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Measuring and analysis of nonlinear characterization of lithium-ion batteries using multisin excitation signal

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Background

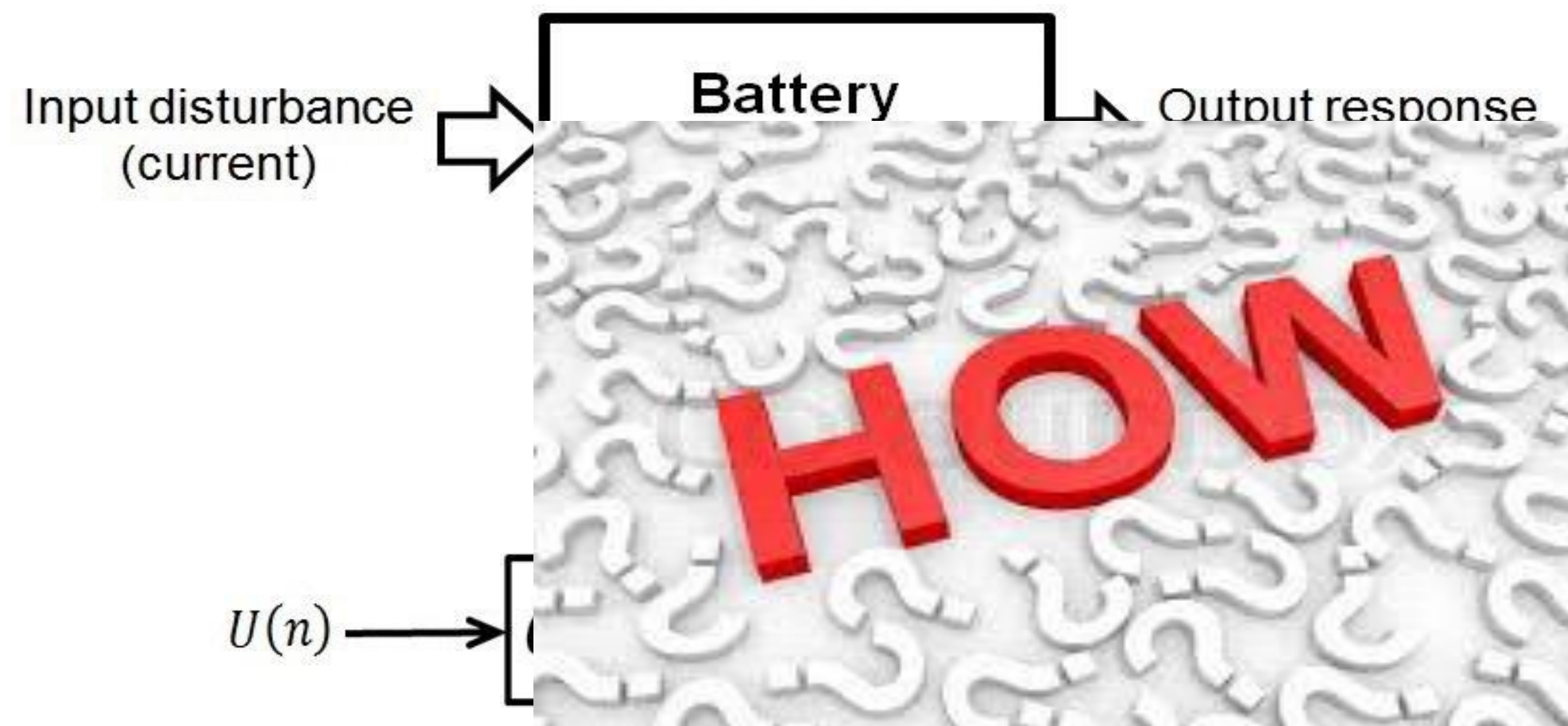
- Energy storage systems play key roll in our daily life



- Energy storage devices need accurate monitoring and control systems, therefore we need:
 - Electrical model for offline and real-time simulations
 - Electrical model for SoC (state of charge) estimation
 - Electrical model for SoH (state of helath) estimation
 - Electro-thermal model for SoF (state of function) estimation and safety evaluation

Battery as a nonlinear system

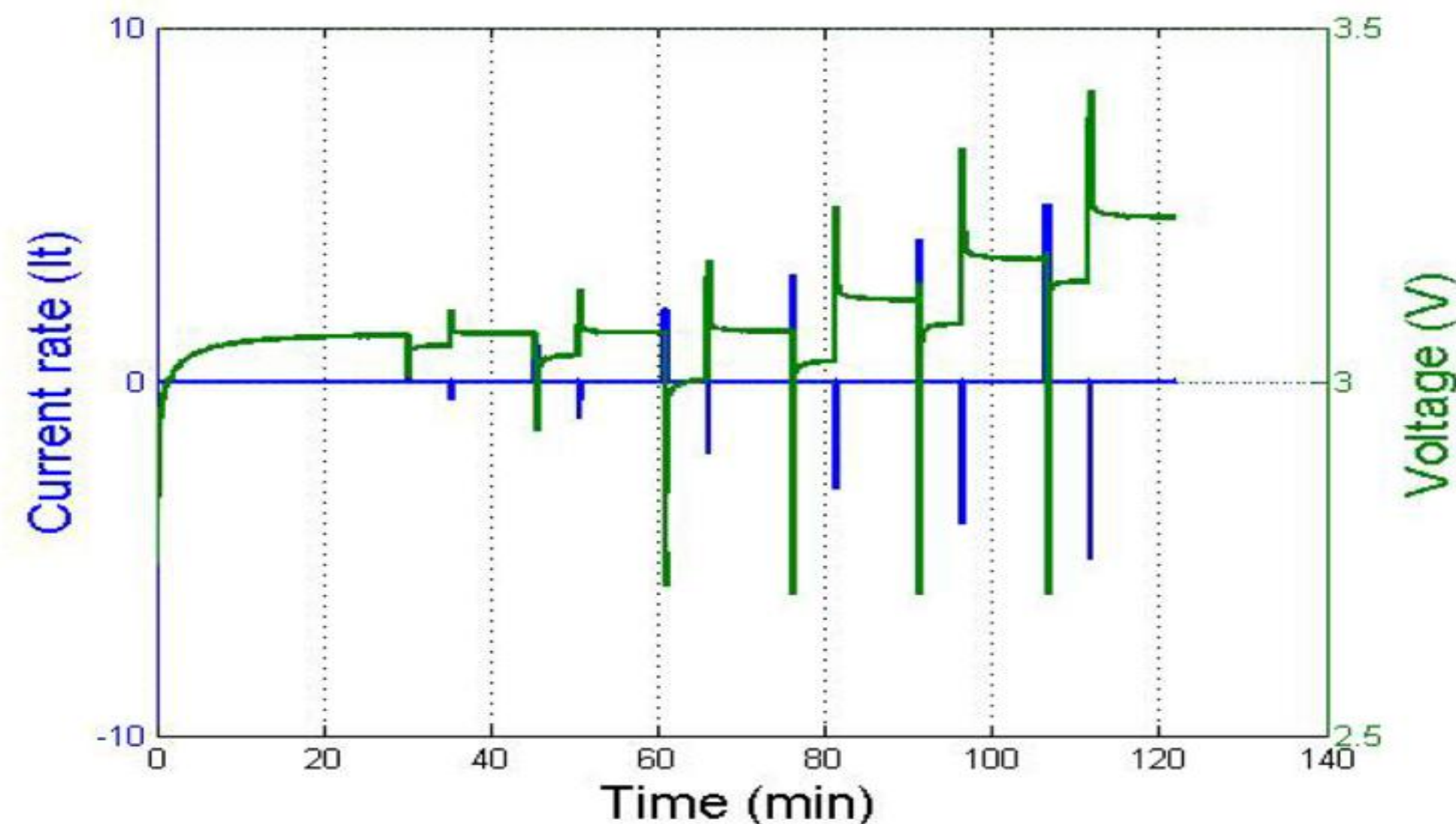
- A battery electrical model can be represented as a *linear system* contaminated with *nonlinear distortions* and *noise*.



$$Y^{[r,p]}(j\omega) = \overset{\text{Linear}}{\boxed{G_{BLA}(j\omega)U^{[r]}(j\omega)}} + \overset{\text{nonlinear}}{\boxed{Y_S^{[r]}(j\omega)}} + \overset{\text{Noise}}{\boxed{Y_N^{[r,p]}(j\omega)}}$$

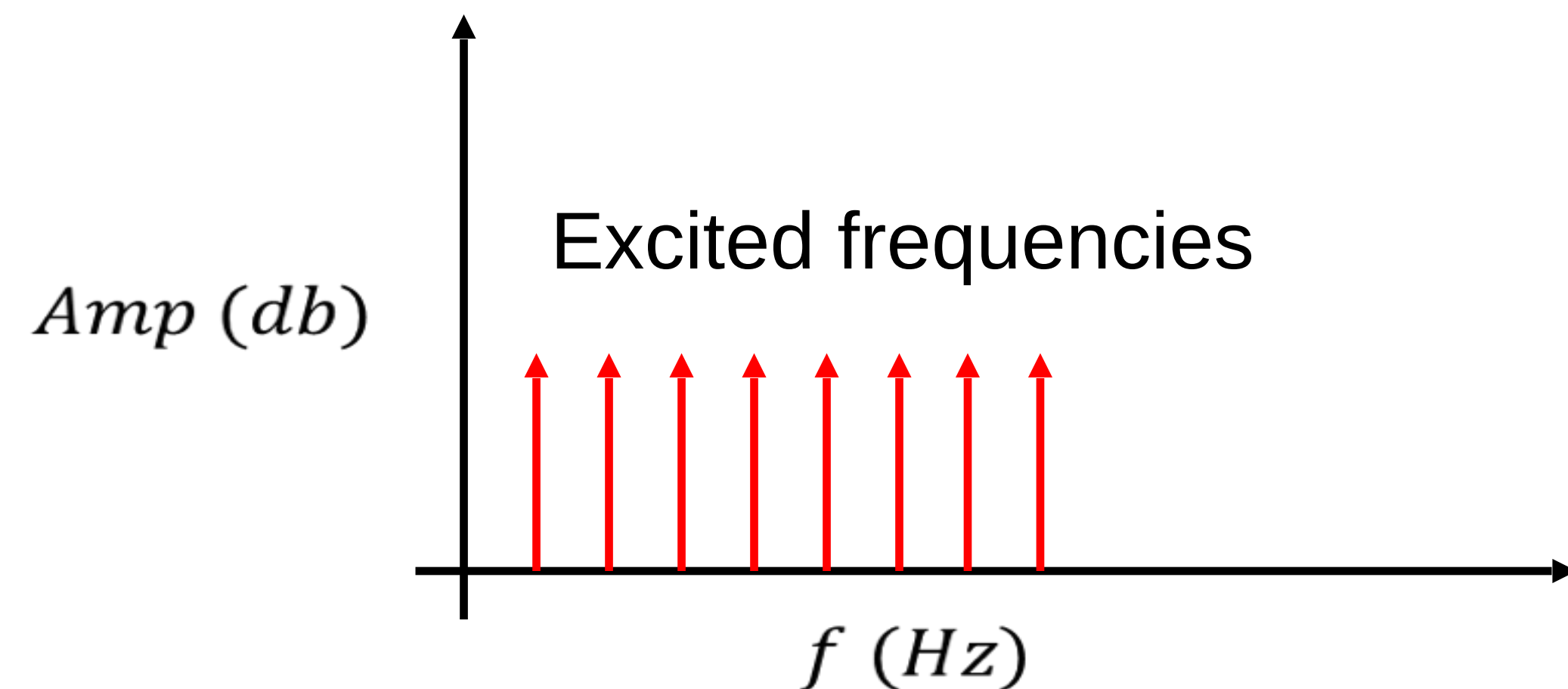
Multisine signal as the identifier

- Hybrid Pulse Power Characterization test (HPPC) has been used widely for battery modeling and parameter extraction
 - ✓ Easy to use in time domain
 - Linear low-ordered systems
 - No noise information
 - SoC variation in case of high current pulses



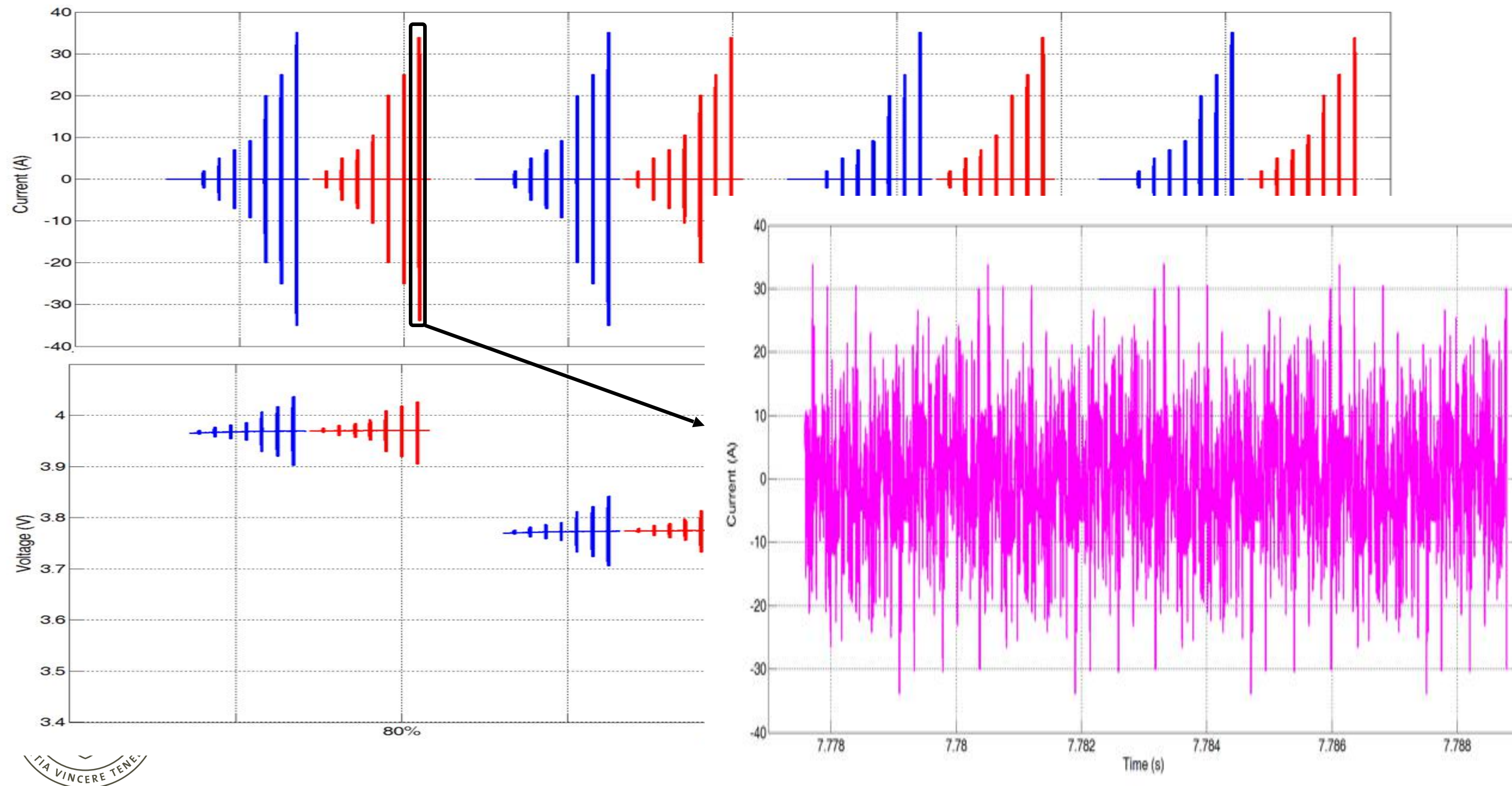
Multisine signal as the identifier

- Periodic signals such as multisine are in general more effective for system identification:
 - ✓ Proper for use in both time and frequency domains
 - ✓ Can be applied as Zero mean signal, No SoC variation
 - ✓ Noise quantification and elimination by averaging
 - ✓ Transient elimination
 - ✓ Nonlinear distortion detection
 - Needs post processing analysis



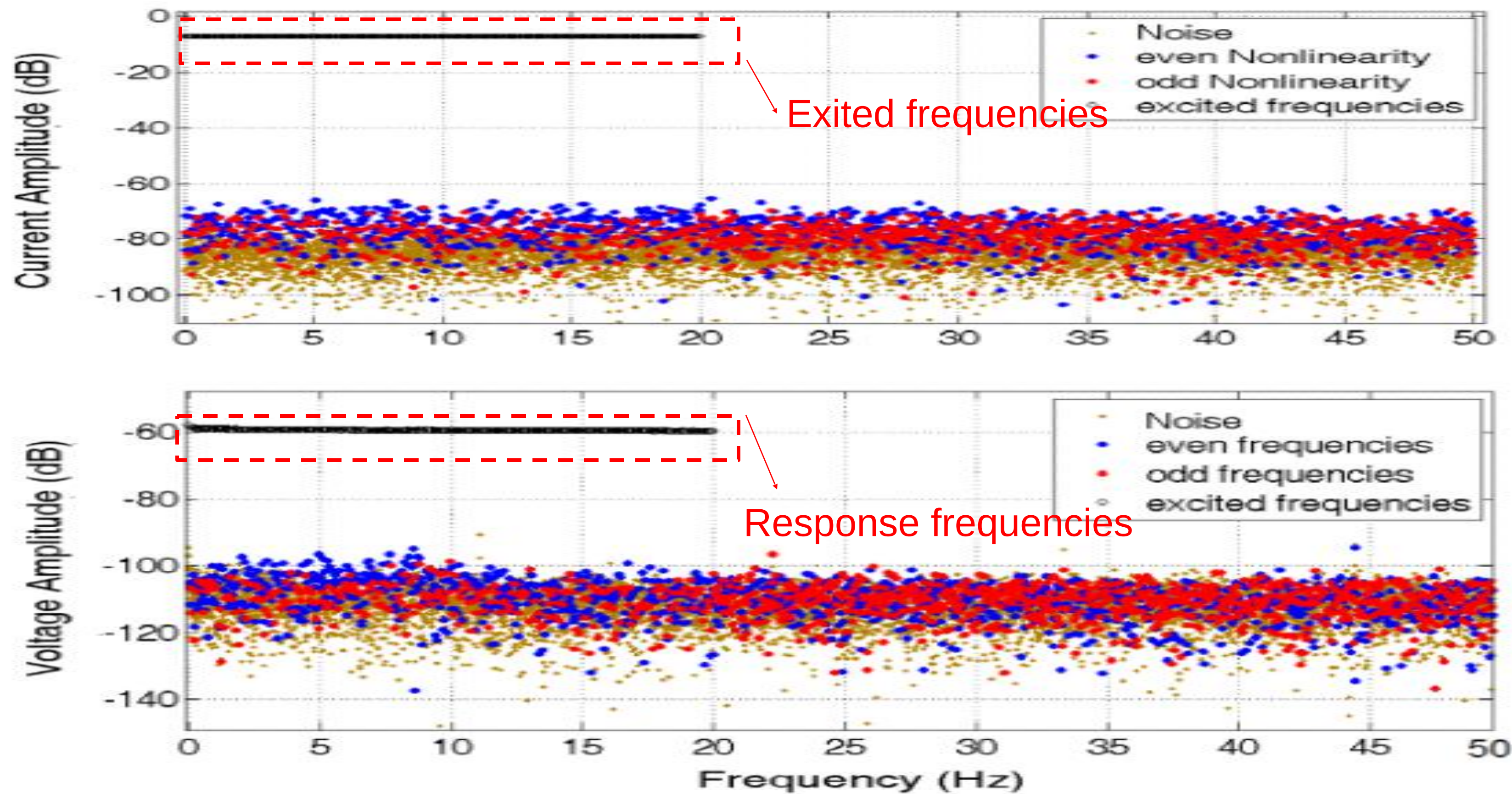
Multisine signal as the identifier

- Current and voltage at time domain



Multisine signal as the identifier

- Current and voltage at frequency domain



Linear part, nonlinear distortion and noise detection

- Best Linear Approximation (BLA)
 - Linear approximation of a nonlinear system:
 - in M realization of the periodic multisine signal (same amplitude of excited frequencies with randomly chosen phases)
 - in N periods of each realization.

$$G_{BLA}(j\omega_n) = \arg \min \sum_{r=1}^M |Y^{[r]}(n) - G(j\omega_n)U^{[r]}(n)|^2 \quad n=1 \dots N$$

$$\hat{G}^{[r]}(j\omega_n) = \frac{\hat{Y}^{[r]}(n)}{\hat{U}^{[r]}(n)}$$



$$\hat{G}_{BLA}(j\omega_n) = \frac{1}{M} \sum_{r=1}^M \hat{G}^{[r]}(j\omega_n)$$

Linear part, nonlinear distortion and noise detection

Noise

Averaging of the $G(j\omega)$
 in each M realizations
 Over all N periods of each realization
 Calculation of noise distortion

$$\sigma_N^2(n) = \frac{1}{M \cdot (P-1)} \sum_{r=1}^M \sum_{p=1}^P \left| G^{[r,p]} - G_p^{[r]} \right|^2$$

Nonlinear distortion

Calculation of total distortion over all realizations and periods:

$$\sigma_{Total}^2(n) = \frac{1}{M \cdot P - 1} \sum_{r=1}^M \sum_{p=1}^P \left| G^{[r,p]} - G_p \right|^2$$

Calculation of nonlinear distortion using noise and total distortion:

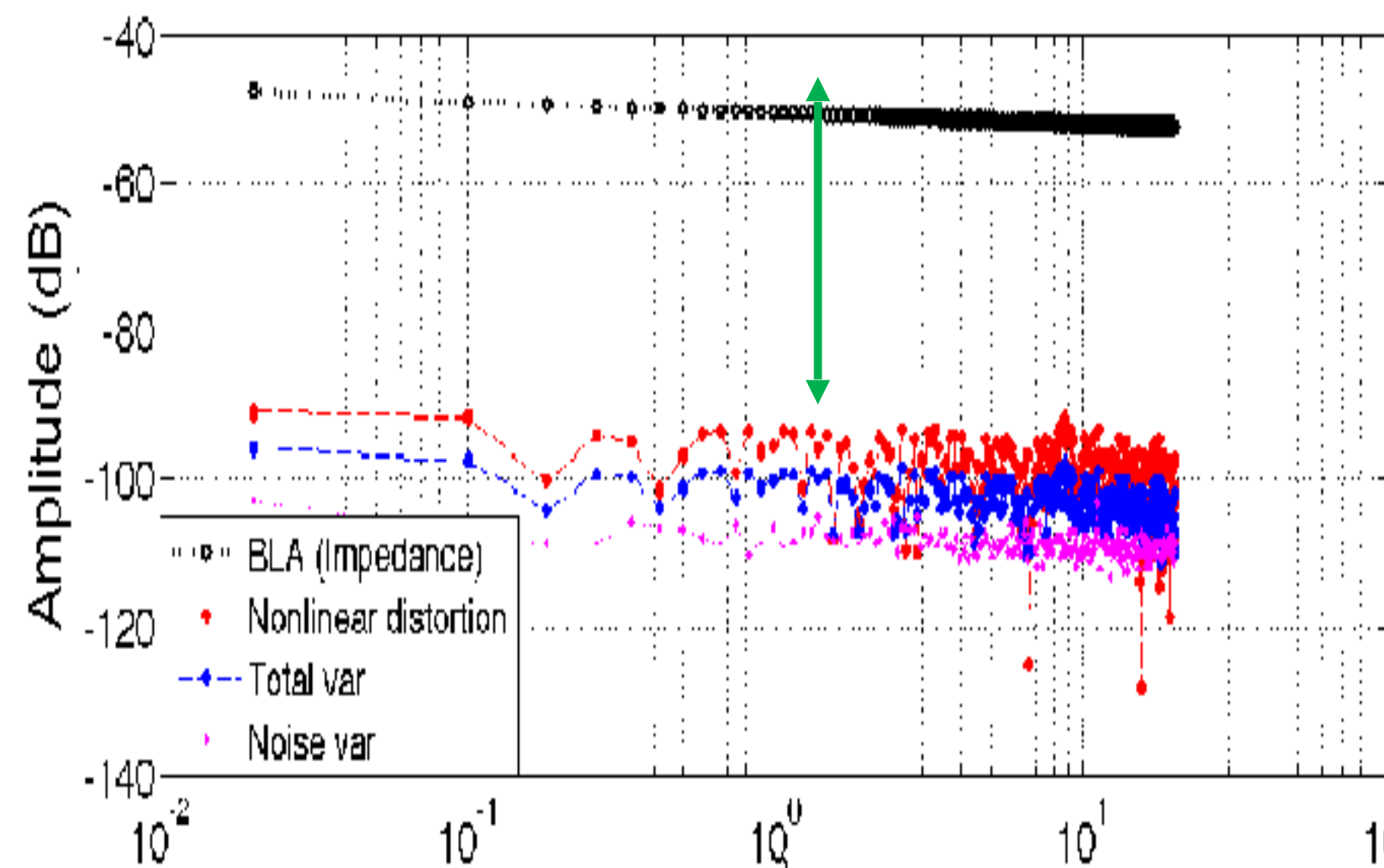
$$\sigma_S^2(n) = M(\sigma_{Total}^2(n) - \sigma_N^2(n))$$

Linear part, nonlinear distortion and noise detection

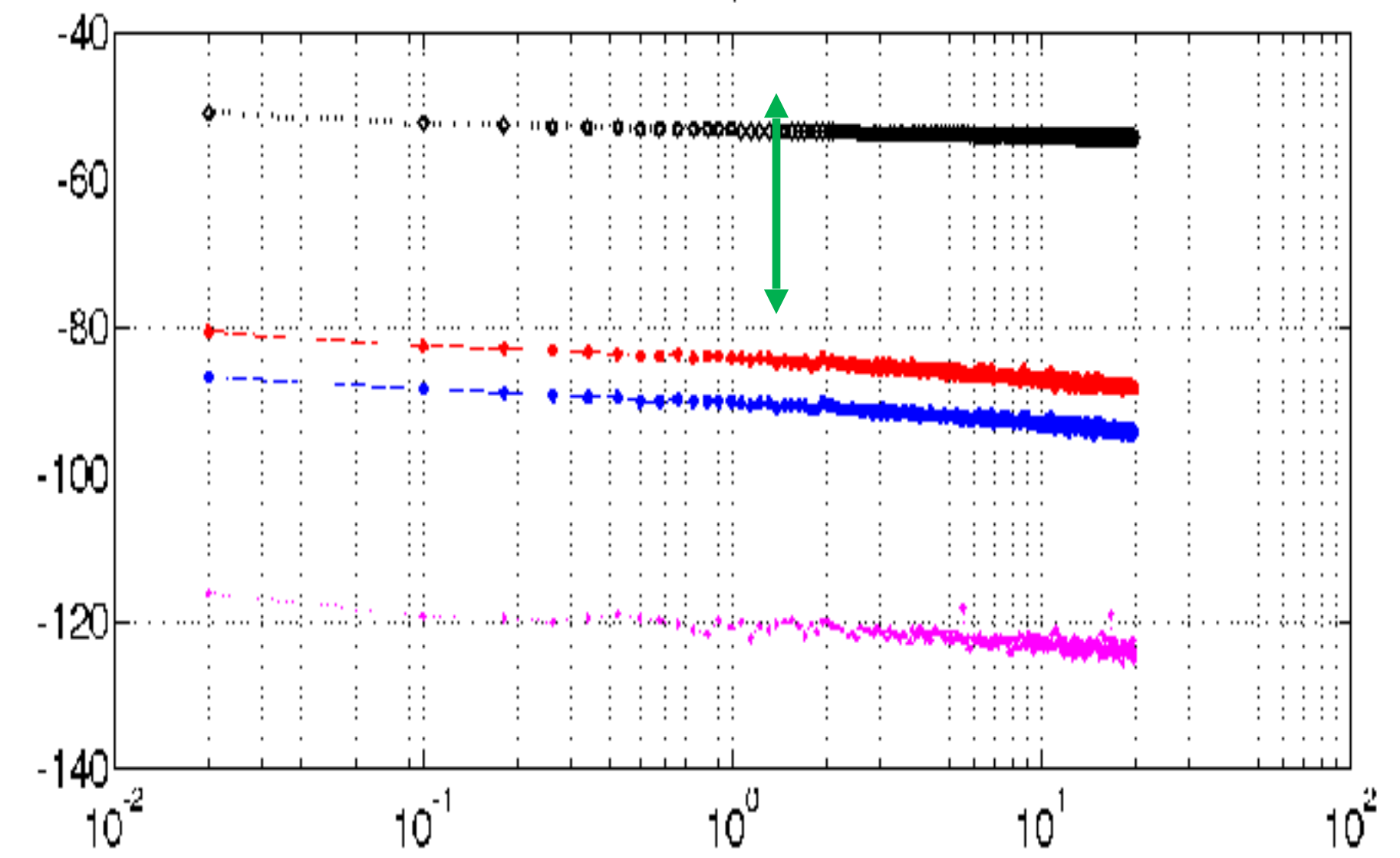
- Nonlinearity detection using proposed method

Linear system (battery at 50% SoC)

Nonlinear system (battery at 10% SoC)



Frequency (Hz)



- In linear systems nonlinear distortions (red dots) are in the noise level (pink dots)

In nonlinear systems, the nonlinear distortion are getting close to the linear part of the system (black dots)

Conclusion

- A new method for battery measurement and modeling has been introduced
- This method is able to:
 - Approximate a nonlinear system to a linear system
 - Detect and quantified the nonlinear distortion
 - Calculated the measurement noise
- Linear part can be used for parametric modeling (equivalent circuit model)
- Nonlinear distortion can be used for qualification of the system for nonlinear modeling
- Calculated noise level helps to evaluate the measurement's environment and also equipment used for the measurements