IT4PQ Final Stakeholder Workshop

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Simplified test procedures for frequency characterization of inductive VTs

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Acknowledgement

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Simplified Procedures: Target

Characterize Inductive MV VT For <u>Harmonics</u> Measurement

Currently, two main approaches are adopted:

APPROACH A

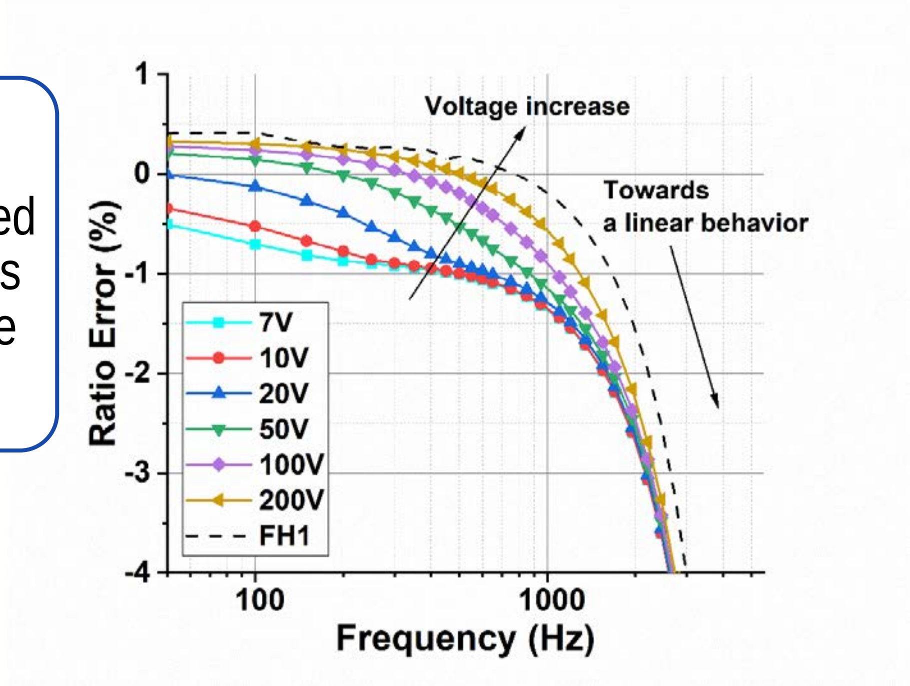
VTs frequency response is evaluated by carrying out a sinusoidal frequency sweep (SFS) at LV

- EASY, AFFORDABLE
- LESS ACCURATE

APPROACH B

VTs frequency response is evaluated under non-standardized waveforms such as bi-tone (FH1) or multi-tone signals (FHN) at MV.

- ACCURATE
- EXPENSIVE SETUP



When a VT is supplied at LV, the magnetization of the iron-core is low compared with the magnetization obtained at rated operating point.

Simplified Procedures: Description

NEW PROPOSED APPROACH: 2-STEPS PROCEDURE FOR VTS FREQUENCY RESPONSE MEASUREMENT

STEP 1

Measurement of the VT:

- errors at power frequency and rated amplitude ($\varepsilon_{50\ Hz}$, $\Delta\varphi_{50\ Hz}$)
- first 10-15 harmonic spurious tones

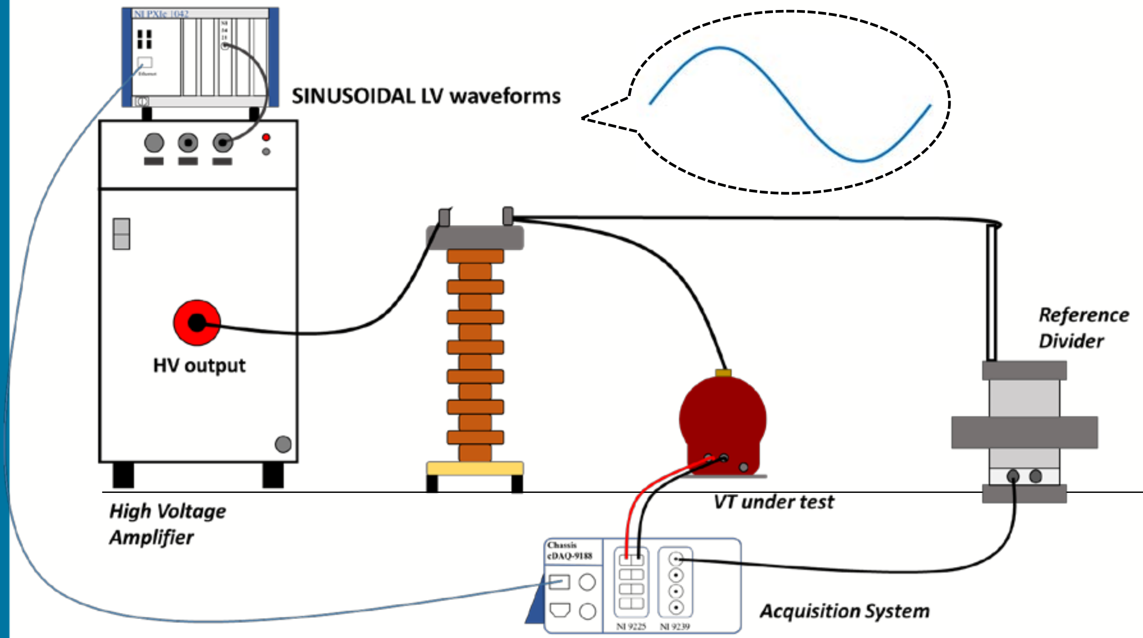
STEP 2

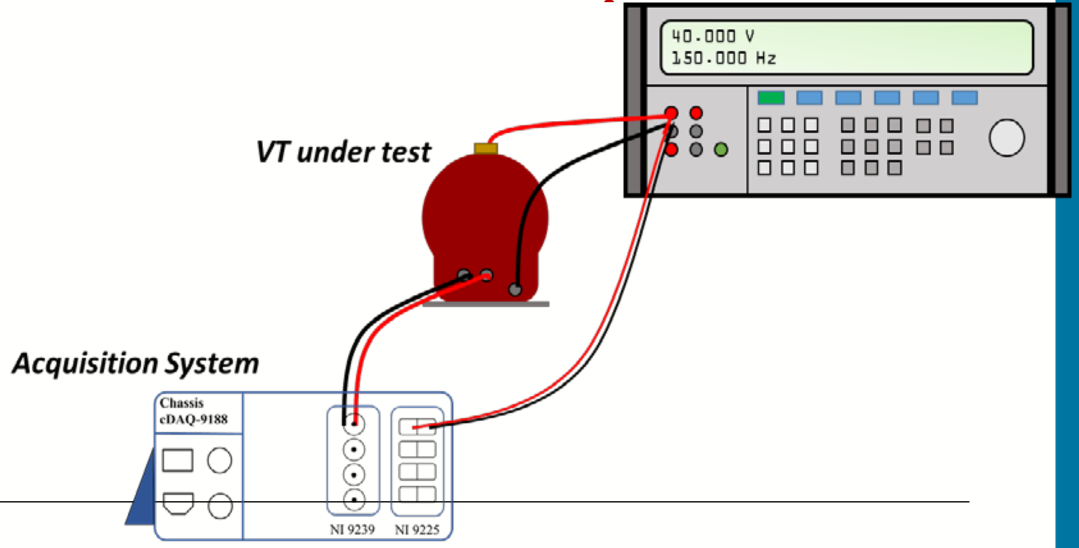
Measurement of the VT:

- harmonics errors under a LV SFS

$$\varepsilon_h = \frac{k_r V_{s,h} - V_{p,h}}{V_{p,h}}$$

$$\Delta\varphi_h = \varphi_{s,h} - \varphi_{p,h}$$





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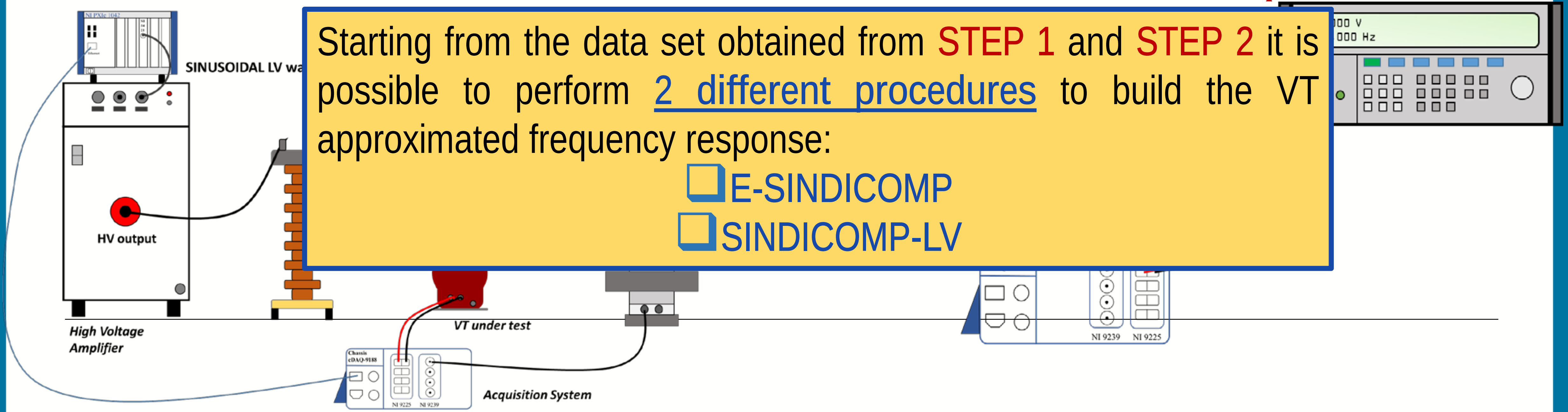
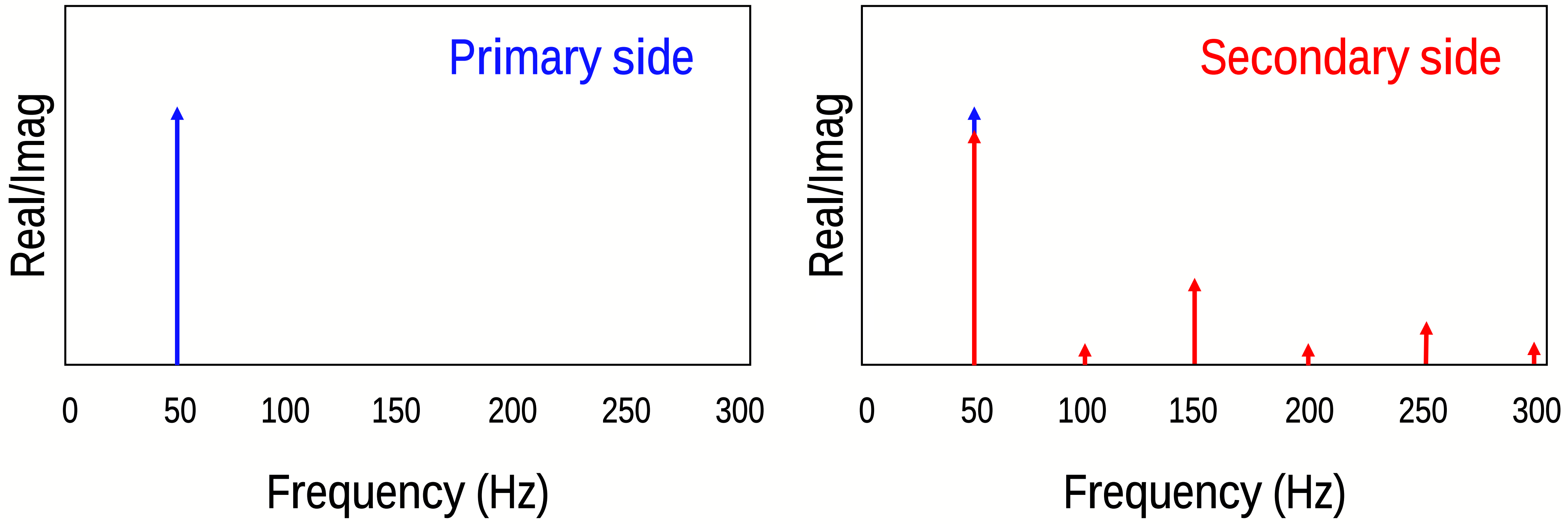


Starting from the data set obtained from STEP 1 and STEP 2 it is possible to perform <u>2 different procedures</u> to build the VT approximated frequency response:

- ❑ E-SINDICOMP
- ❑ SINDICOMP-LV

E-SINDICOMP and SINDICOMP-LV: Preliminary Step (1/2)

Shared Preliminary Step: Non Linearity Compensation

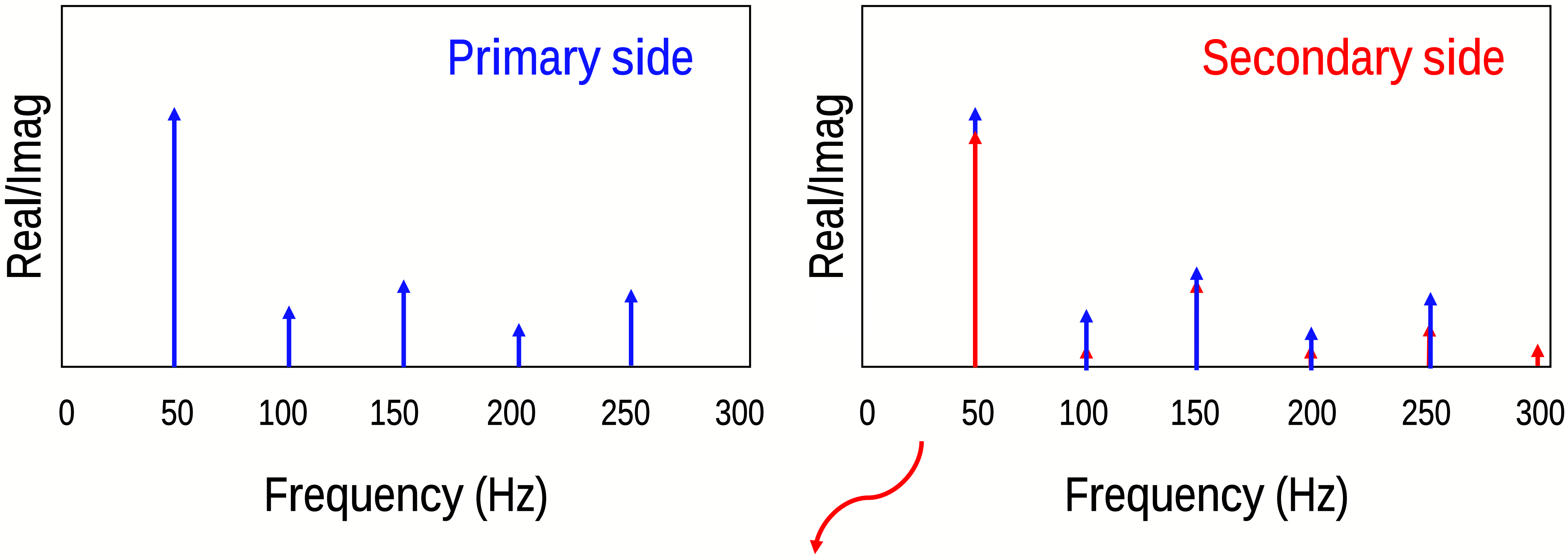


Harmonic Distortion ⇒

Spurious harmonic generated by the fundamental tone because of the B-H curve non-linearity of the VT.

E-SINDICOMP and SINDICOMP-LV: Preliminary Step (1/2)

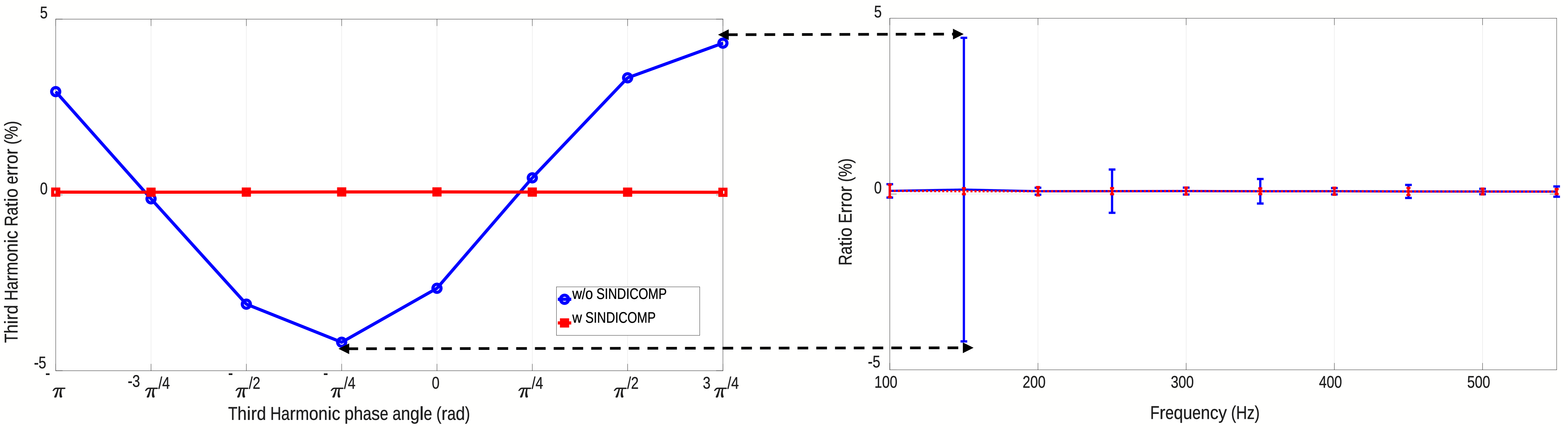
Shared Preliminary Step: Non Linearity Compensation



Combination of the harmonic applied to the input of the VT and the spurious harmonic generated by the fundamental.

E-SINDICOMP and SINDICOMP-LV: Preliminary Step (2/2)

SINDICOMP: SINusoidal characterization for DIstortion COMPensation



$U_h = 1$ % of rated voltage

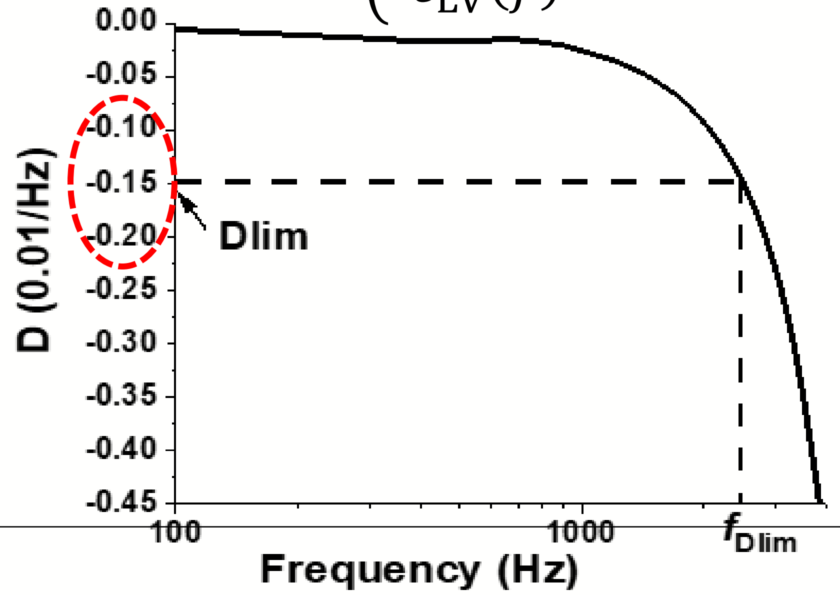
More information: *A. Cataliotti et al., "Compensation of Nonlinearity of Voltage and Current Instrument Transformers," in IEEE Transactions on Instrumentation and Measurement, vol. 68, no. 5, pp. 1322-1332, May 2019, doi: 10.1109/TIM.2018.2880060.*

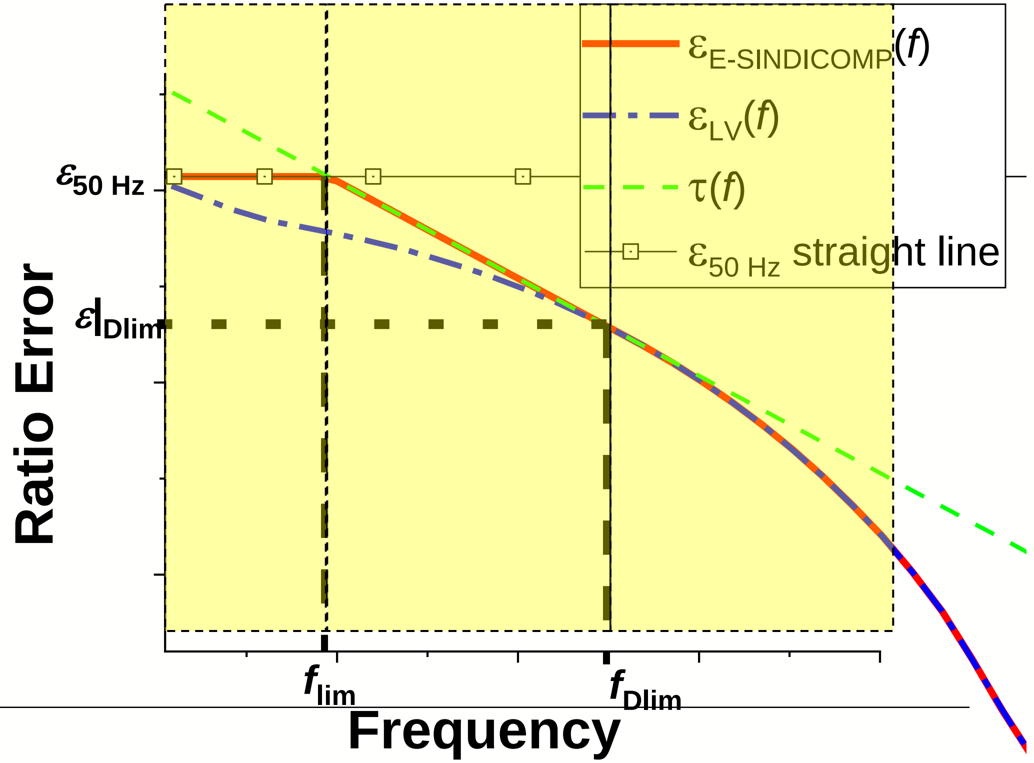
E-SINDICOMP: Description

APPROXIMATED RATIO ERROR FREQUENCY RESPONSE:

1. the VT ratio error at power frequency and rated amplitude $\varepsilon_{50\ Hz}$
2. the low voltage frequency responses $\varepsilon_{LV}(f)$,
3. the $\tau(f)$ curve obtained through the study of the derivative D of the low voltage frequency response $\varepsilon_{LV}(f)$.

$$\varepsilon_{E-SINDICOMP}(f) = \begin{cases} \varepsilon_{50\mathrm{Hz}} & 50\ \mathrm{Hz} \leq f < f_{\mathrm{lim}} \\ \tau(f) & f_{\mathrm{lim}} \leq f < f_{\mathrm{Dlim}} \\ \varepsilon_{\mathrm{LV}}(f) & f \geq f_{\mathrm{Dlim}} \end{cases}$$





More information: *G. Crotti, G. D'Avanzo, D. Giordano, P.S. Letizia, M. Luiso, "Extended SINDICOMP: Characterizing MV Voltage Transformers with Sine Waves", Energies 2021, 14, 1715, doi: 10.3390/en14061715*

SINDICOMP-LV: Description (1/2)

APPROXIMATED <u>RATIO ERROR</u> FREQUENCY RESPONSE:

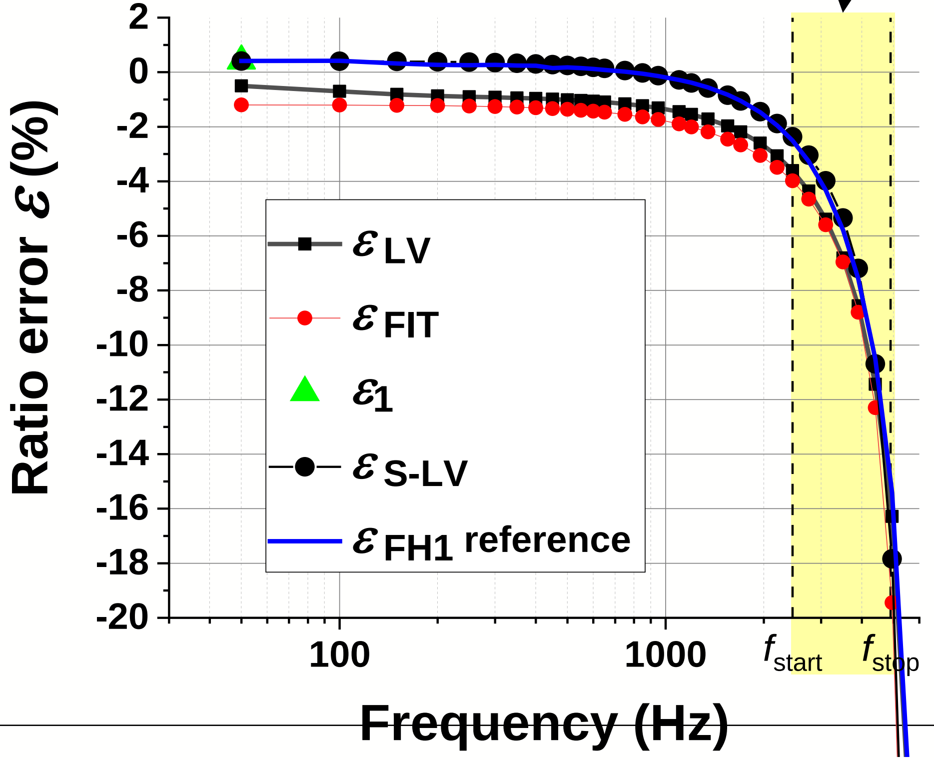
1. the low voltage frequency responses $\varepsilon_{LV}(f)$ (■),
2. the $\varepsilon_{FIT}(f)$ function (●)
3. the VT ratio error at rated frequency and rated amplitude ε_1 (▲)

$$\varepsilon_{S-LV}(f) = \begin{cases} \varepsilon_{FIT}(f) + \varepsilon_{OFS,a} & f_1 \le f < f_{start} \\ \varepsilon_{LV}(f) + \varepsilon_{OFS,b} & f_{start} \le f < f_{stop} \end{cases}$$

$$\varepsilon_{FIT}(f) = \frac{\sqrt{(2\pi f a)^2 + b^2}}{\sqrt{\left(1 - \left(\frac{f}{f_R}\right)^2\right)^2 + \left(\frac{f}{2\pi f_R^{\,2}} \cdot \frac{b}{a}\right)^2}}$$

f_R is the first resonance frequency.

Linear effects are predominant on the non-linear behaviour



More information: *G. Crotti, D. Giordano, G. D'Avanzo, P.S. Letizia, M. Luiso, “A New Industry-Oriented Technique for the Wideband Characterization of Voltage Transformers”, Measurement, Volume 182, 2021, 109674, ISSN 0263-2241, doi: 10.1016/j.measurement.2021.109674*

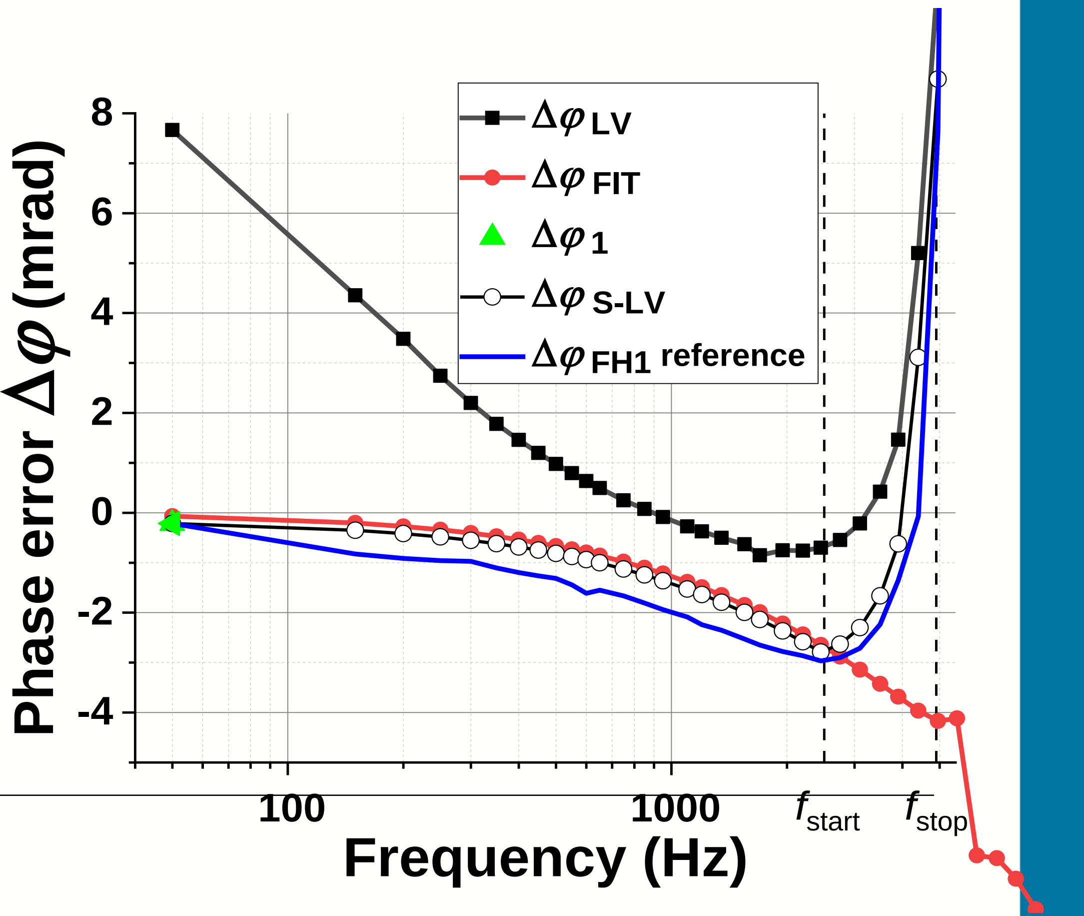
SINDICOMP-LV: Description (2/2)

APPROXIMATED PHASE ERROR FREQUENCY RESPONSE:

1. the low voltage frequency responses $\Delta\boldsymbol{\varphi}_{LV}(f)$ (■)
2. the fit function with the parameter a and b found for the ratio error approximation (●)
3. the VT phase error at rated frequency and rated amplitude $\Delta\boldsymbol{\varphi}_1$ (▲)

$$\Delta\varphi_{S-LV}(f) = \begin{cases} \Delta\varphi_{FIT}(f) + \Delta\varphi_{OFS,a} & f_1 \le f < f_{start} \\ \Delta\varphi_{LV}(f) + \Delta\varphi_{OFS,b} & f_{start} \le f < f_{stop} \end{cases}$$

$$\varphi_{FIT}(f) = \operatorname{artctan}\left(2\pi f \cdot \frac{a}{b}\right) - \arctan\left(\frac{\frac{f}{2\pi f_R^2} \cdot \frac{b}{a}}{\left(1 - \left(\frac{f}{f_R}\right)^2\right)^2}\right) + 2\pi f \cdot \frac{a}{b}$$



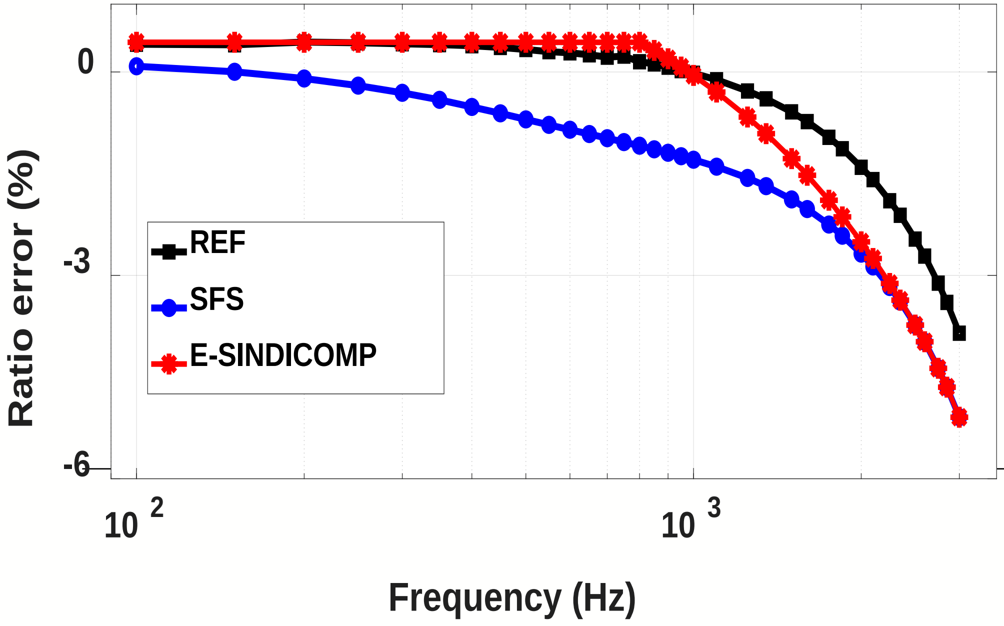
More information: *G. Crotti, D. Giordano, G. D'Avanzo, P.S. Letizia, M. Luiso, "A New Industry-Oriented Technique for the Wideband Characterization of Voltage Transformers", Measurement, Volume 182, 2021, 109674, ISSN 0263-2241, doi: 10.1016/j.measurement.2021.109674*

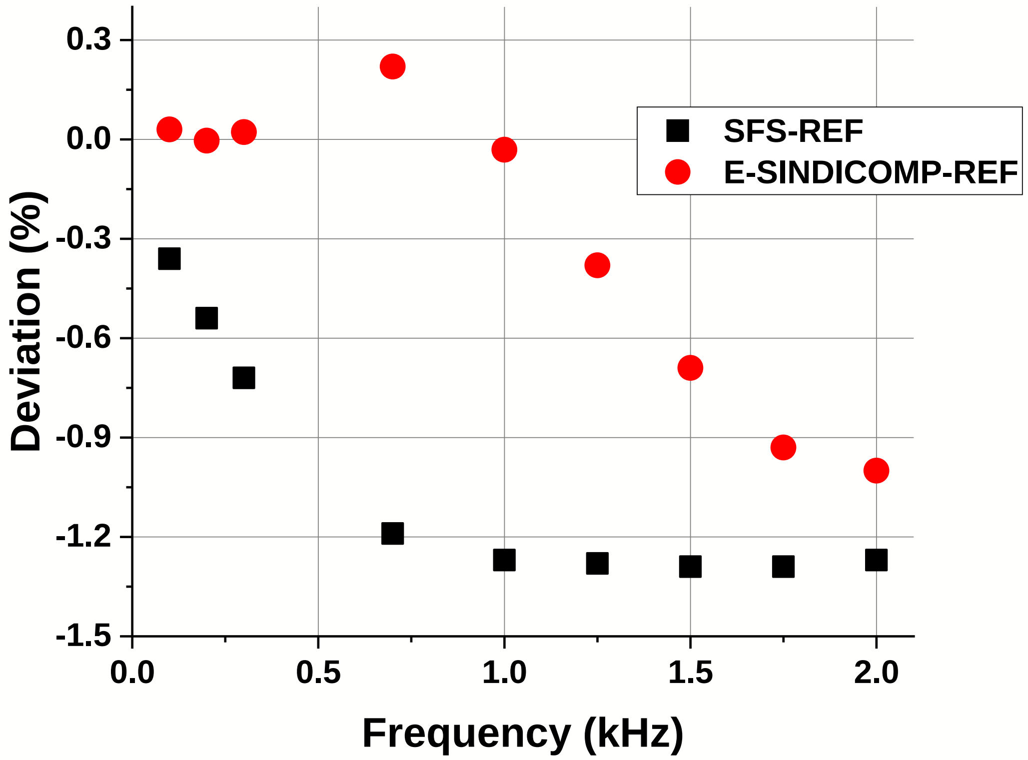
E-SINDICOMP: Application

- Device under test: MV inductive VT

  20/√3 kV / 100 /√3 V; 30 VA; 0.5 accuracy class
- SFS at 40 V

D_{lim} (0.01/Hz)	f_{Dlim} (Hz)	f_{lim} (Hz)
-0.15	2500	800





@ 300 Hz: from -0.72 % to 0.02%

@ 1 kHz: from 1.3 % to 0.03%

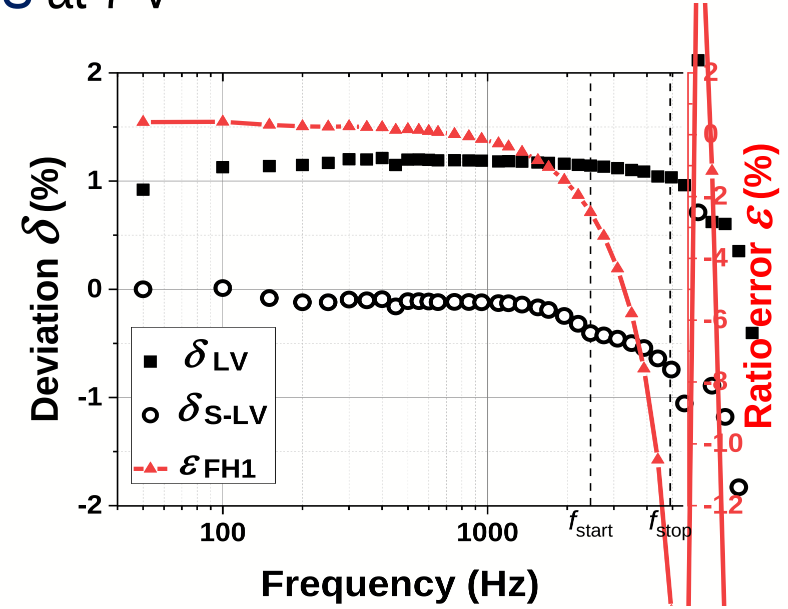
@ 2 kHz: from -1.27% to -1%

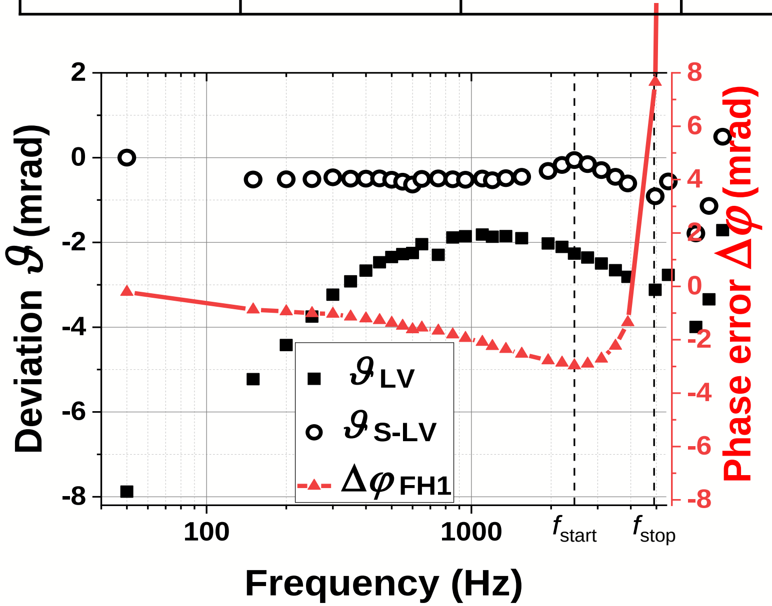
SINDICOMP-LV: Application

- Device under test: MV inductive VT

  20/√3 kV / 100 /√3 V; 30 VA; 0.5 accuracy class
- SFS at 7 V

f_R (Hz)	f_{start} (Hz)	f_{stop} (Hz)	a (s)	b
5900	2450	4900	0.2	1.7





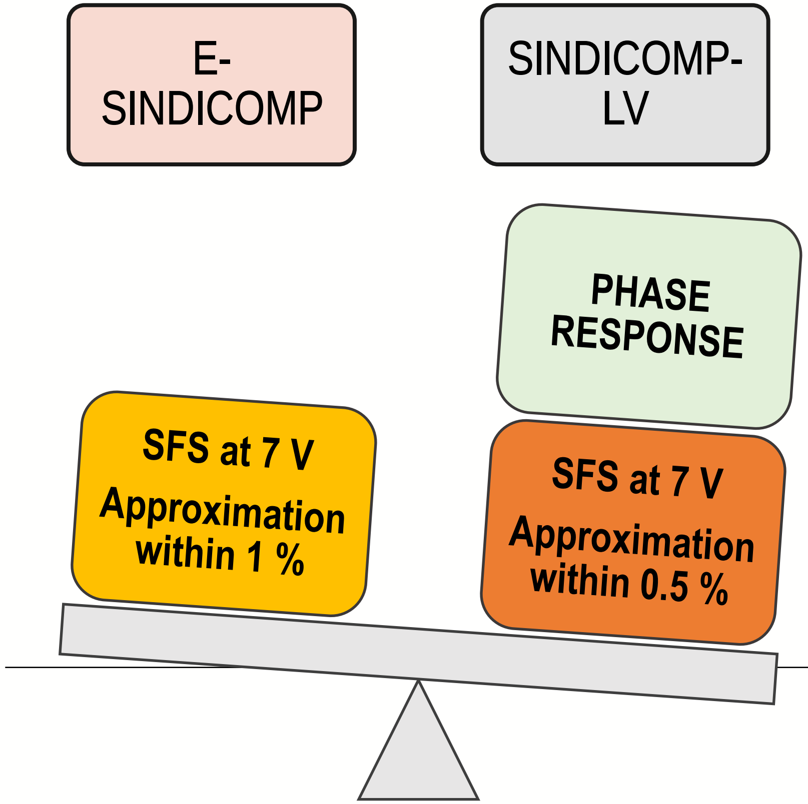
@ 400 Hz: from -1.14 % to 0.08% and from -2.67 mrad to -0.5 mrad

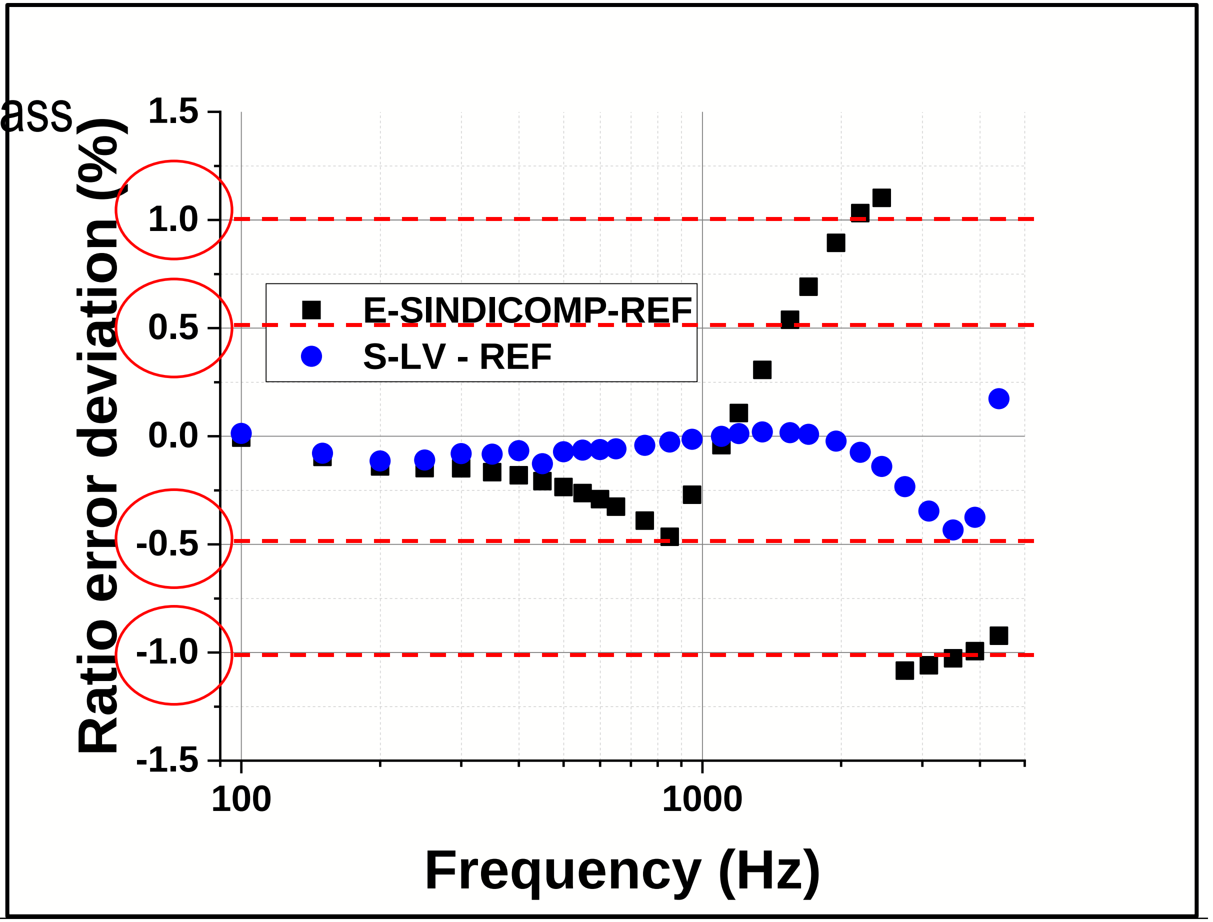
@ 1.2 kHz: from 1.18 % to -0.10% and from -1.88 mrad to -0.54 mrad

@ 3.5 kHz: from 1.05 % to -0.43% and from -2.65 mrad to -0.58 mrad

E-SINDICOMP vs SINDICOMP-LV: Comparison among the two techniques

- **Device under test:** MV inductive VT
  20/√3 kV / 100 /√3 V; 30 VA; 0.5 accuracy class
- SFS at 7 V





Conclusion

- ✓ Two simplified procedures (E-SINDICOMP and SINDICOMP-LV) for the measurement of the frequency response of the MV VTs in common industrial laboratories.
- ✓ The E-SINDICOMP technique provides a method for the only approximation of VT ratio error response whereas SINDICOMP-LV allows to build the VT frequency response in terms of both amplitude and phase.
- ✓ The simplified methods have been applied for the frequency characterization of three different VTs and validated by comparison with results obtained using the FH1 reference measurement method.
- ✓ Both the simplified procedures allow reaching an accuracy improvement with respect to the use of a conventional LV SFS technique up to one order of magnitude for the ratio error.
- ✓ The results provided by the two simplified techniques are then compared with each other and it is found that SINDICOMP-LV produces a better approximation of the VT ratio error frequency response. In particular, SINDICOMP-LV accuracy performance in the VT ratio error evaluation is found within 0.4% up to 20th harmonic, and within 1% close to the resonance frequency; as to the phase error, it is always within 0.8 mrad.

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IT4PQ Instrument Transformers for Power Quality

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