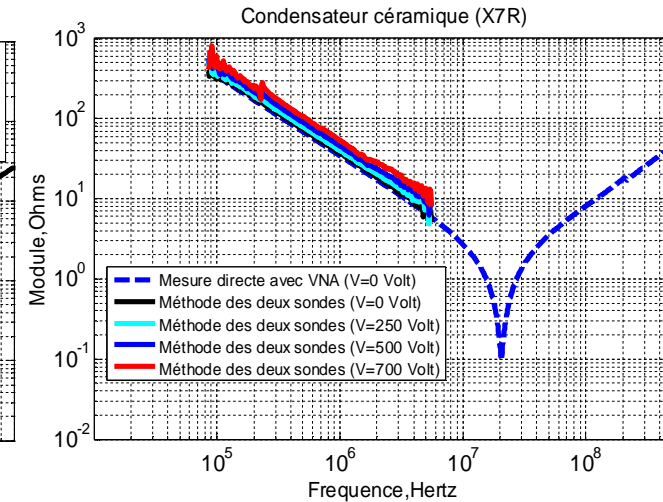
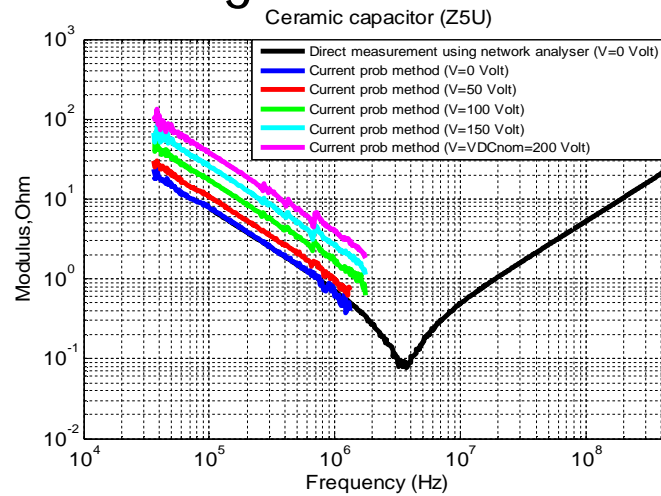
# Frequency & Voltage-Dependent Behavior of CM capacitors

## ➤ HF Characterization under bias-voltage variation

### ☐ Measurement results

✓ Ceramic capacitors are sensitive to the bias voltage

✓ Film and electrolytic capacitors are stable with respect to the bias voltage

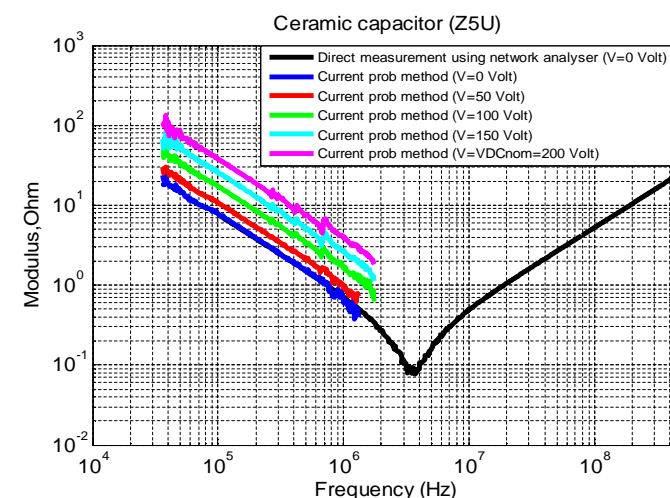


# Frequency & Voltage-Dependent Behavior of CM capacitors

## ➤ HF Characterization under bias-voltage variation

□ Variation of C and the ESR of a ceramic capacitor as a function of the bias voltage:

Condensateur céramique (Z5U)						
<i>Freq</i>	<i>C</i> ( <i>V=0 volt</i> )	<i>C</i> ( <i>V=Vnom</i> )	(%)	<i>ESR</i> ( <i>V=0 volt</i> )	<i>ESR</i> ( <i>V=Vnom</i> )	(%)
100kHz	206.29 nF	43.169 nF	79.07%	0.4 Ohm	0.044 Ohm	89%
415kHz	210 nF	52.44 nF	75.2%	2.12 Ohm	0.07 Ohm	96.7%
700kHz	209.49 nF	57 nF	72.3%	3.12 Ohm	0.07 Ohm	97.76%
1MHz	218.8 nF	40.19 nF	80.04%	0.3 Ohm	0.069 Ohm	77%
2MHz	227 nF	51.8 nF	77.07%	0.433 Ohm	0.07 Ohm	83.83%



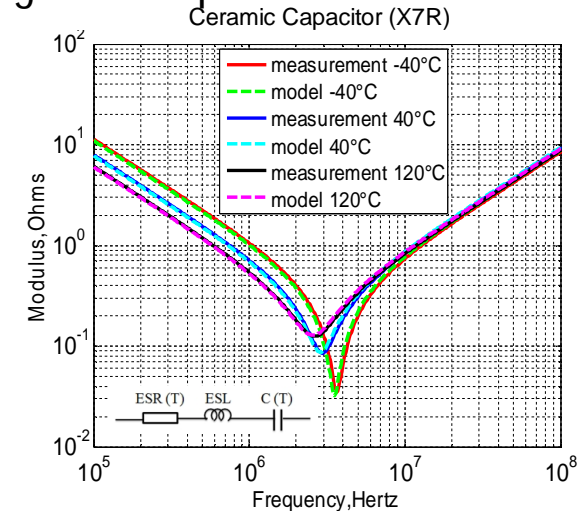
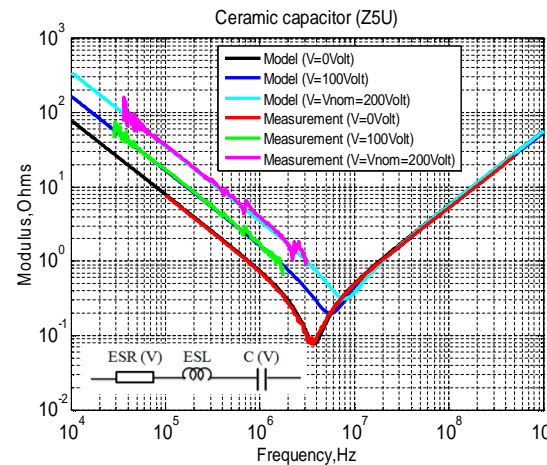
✓ A drop of up to 97% for the ESR and up to 80% for the capacity C when the bias-voltage goes from 0 to Vnom

# Frequency & Voltage/temperature-Dependent Behavior of CM capacitors

## ➤ Behavioral modelling of CM capacitors

☐ Variation of C and the ESR of a ceramic capacitor as a function of the bias voltage or temperature:

- Empirical identification of electric parameters and their voltage dependence
- Only ESR and C vary according to voltage and temperature variations
- ESL is assumed to be constant in this modelling approach.
- Use of high degree polynomial approximations for voltage and temperature variations of each electric parameter
- The model presents significant reduction in residual values, offering superior fitting of measurement data.



$$C(V) = C(0)[1 + VCC_1(V) + VCC_2(V)^2 + \dots + VCC_n(V)^n]$$

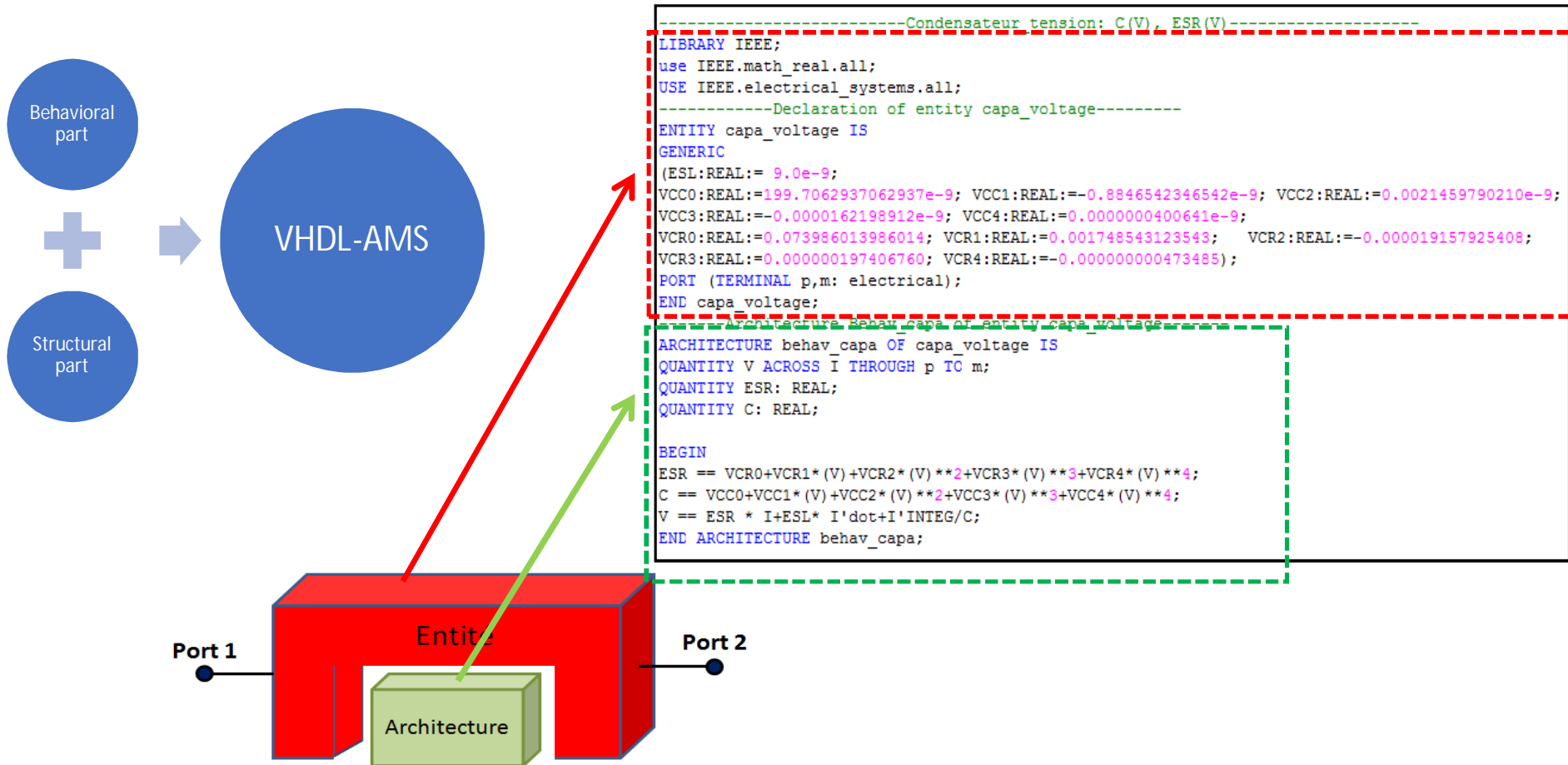
$$ESR(V) = ESR(0)[1 + VCR_1(V) + VCR_2(V)^2 + \dots + VCR_n(V)^n]$$

$$C(T) = C(T_0)[1 + TCC_1(T - T_0) + TCC_2(T - T_0)^2 + \dots + TCC_n(T - T_0)^n]$$

$$ESR(T) = ESR(T_0)[1 + TCR_1(T - T_0) + TCR_2(T - T_0)^2 + \dots + TCR_n(T - T_0)^n]$$

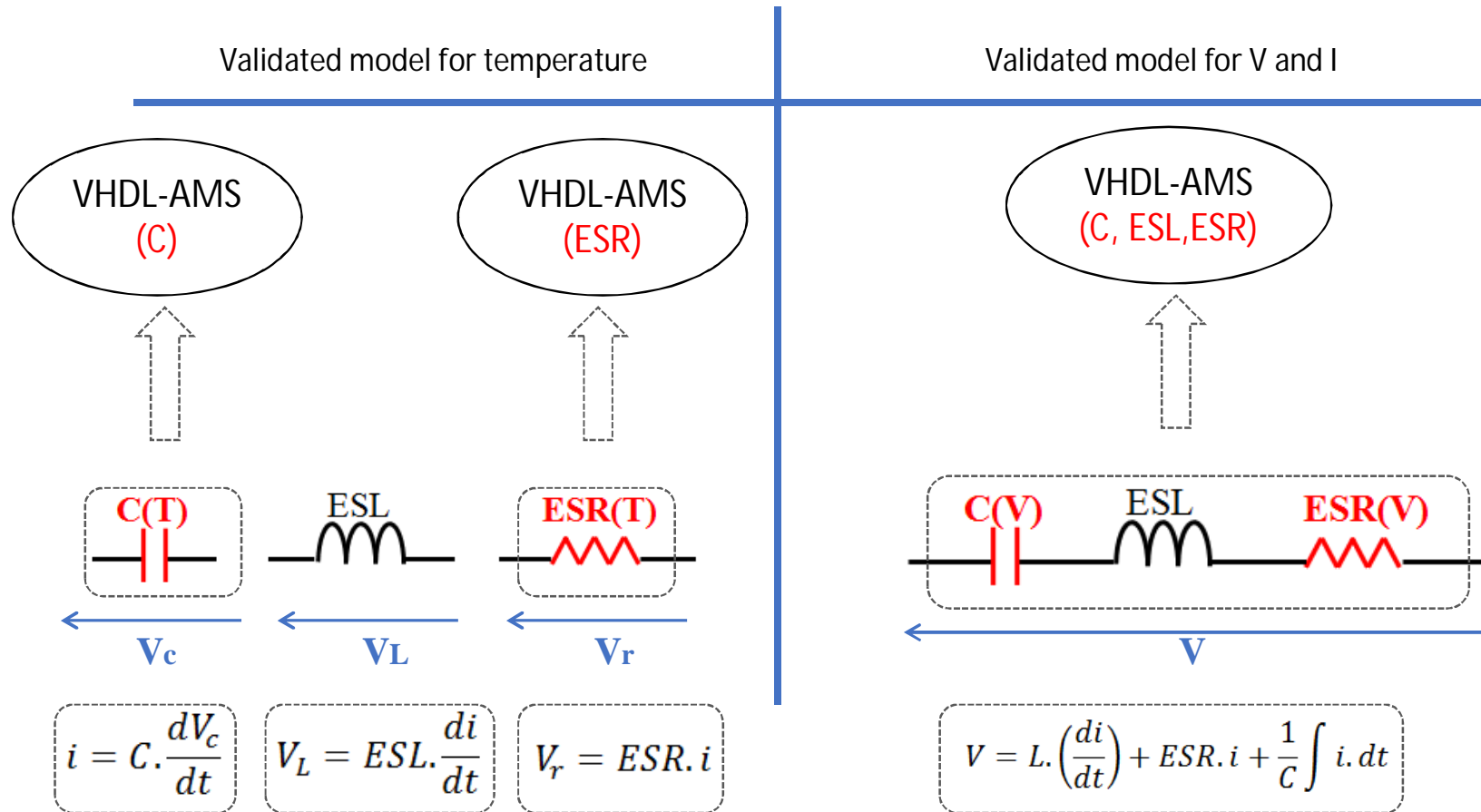
# Frequency & Voltage/temperature-Dependent Behavior of CM capacitors

## ➤ Behavioral modelling of CM capacitors/ Implementation in VHDL-AMS



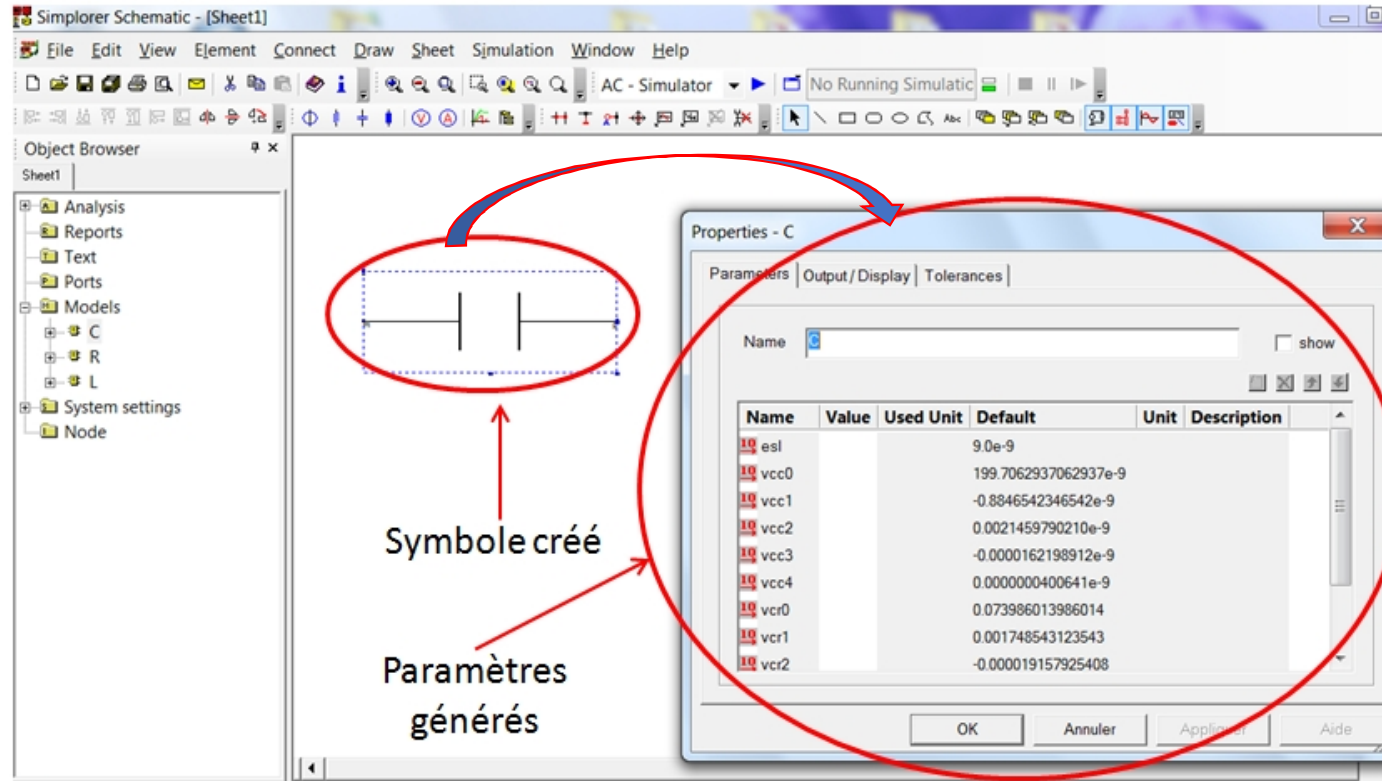
# Frequency & **Voltage/temperature**-Dependent Behavior of CM capacitors

## ➤ Behavioral modelling of CM capacitors/ translation in VHDL-AMS



# Frequency & Voltage/temperature-Dependent Behavior of CM capacitors

## ➤ Behavioral modelling of CM capacitors/ Implementation in SIMPLORER



Object Browser

Sheet1

- Analysis
- Reports
- Text
- Ports
- Models
  - C
  - R
  - L
- System settings
- Node

Properties - C

Parameters | Output / Display | Tolerances

Name:  show

Name	Value	Used Unit	Default	Unit	Description
esl			9.0e-9		
vcc0			199.7062937062937e-9		
vcc1			-0.8846542346542e-9		
vcc2			0.0021459790210e-9		
vcc3			-0.0000162198912e-9		
vcc4			0.0000000400641e-9		
vcr0			0.073986013986014		
vcr1			0.001748543123543		
vcr2			-0.000019157925408		

OK Annuler Appliquer Aide

Editor

Symbole créé

Paramètres générés

$C(V)$  ESL  $ESR(V)$   $Zc(V)$

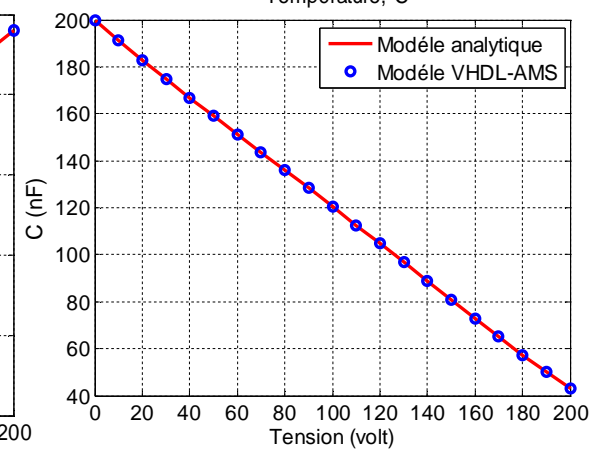
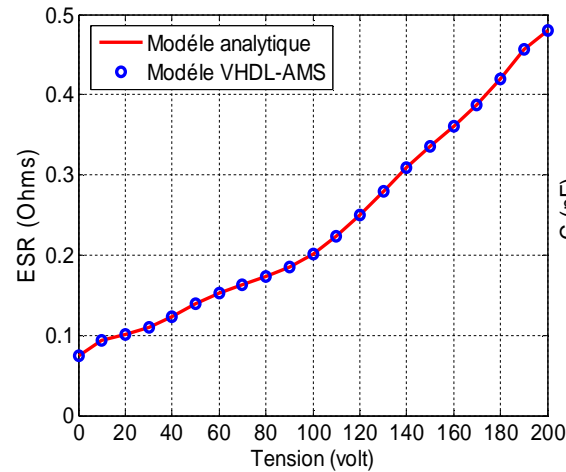
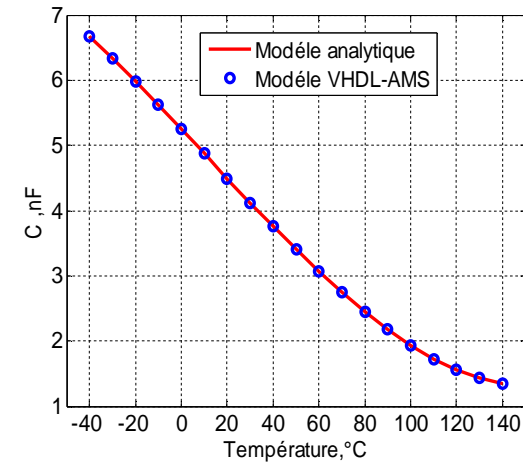
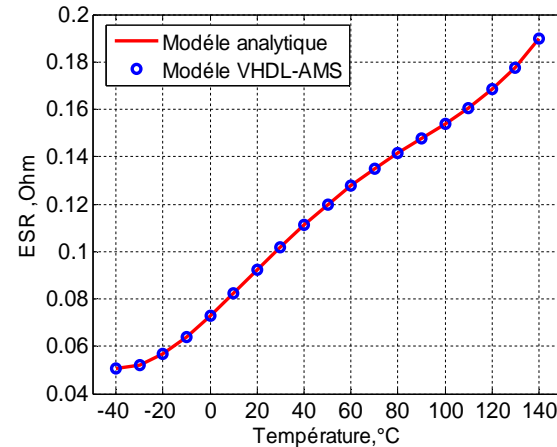
# Frequency & Voltage/temperature-Dependent Behavior of CM capacitors

## ➤ Behavioral modelling of CM capacitors/ SIMPLORER simulation validation

- ✓ Simulation results of VHDL-AMS temperature-dependent model (X7R type)
- ✓ Comparison with analytical model

Relative error is less than 3%

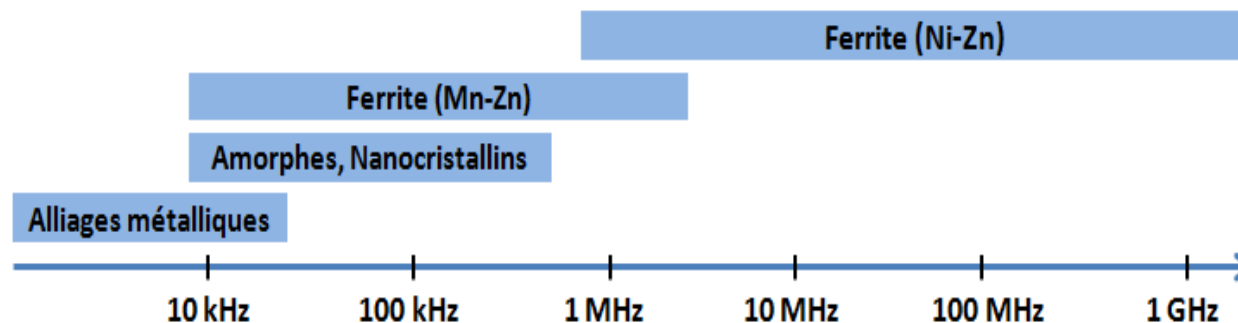
- ✓ Simulation results of VHDL-AMS Bias voltage-dependent model (Z5U type)
- ✓ Comparison with analytical model



# Frequency & Temperature/current-Dependent Behavior of inductors

## ➤ HF Characterization under temperature/current variation

- Operating frequency range and the effectiveness of coupled inductors → limited by the parasitic elements and their dependence to temperature\*
- The identification of these parasitic elements and their temperature sensitivity allows predicting the real behavior of coupled inductors in a wide frequency range\*\*
- There is different technologies of inductors (magnetic components)



\* F. Hami & al, "Wideband Characterization and Modeling of Coupled Inductors under Temperature Variations," , IEEE Intern. Symp. on EMC and EMC Europe conference, Dresden, 16-22 Aug. 2015.



# Frequency & Temperature-Dependent Behavior of inductors

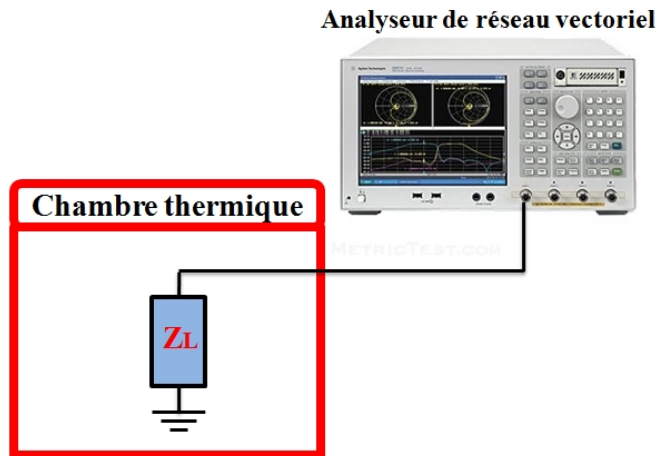
➤ HF Characterization under temperature/current variation

■ Test bench

□ Temperature variation

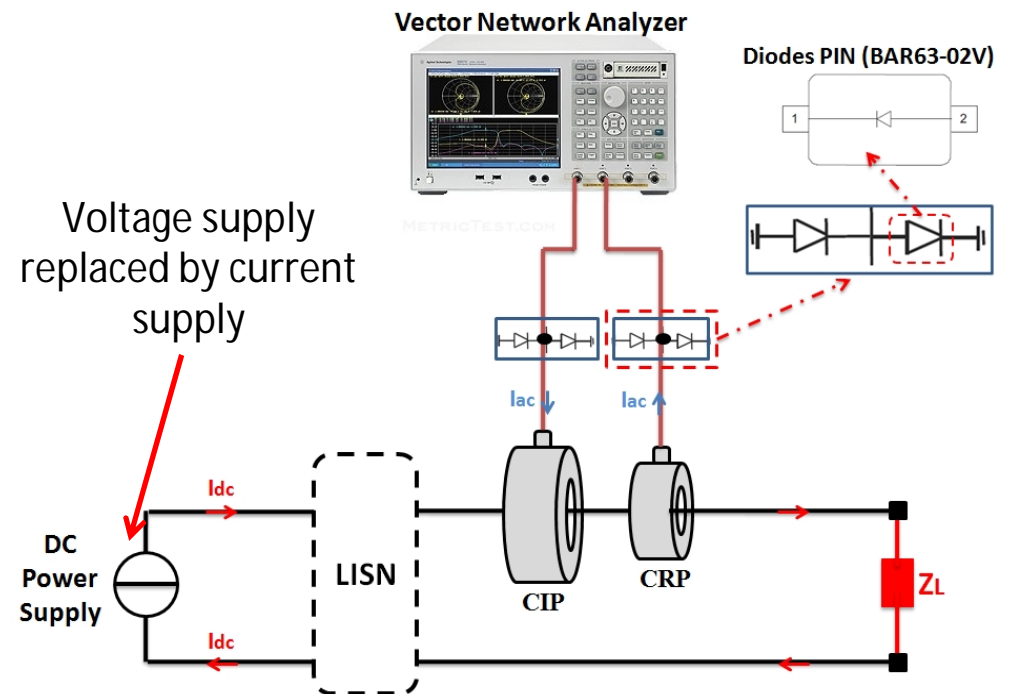


Same test bench as capacitors



$$Z(f) = Z_0 * \frac{1 + S_{11}(f)}{1 - S_{11}(f)}$$

□ Saturation current variation



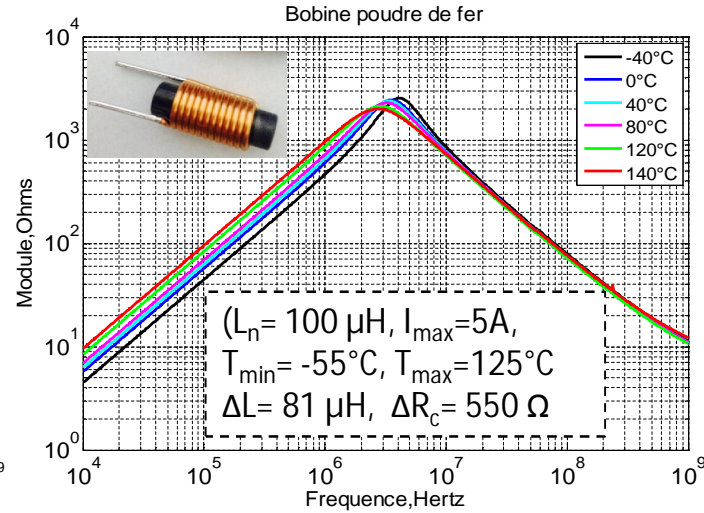
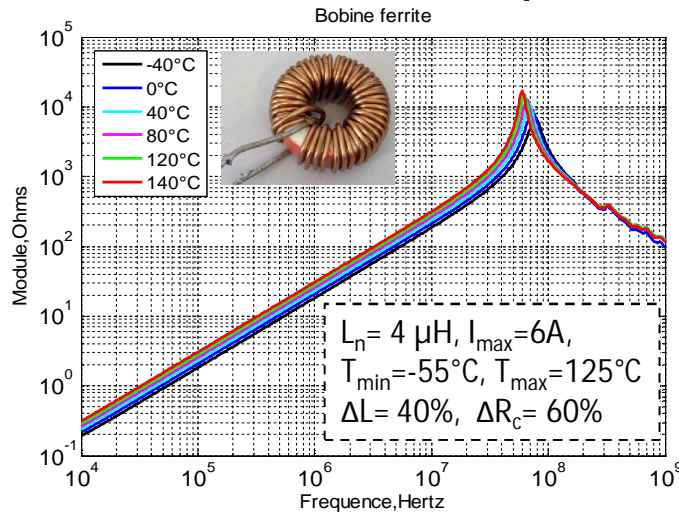
$$Z_L(f) = K * \frac{S_{11}(f) + 1}{S_{21}(f)} - Z_{setup}(f)$$

# Frequency & Temperature-Dependent Behavior of inductors

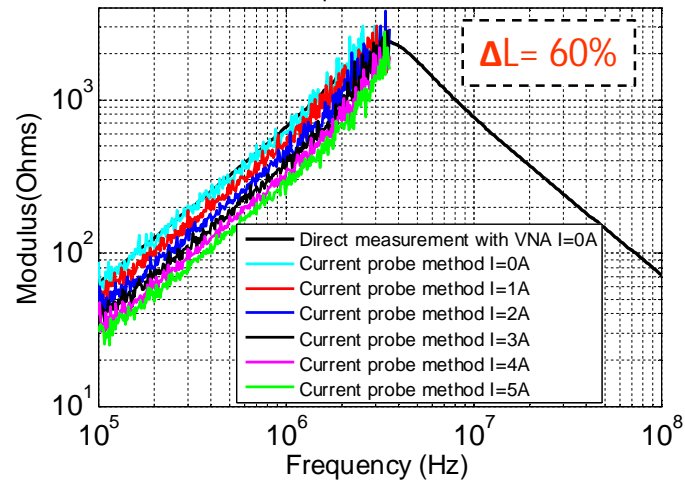
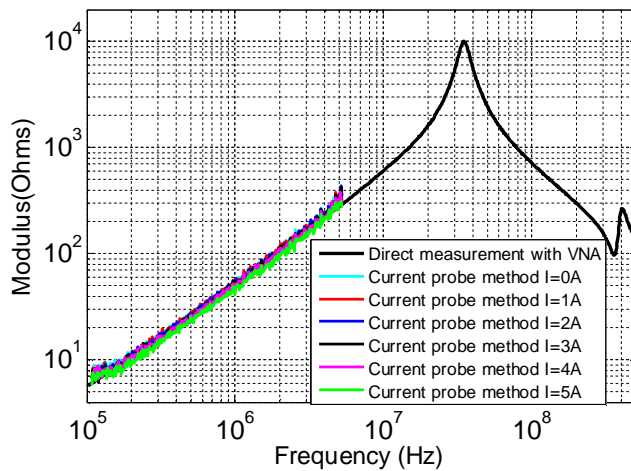
## ➤ HF Characterization under temperature/current variation

### ■ Results

Temperature variation



Saturation current variation

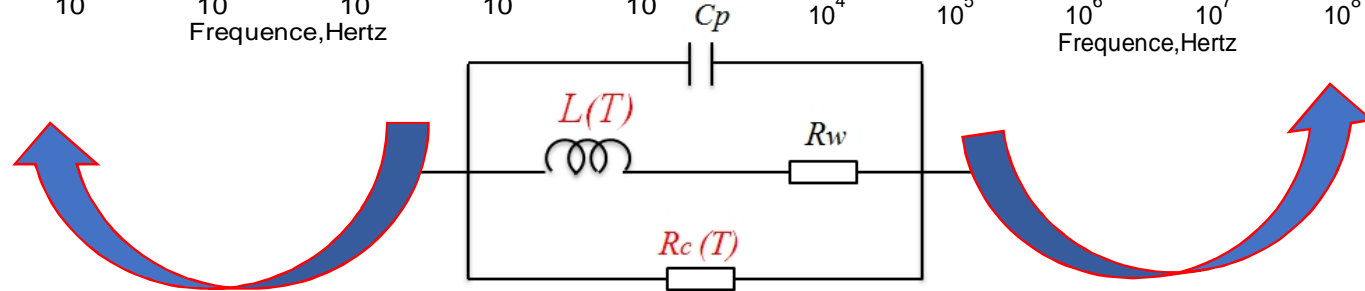
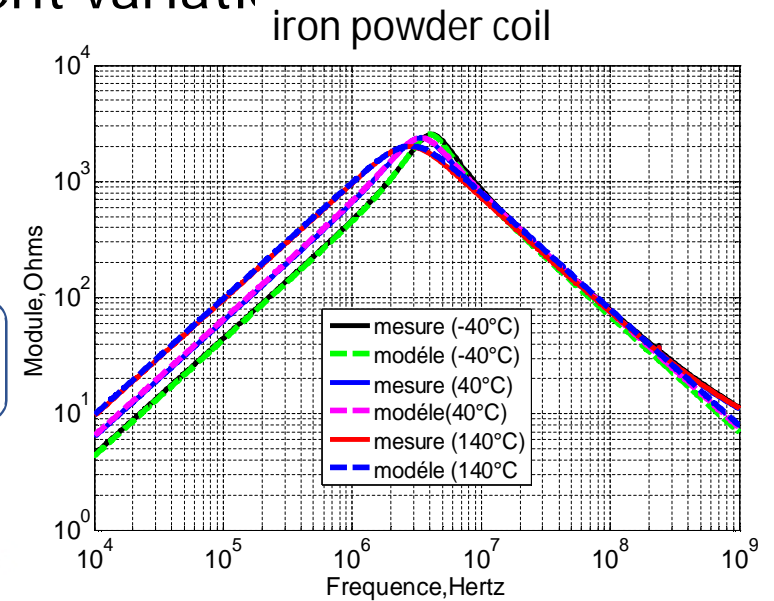
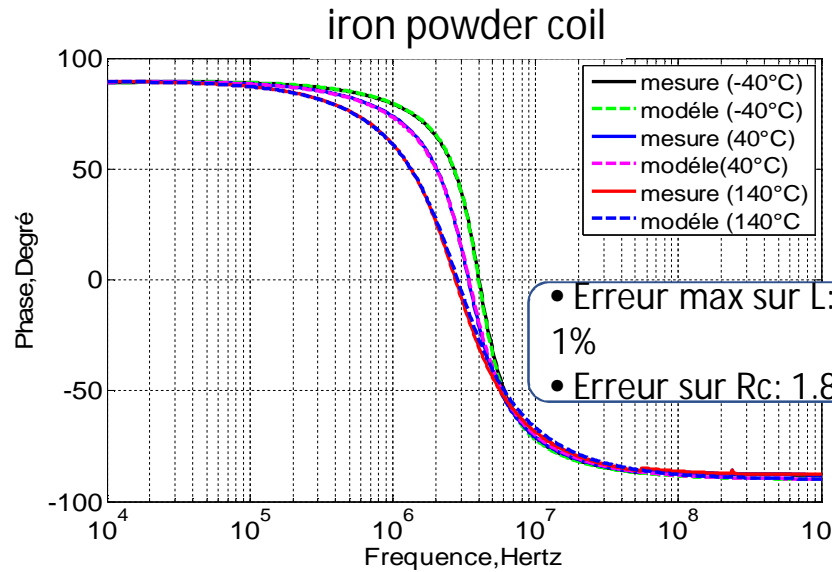


# Frequency & Temperature-Dependent Behavior of inductors

## ➤ HF Characterization under temperature/current variations

### ■ Modelling

Temperature variation

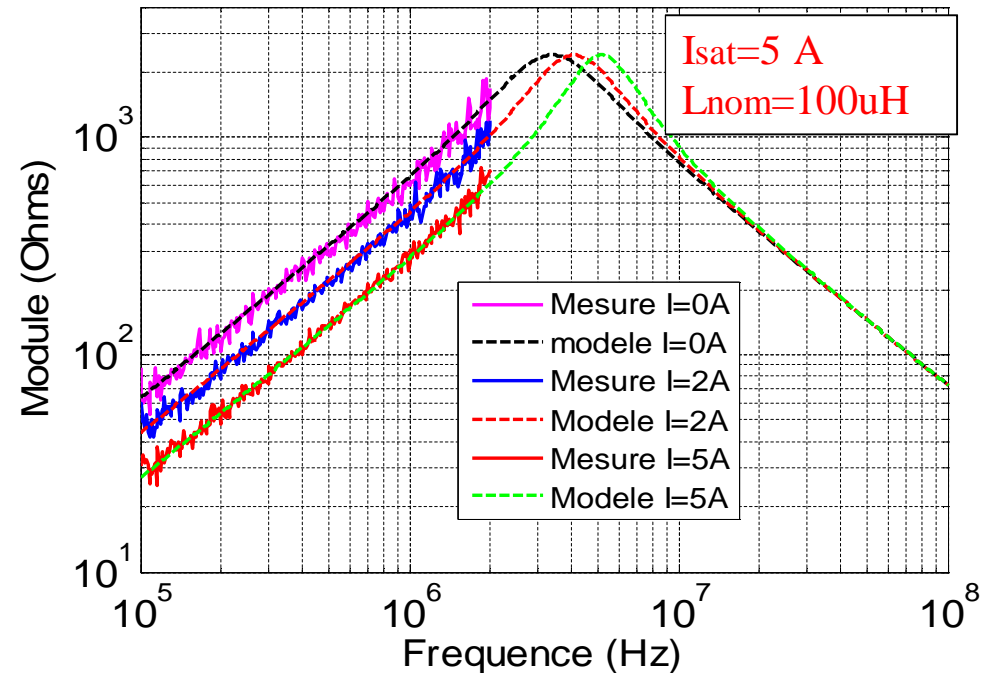
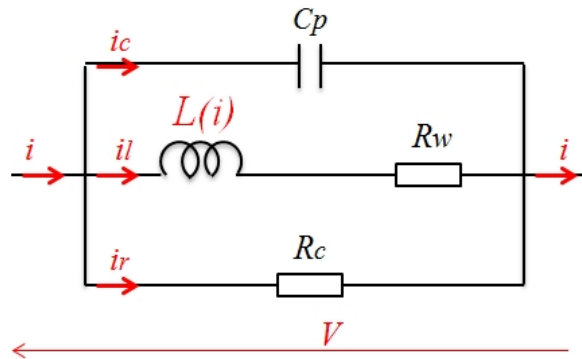


- The value of the inductance  $L$  and the resistance  $R_c$  depend strongly on the temperature  $T$ .
- $C_p$  and  $R_w$  remain unchangeable with respect to these variations.

# Frequency & Temperature-Dependent Behavior of inductors

- HF Characterization under temperature/current variation
- Modelling (high degree polynomial)

Current variation



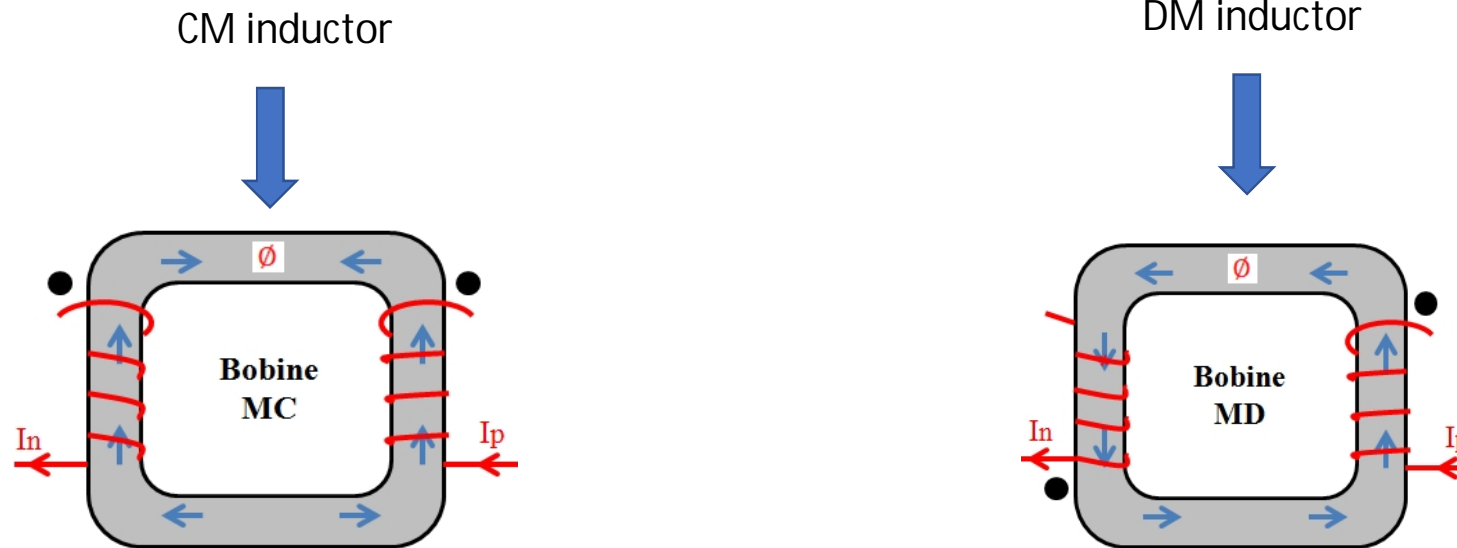
- The saturation current  $I_{dc}$  mainly influences the inductance  $L$

# Frequency & Temperature-Dependent Behavior of inductors

## ➤ HF Characterization under temperature variation

### ■ CM & DM Coupled inductors

- ✓ Composed of two windings on the same core.
- ✓ The winding direction makes it possible to distinguish between the coils of CM and those of DM.

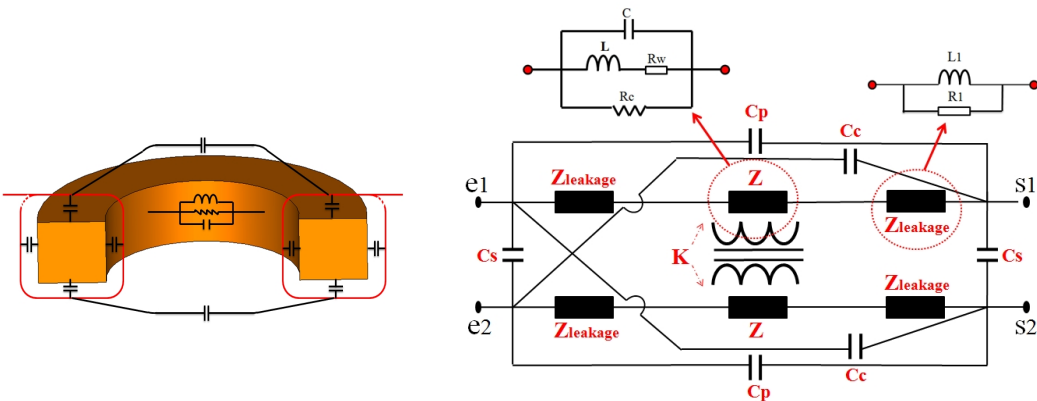


- The two windings must be: identical and coupled together by a coupling factor, called K.

# Frequency & Temperature-Dependent Behavior of inductors

## ➤ HF Characterization under temperature variation/ **Coupled inductors**

- Operating frequency range and the effectiveness of coupled inductors → limited by the parasitic elements and their dependence to temperature\*
- The identification of these parasitic elements and their temperature sensitivity allows predicting the real behavior of coupled inductors in a wide frequency range\*\*
- Proposed model including its different impedances and parasitic elements is shown below; a symmetric equivalent circuit is chosen\*



- Coupling factor  $K$
- 3 types of parasitic capacitances ( $C_s$ ,  $C_c$  and  $C_p$ )
- 2 types of impedances :  
Leakage impedances ( $Z_{leakage}$ )  
Magnetizing impedances ( $Z$ )

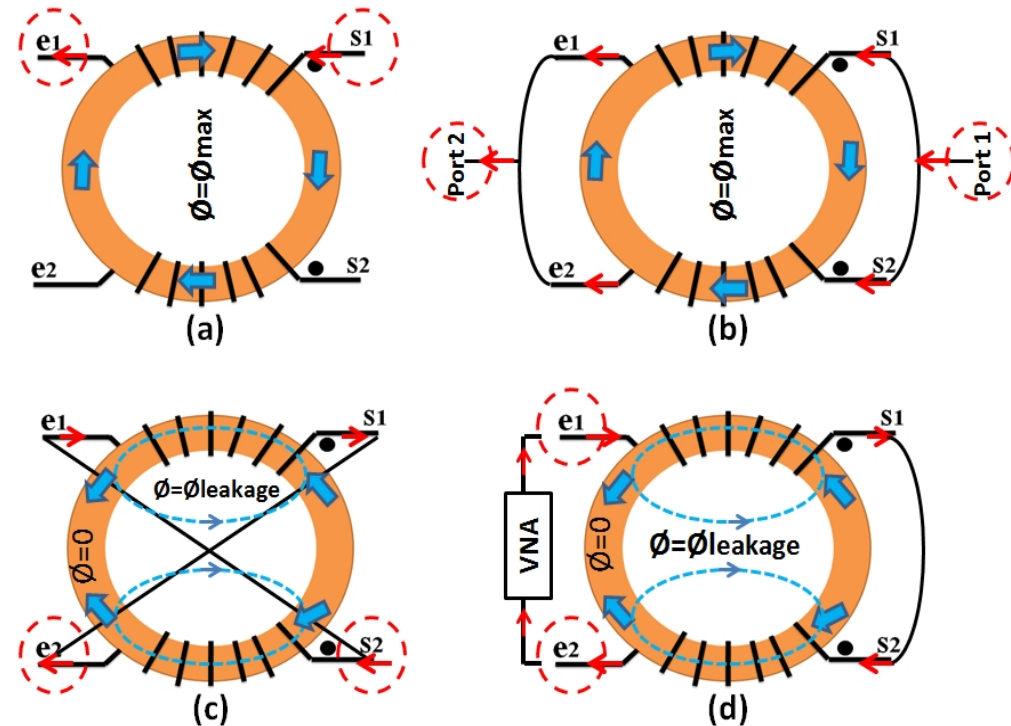
\* F. Hami & al, "Wideband Characterization and Modeling of Coupled Inductors under Temperature Variations," , IEEE Intern. Symp. on EMC and EMC Europe conference, Dresden, 16-22 Aug. 2015.

\*\* J. L. Kotny & al, "EMI Filter design using high frequency models of the passive components," [Workshop on Signal Propagation on Interconnects \(SPI\), IEEE 15th](#), pp. 643-646. 2011

# Frequency & Temperature-Dependent Behavior of inductors

## ➤ HF Characterization under temperature variation/ **Coupled inductors**

- To identify the various impedances of coupled inductors, only 4 impedance measurements (VNA) are sufficient
- We assumed that the tested component have a symmetrical form.
- Electrical parameters are identified from equivalent circuit of each impedance measured.
  
- configuration a → compute the magnetizing impedance ( $Z$ );
- configuration b → allows measuring the CM impedance;
- Configurations c and d → identify the leakage parameters and parasitic capacitances through the leakage and DM impedances

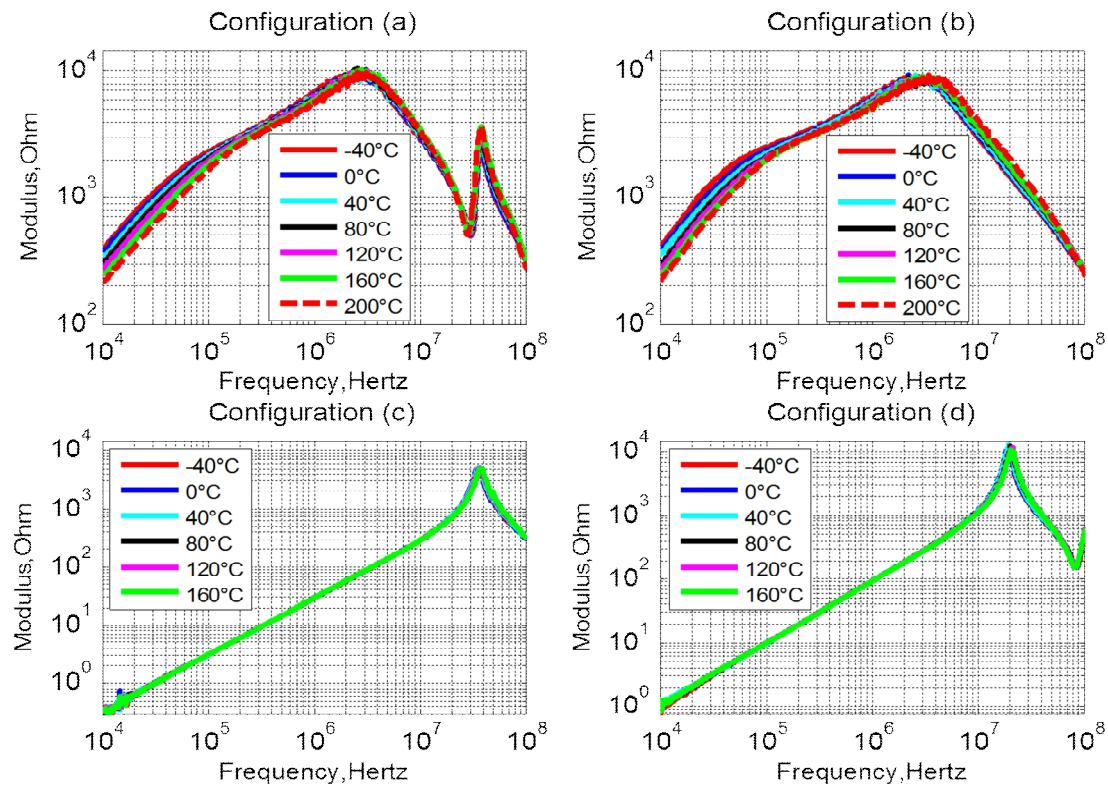




# Frequency & Temperature-Dependent Behavior of inductors

## ➤ HF Characterization under temperature variation/ **Coupled inductors**

### Nanocrystalline core [- 40°C, 200°C]

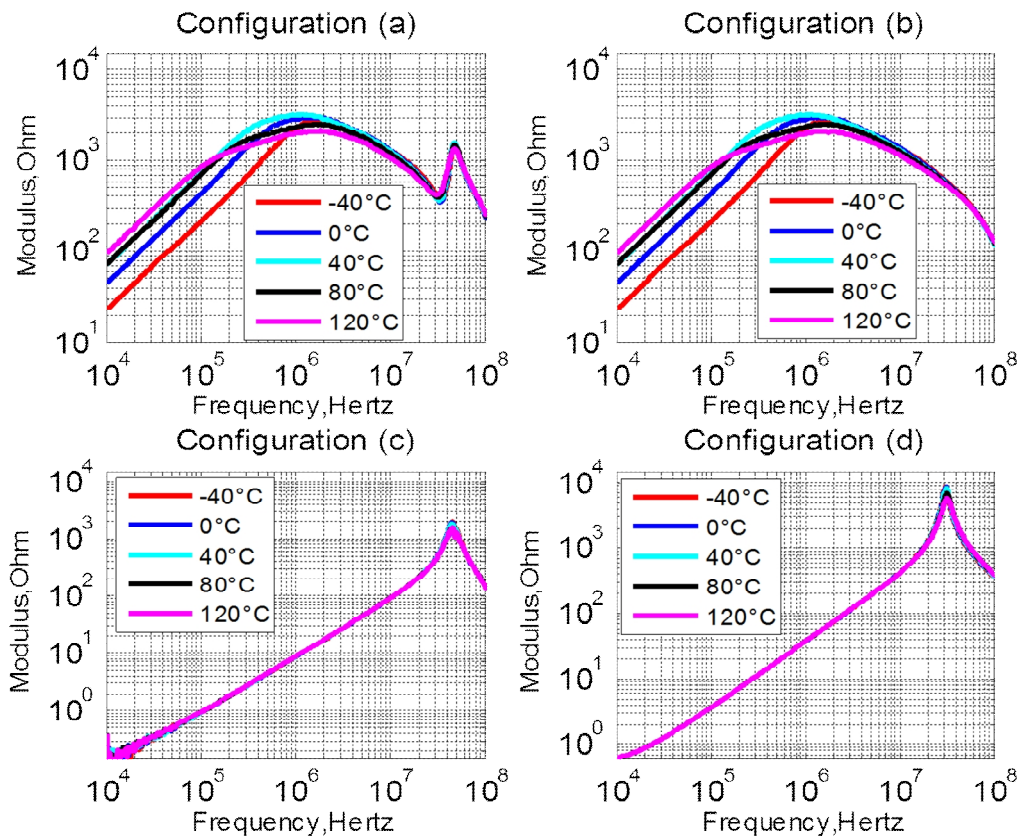




# Frequency & Temperature-Dependent Behavior of inductors

## ➤ HF Characterization under temperature variation/ **Coupled inductors**

### Ferrite MnZn core [-40°C, 120°C]



For both materials, only the magnetizing impedance (configuration a) and CM impedance (configuration b) vary according to temperature.

This temperature dependency of impedances is related to the complex permeability ( $\mu$ ) of the used magnetic core (MnZn ferrite) which is very sensitive to temperature

Electrical parameters calculated from the configurations (c) and (d) are constant according to temperature variations

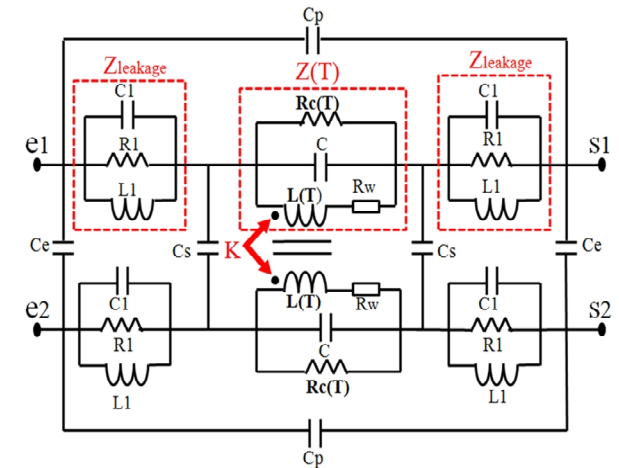
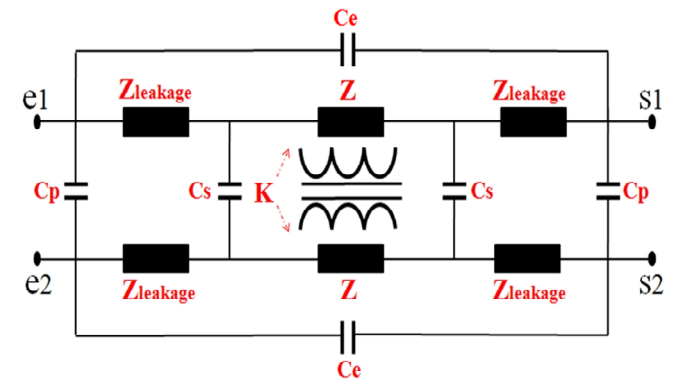
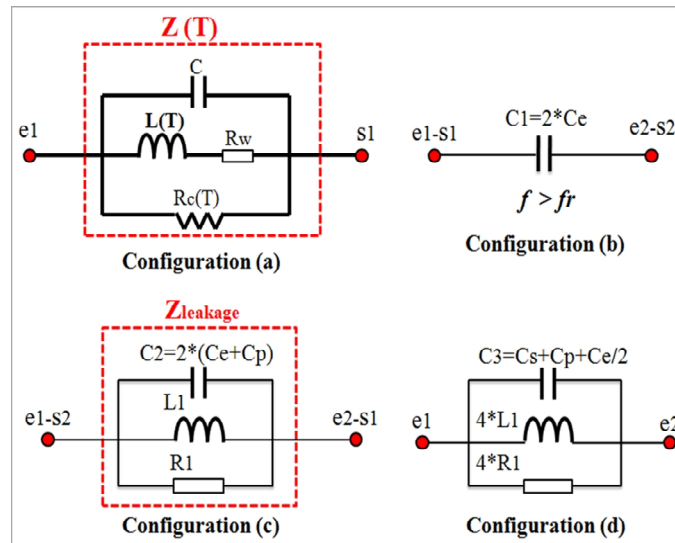
# Frequency & Temperature-Dependent Behavior of inductors

## ➤ HF modelling under temperature variation/ **Coupled inductors**

$$K = \frac{M}{\sqrt{L_1 L_2}} = \frac{M}{L} = 1 - \left(\frac{f r_1}{f r_2}\right)^2$$

➤ Identification of electric parameters and their temperature dependence via measurements data

➤ Only L and R<sub>c</sub> vary **according to** temperature



$$L(T) = L(T_0) * [1 + T_{CL1} * (T - T_0) + T_{CL2} * (T - T_0)^2 + \dots + T_{CLn} * (T - T_0)^n]$$

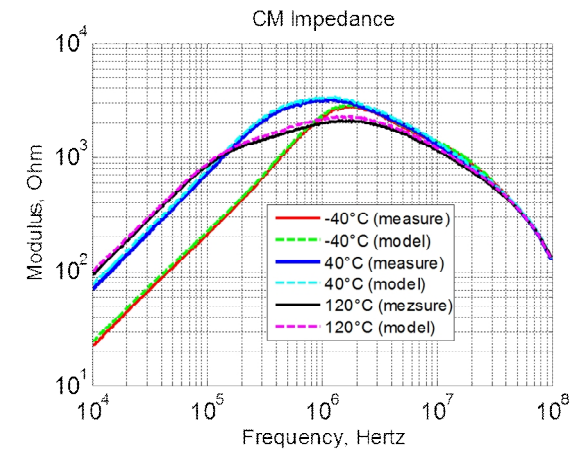
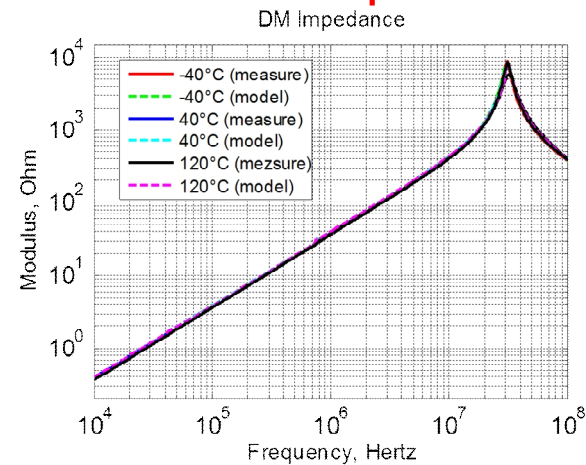
$$R_c(T) = R(T_0) * [1 + T_{CR1} * (T - T_0) + T_{CR2} * (T - T_0)^2 + \dots + T_{CRn} * (T - T_0)^n]$$

# Frequency & Temperature-Dependent Behavior of inductors

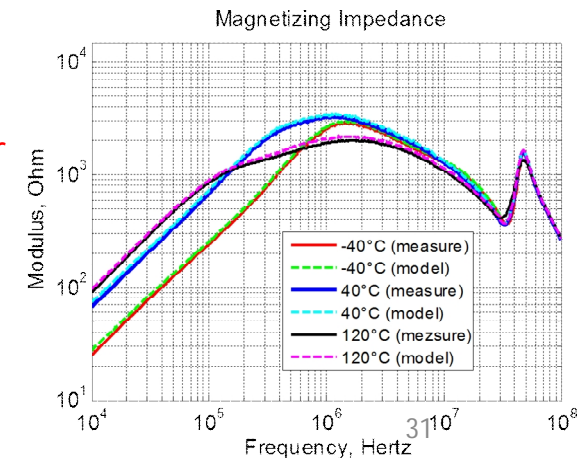
## ➤ HF modelling under temperature variation/ **Coupled inductors**

➤ Comparison confirms the validity of the proposed model.

➤ both temperature sensitivity and parasitic elements have to be considered in the modeling and the design of coupled inductors in order to increase their performance

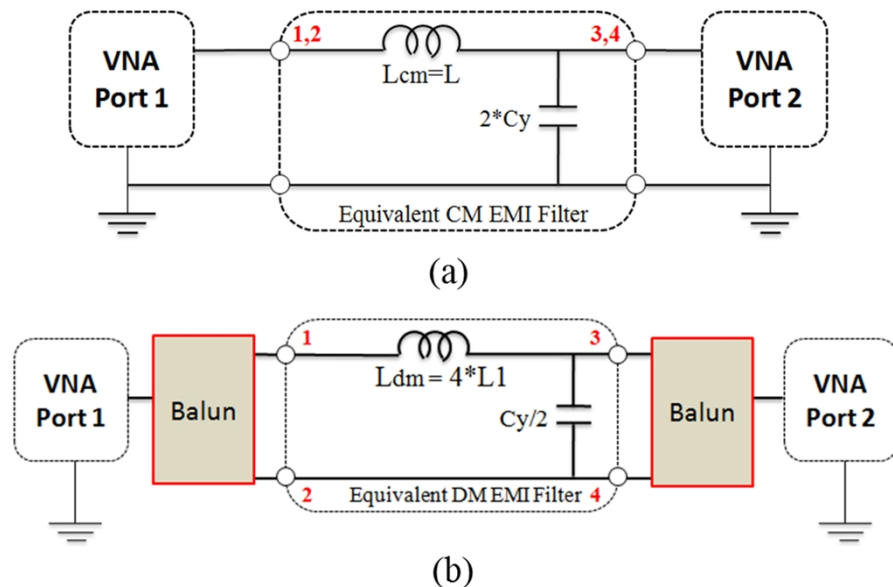


**Mn-Zn ferrite coupled inductor**



# Application on EMI Filter

- CM EMI filter is obtained by connecting the coupled inductor (Mn-Zn ferrite core) with CM capacitor (X7R ceramic)
- The developed models of these components are combined together in order to compare the frequency behavior predicted by simulation of the EMI filter with the real measurements extracted under temperature variations



Measurement configurations of EMI Filter

Fig. 1. a-CM and b-DM equivalent circuit of the tested EMI filter

# Application on EMI Filter

- Comparison between experimental and model datas (CM and DM Insertion losses of EMI filter)

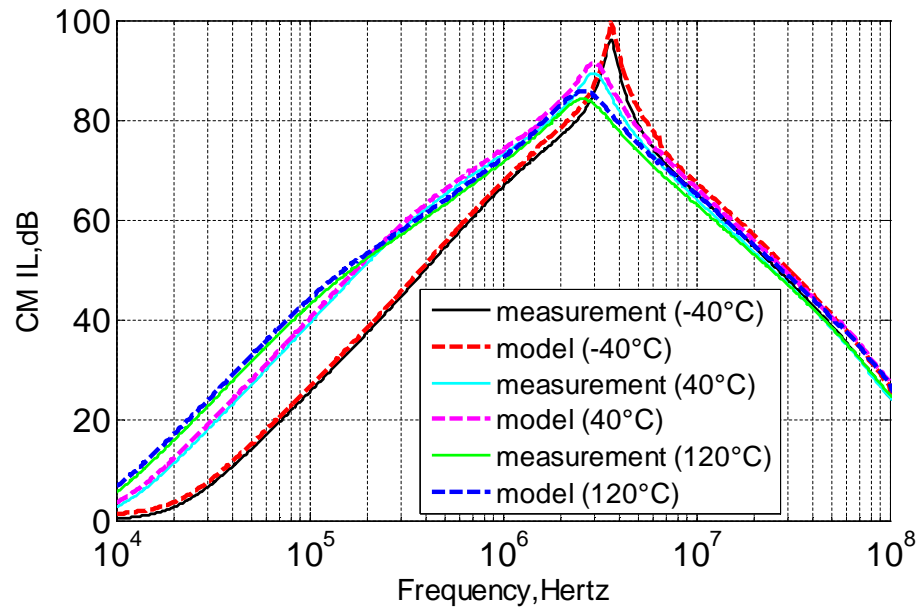


Fig. 1. CM Insertion Losses (IL) of EMI filter under temperature variations (model and measurement).

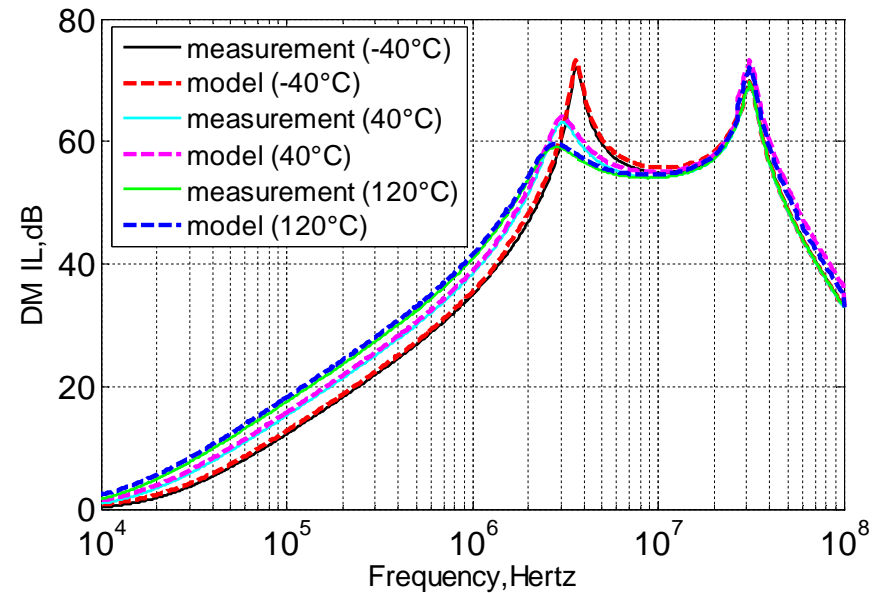


Fig. 1. DM Insertion Losses (IL) of EMI filter under temperature variations (model and measurement).

# Application on EMI Filter

- In practice (Temperature-dependent efficiency of EMI filter vs DO160F standard)

Circuit used in simulation

Ferrite Inductors and X7R capacitor

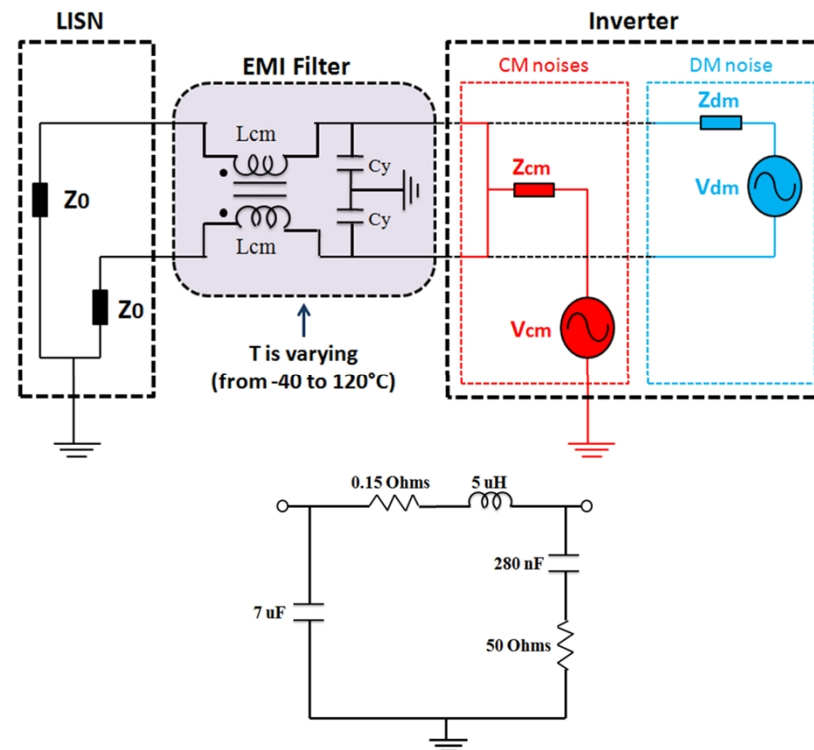
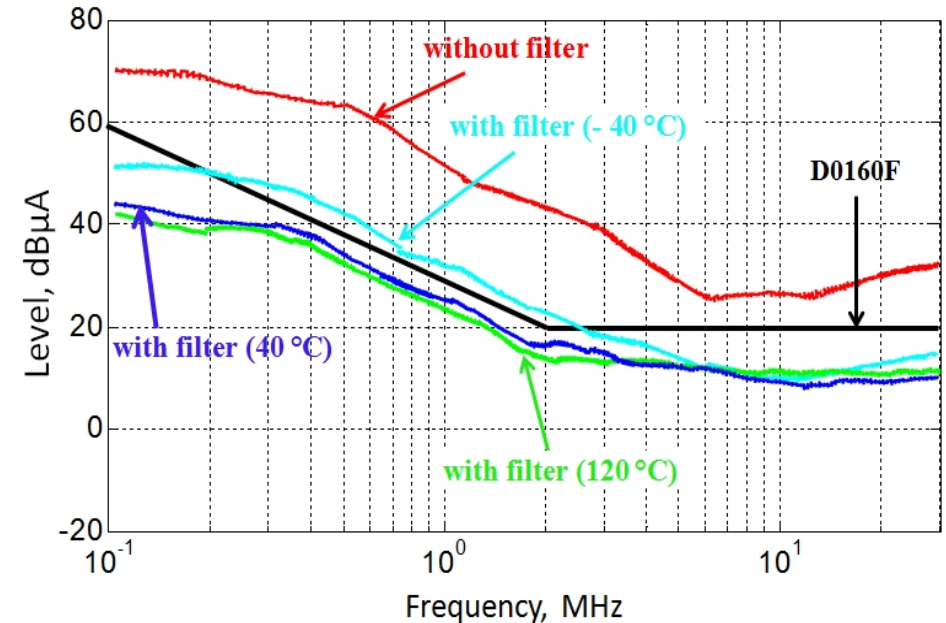


Fig. 1. Power electronic system model.

# Application on EMI Filter

- In practice (Temperature-dependent efficiency of EMI filter vs DO160F standard)

The filtered perturbation spectrum under several temperature values (-40 °C, 40 °C, 120 °C)



- Disturbance is lower than the limit of EMC standard for T=40°C and T=120°C but slightly higher than this EMC standard limit from 200 KHz up to 3MHz when the temperature is equal to -40°C.
- Depending on how the temperature affects the components constituting the EMI filter, the temperature variation can improve or degrade the attenuation of conducted emissions level.



# CONCLUSION

- High frequency modeling methods and characterization process using impedance measurements are investigated in order to develop high frequency models of capacitors and coupled inductors usually used in EMI power filters.
- These models allow to study, by simulation, the influence of the parasitic elements and the rated operating conditions (e.g. temperature) on the frequency behavior of each passive component.
- The obtained results show very good agreement between models and simulation
- Performance of EMI filter is determined by its parasitic elements and the sensitivity of its passive components to the operating condition variations
- If applied operating conditions are varied jointly, the measurement results can exhibit complex interactive behavior and need complex equations to define the models which can consider all these factors together