# 22NRM06 ADMIT

## Characterisation of AC and DC MV instrument transformers in extended frequency range up to 150 kHz

## WP1 - Performance requirements, parameters and test procedures for accuracy evaluation

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# Acknowledgement

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# Content

- Review of literature and standards for Power Grids and Instrument Transformers up to 150 kHz
- High Frequency Distortion (supraharmonics) effects
- Measurement campaign
- Laboratory test setup and VT testing results

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# Scientific literature

# Scientific Literature review

- Typical amplitudes and frequencies of High Frequency Distortions (HFDs)
- Measurement methods for HFDs
- Propagation of HFDs
- Mitigation strategies for HFDs

# Typical amplitudes and frequencies of HFDs

- **Sources**: Mainly PhotoVoltaic (PV) power parks and Electric Vehicle (EV) Chargers (EVC). Their emissions are mainly concentrated in the range 2-50 kHz
- **Typical switching frequencies:** 10, 16, 45 kHz
- **Typical HFD Frequencies**:
  - PV: 10, 16, 26, 36, 126 kHz
  - EVC: 16, 32, 45, 48, 90 kHz
  - Intermodulation between PV and EVC: 16, 32, 48, 52, 64, 68, 80, 84, 96, 100 kHz
- **Typical HFD Amplitudes:** < 0.1 % for voltage, < 0.25 % for current
- **Typical transfer ratios:**
  - LV -> MV: 1 A/A, 0.01 to 1.0 V/V
  - MV -> LV: 0.5 to 3.0 V/V

# Measurement methods for HFDs

- **Standard Measurement Techniques**: IEC 61000-4-7, IEC 61000-4-30, and CISPR 16-1
- **Other techniques**:
  - **Time-domain** methods include Digital CISPR, Light-QP, Numerical Heterodyne, matrix pencil method. They offer high time resolution, reduction of coloured noise but limitations on computational complexity and lower accuracy for high-amplitude components
  - **Frequency-domain** methods are based on Fourier Transform; they provide detailed frequency resolution but require higher sampling rates
- **Challenges**: Measurement devices may struggle with low-amplitude HFDs, leading to reduced accuracy, especially when the amplitude is below 5% of the fundamental frequency

- Analyzed literature do not consider the influence of Instrument Transformers on HFD measurements

# Propagation of HFDs

- **Grid Impedance**: HFD propagation depends on the impedance of both low-voltage (LV) and medium-voltage (MV) grids. Propagation is simplified by the resonances, present both in AC as well as in DC grids

- **Propagation Mechanism**: HFDs can propagate from MV to LV grids and vice versa, especially through transformers, affecting the connected devices at both sides

# Mitigation strategies for HFDs

- **Filters**: Various filters, including EMC filters, passive filters, and active filters, are employed to reduce HFDs by providing low-impedance paths for high-frequency signals
- **Resonance and Impedance Control**: Managing resonance and grid impedance can help to mitigate the propagation of HFDs
- **Challenges in Mitigation**: The propagation of HFDs through transformers complicates the mitigation process. Additionally, interference with power delivery equipment and end-user devices can complicate identifying the source of disturbances.

# Standard review

# International standards for HFDs

There is not a specific standard that cover disturbances in the range 9-150 kHz

1. **Voltage Characteristics of Electricity Supplied by Public Distribution Networks**
   - **EN 50160**: Defines voltage characteristics for public electricity distribution systems
   - **IEC 62749**: Relates to power quality in the grid.
2. **Recommended Practice for Monitoring Electric Power Quality**
   - **IEEE 1159**: Provides guidelines for monitoring and analyzing power quality, including HFDs.
3. **Electromagnetic Compatibility (EMC)**
   - **IEC 61000**: Specifies immunity and emission requirements for electrical and electronic equipment in the context of EMC.
4. **Instrument Transformers (ITs)**
   - **IEC 61869**: Standards related to current and voltage transformers, crucial for accurately measuring HFDs in MV grids.

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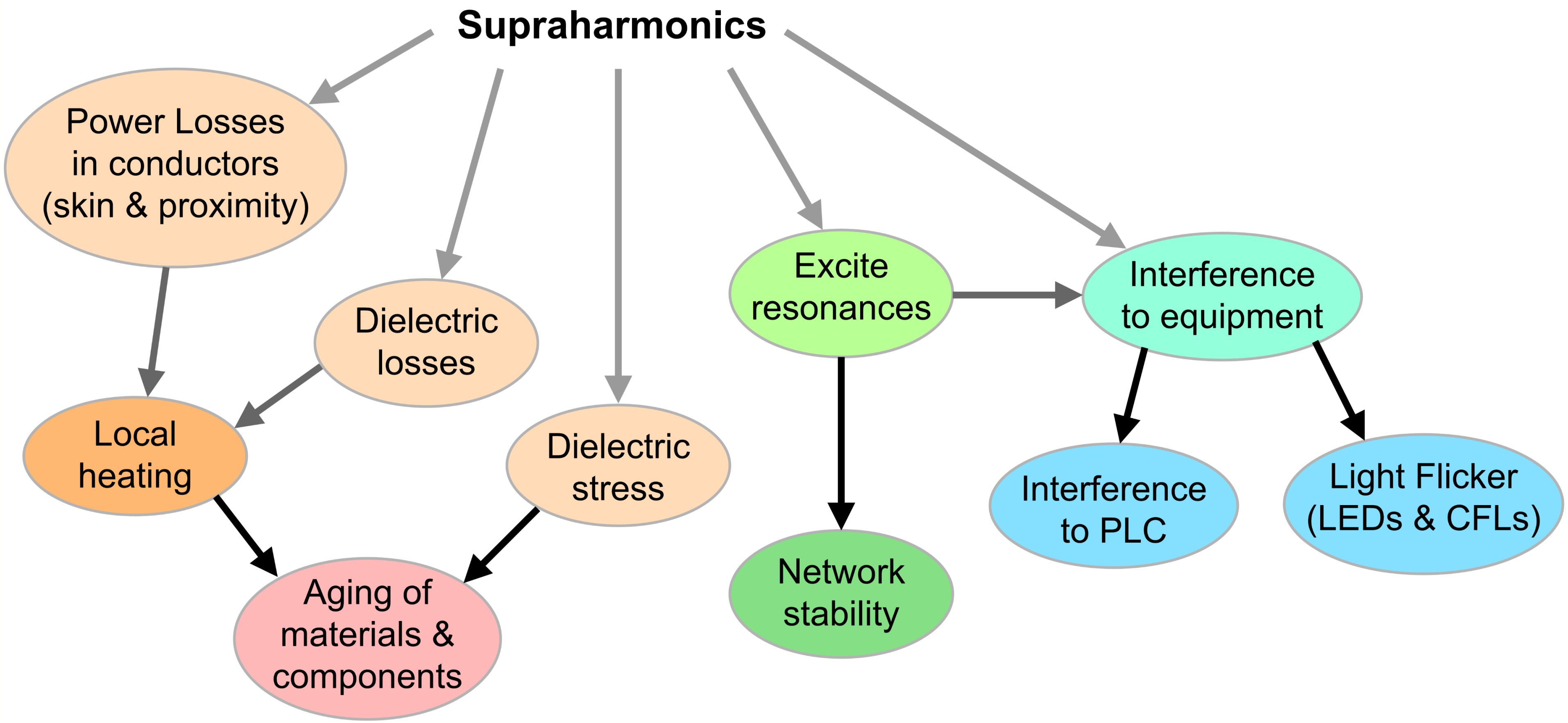
# Overview of supraharmonics negative effects

- Power losses in conductors, such as skin effects and proximity effects
- Aging of insulating materials and capacitors
- Damage to MV cable terminations caused by local heating and electric field gradient;

# Overview of supraharmonics negative effects

- Triggering of network resonances
- Interference with equipment connected at the LV level (domestic appliances, information technology (IT), lighting, energy meters, etc…)
- Flicker phenomena on LED and fluorescent lamps
- Specific interference with power line communication (PLC)


Supraharmonics
Power Losses in conductors (skin & proximity)
Dielectric losses
Local heating
Dielectric stress
Aging of materials & components
Excite resonances
Network stability
Interference to equipment
Interference to PLC
Light Flicker (LEDs & CFLs)

# Copper losses

Harmonic losses due to skin effect are already accounted for in normative limits

Supraharmonics (increased frequency, but reduced amplitude) add another 20% of losses

# Dielectric losses

**Contribution to Partial Discharges**

- Quicker degradation of the material
- Both localized large electric field intensity and larger rate of change of the electric field (derivative term) matter

**Self heating of dielectrics**

- Non-linear phenomena take place in the wide SH range, accelerating ageing and requiring increased margin on the designed working voltage for cables (in terms of kV/mm)

**Ageing of capacitors**

- Supraharmonics cause increased heating (dielectric losses)
- Capacitors wear is relevant due to secondary emissions (exchange of large SH current between adjacent equipment).

# Deterioration of MV cable joints

- Local heat $Q_{pu}$ is proportional to: $Q_{pu} = \frac{f_{sh} V_{sh}^2}{f_1 V_1^2}$
  - SH distortion intensity (square) and frequency (linear);
  - $Q_{pu} = 20$ is considered critical leading to likely failure

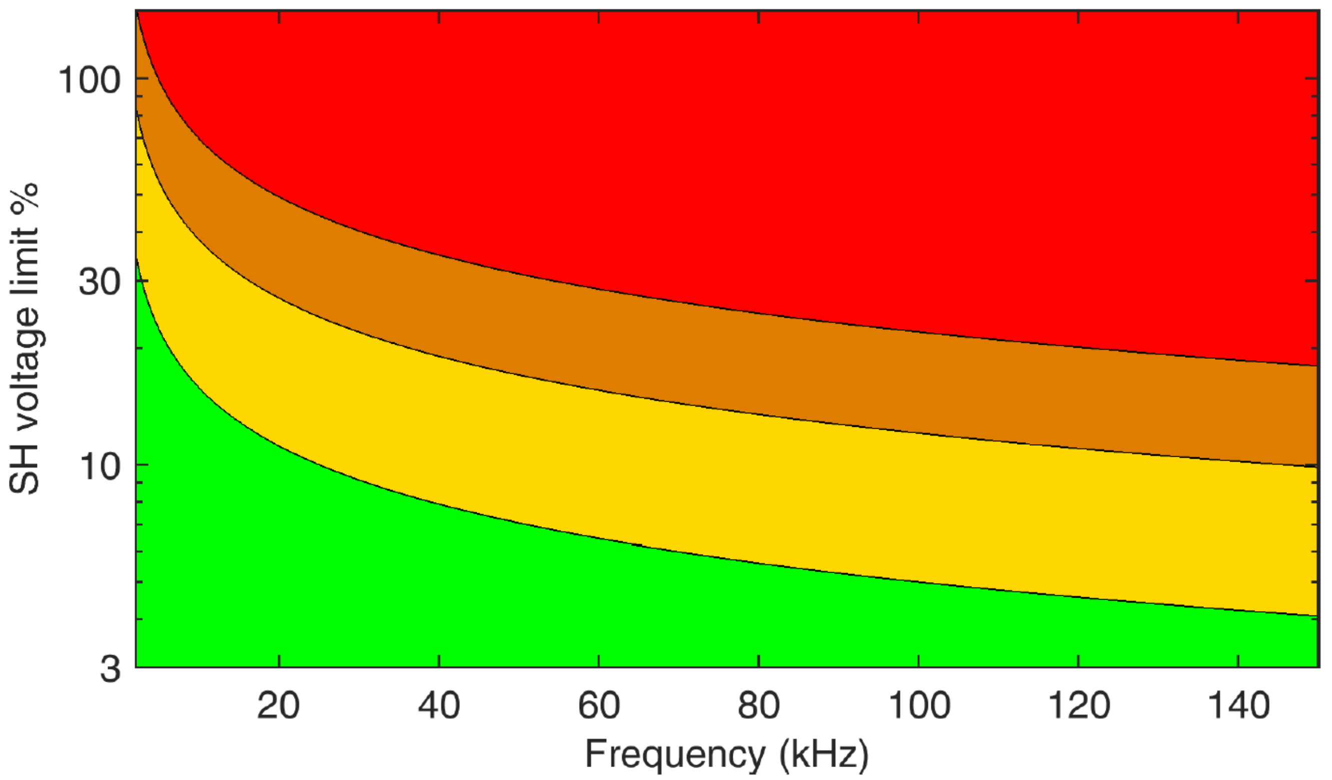



**Figure 6.** Limit curves for the percent SH voltage distortion based on the assumed $Q_{lim} = 20$ of [20] and for $m$ values covering $m <= 0.25$, $0.25 < m <= 0.5$, $0.5 < m <= 1.0$, and $m > 1.0$, with meaning of colors as in [20], namely "no risk", "moderate risk", "significant risk", and "unacceptable".

Green = no risk

Yellow = moderate risk

Orange = significant risk

Red = unacceptable

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# Location

MILAN


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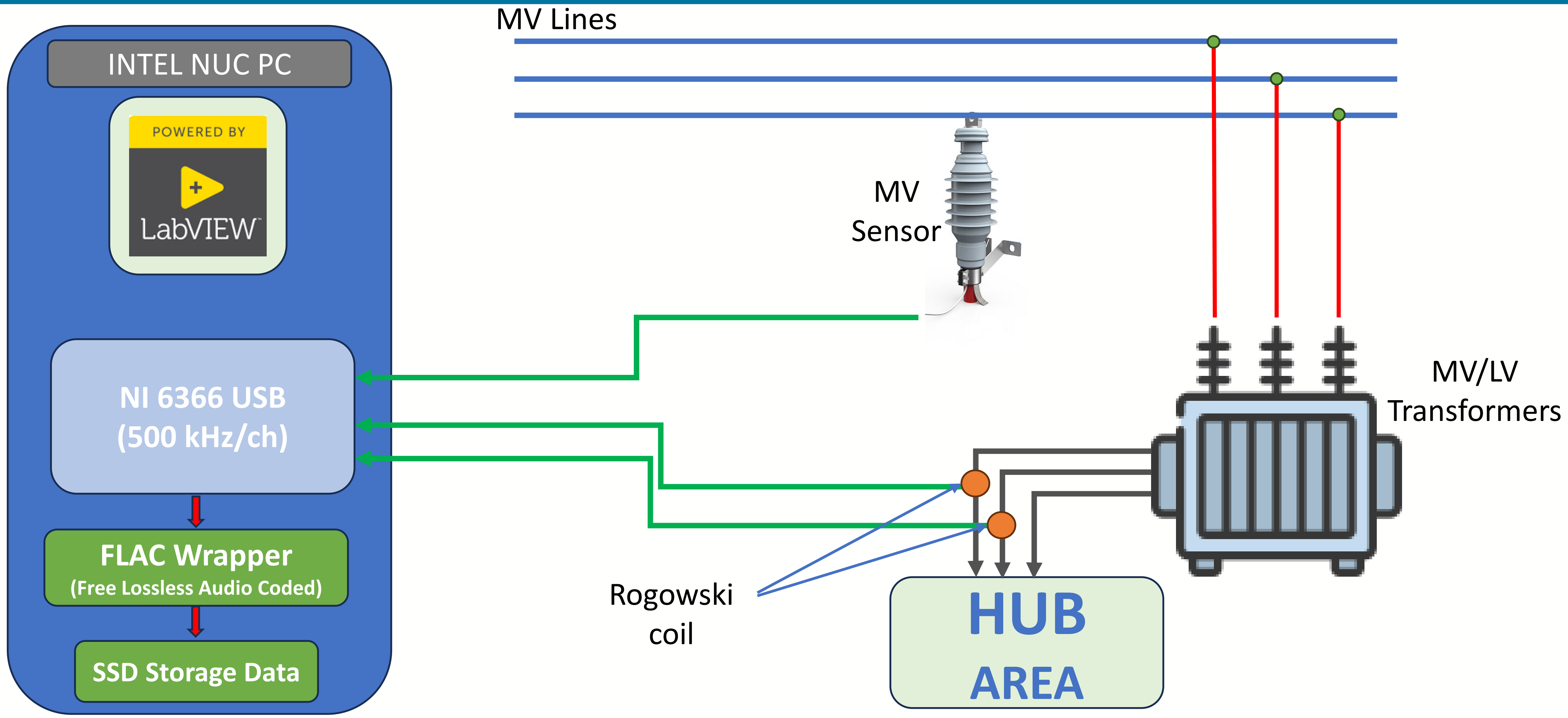
# MT/BT Cabin of EV HUB

Power: 630 kVA
Vs = 400V
Vp = 23kV
Is = 909A
Ip = 15A

Power: 400 kVA
Vs = 400V
Vp = 23kV
Is = 577.4A
Ip = 10.04A

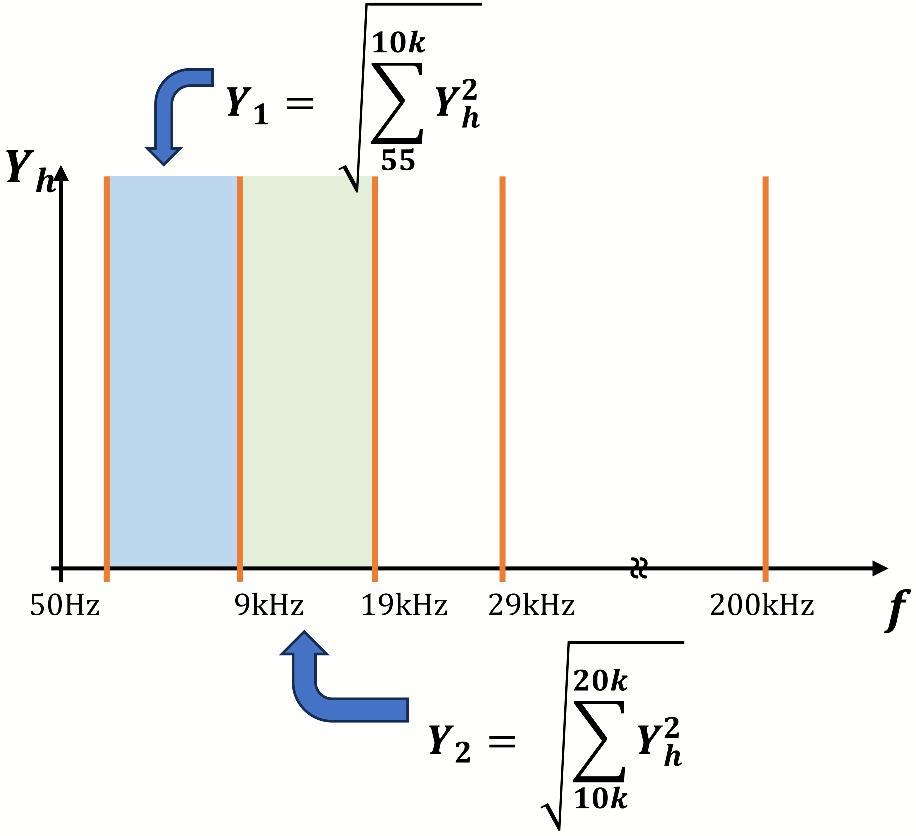

INTEL NUC PC
POWERED BY
LabVIEW
NI 6366 USB
(500 kHz/ch)
FLAC Wrapper
(Free Lossless Audio Coded)
SSD Storage Data
MV Lines
MV
Sensor
MV/LV
Transformers
Rogowski
coil
HUB
AREA

The **VS-24-I** is a MV electronic voltage transformer for Indoor use. Its main electrical and mechanical characteristics are listed in the table below.

* *marks the parameters customizable upon request.*

| | |
|---|---|
| Rated insulation level | 24/50/125 kV |
| Accuracy class * | 0.5 |
| Rated primary voltage, $U_{pn}$ * | 20/√3 kV |
| Maximum voltage, $U_m$ | 24 kV |
| Rated secondary voltage, $U_{sn}$ * | 1 V |
| Rated voltage factor, $K_u$ | 1.9 for 8h |
| Nominal frequency | 50 / 60 Hz |
| Nominal transformation ratio, $K_n$ * | 20/√3 kV / 1 V |
| Auxiliary Supply voltage<br>Max. Supply current | ±12 Vdc<br>15 mA |
| Creepage | 375 mm |
| Primary terminal capacity | 1 pF |
| Bandwidth (-1 dB) | 30 Hz – 20 kHz, 1 MHz for HF version |
| Applicable Standards | IEC 60044-7, IEC 60660 |
| Accuracy on harmonics | According to IEC 60044-8 |
| Weight | 1.6 kg |
| Temperature range | [- 5 °C, 40 °C] |

# Measurement indices




**Band Group**

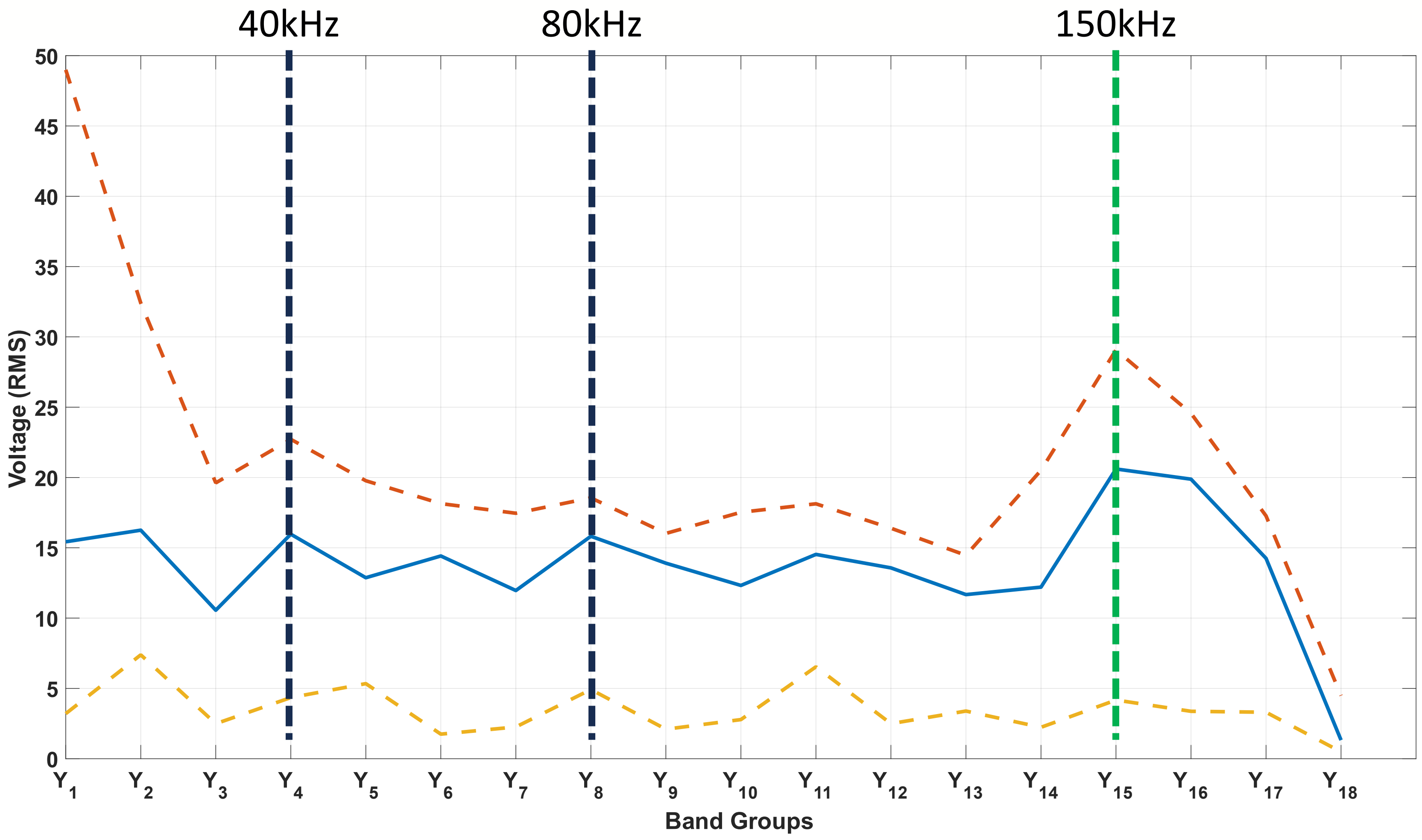
$$Y_g = \sqrt{\sum_{f_a}^{f_b} Y_h^2} \rightarrow \begin{cases} Y_{g_{max}} \\ Y_{g_{mean}} \\ Y_{g_{min}} \end{cases}$$

Where $|f_b - f_a| = 10$ kHz

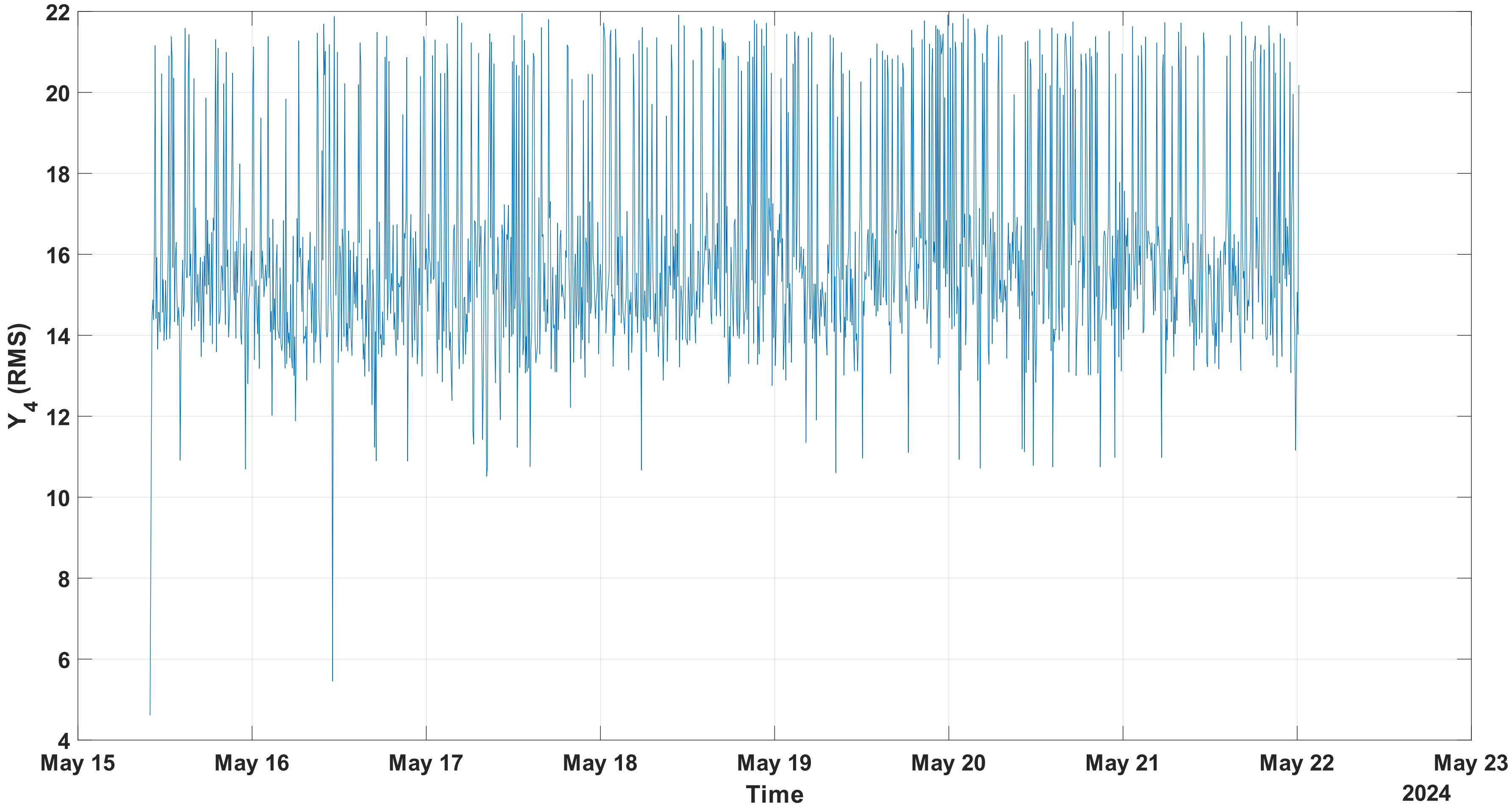
$FFT \rightarrow Y_h$ **Window Size 200 ms**

Fundamental voltage

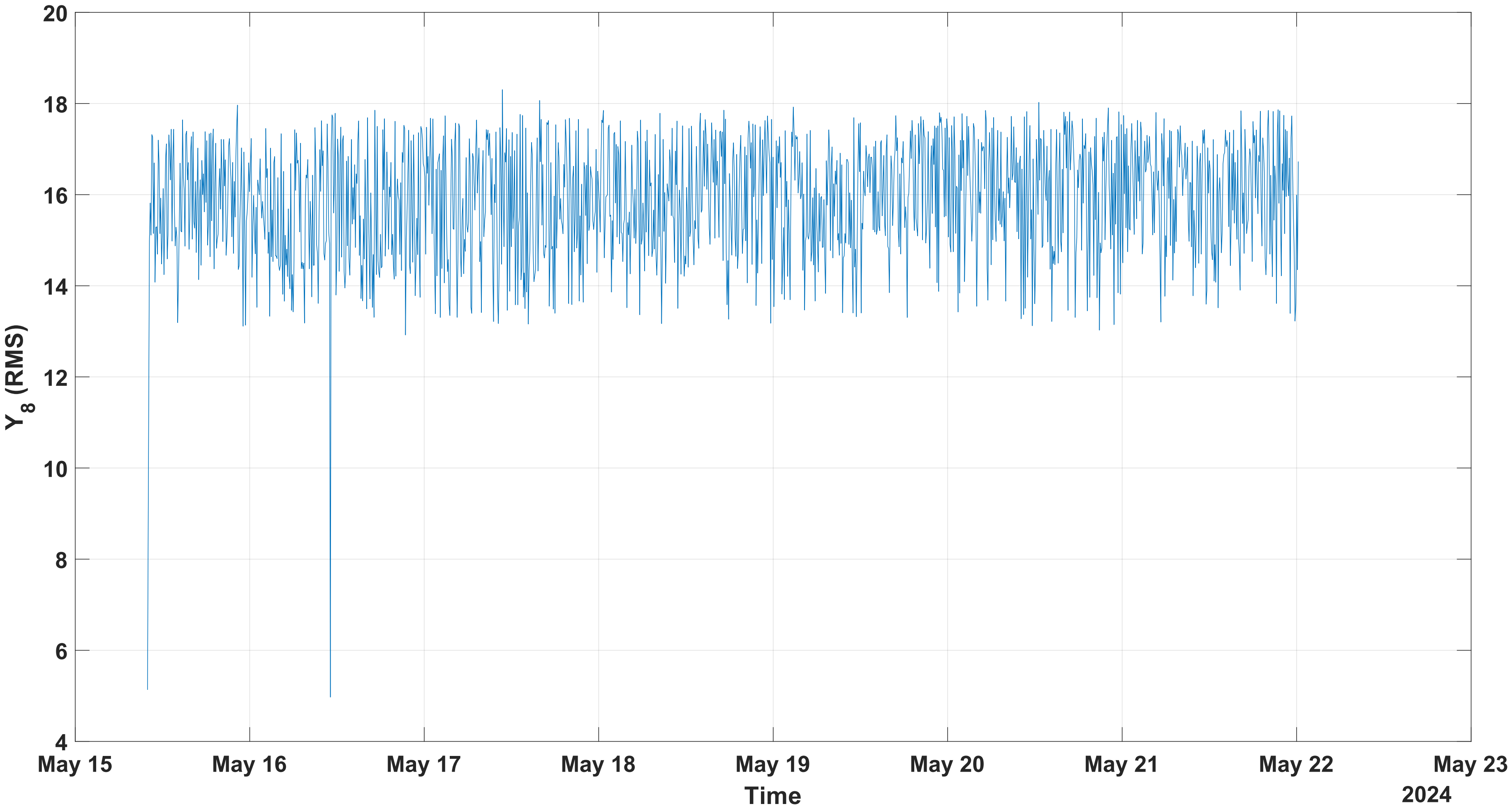
$$V_1 = 15\ kV\ (RMS)$$



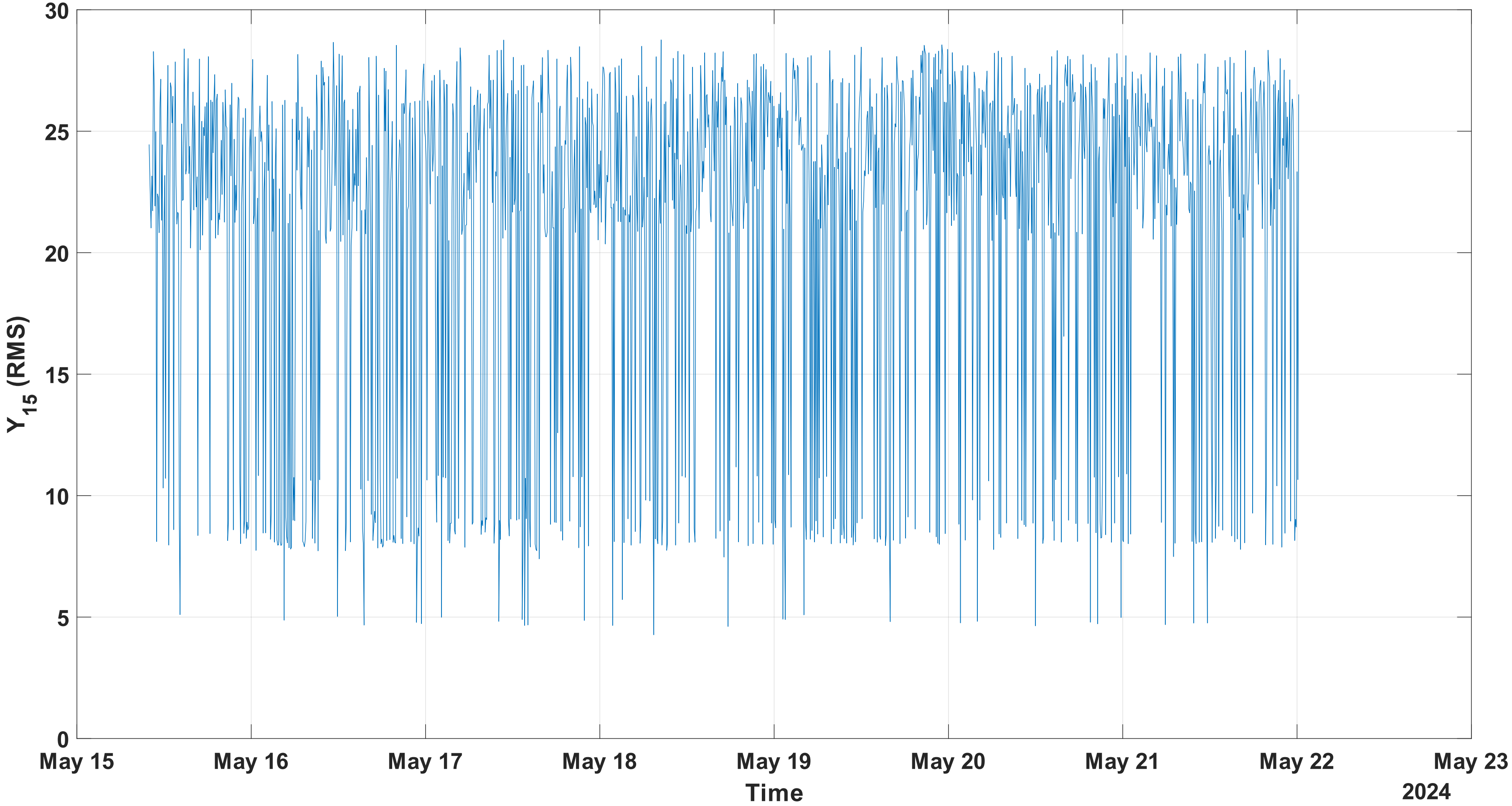
$$Y_4 = \sqrt{\sum_{30k}^{40k} Y_h^2}$$



$$Y_8 = \sqrt{\sum_{70k}^{80k} Y_h^2}$$



$$Y_{15} = \sqrt{\sum_{140k}^{150k} Y_h^2}$$



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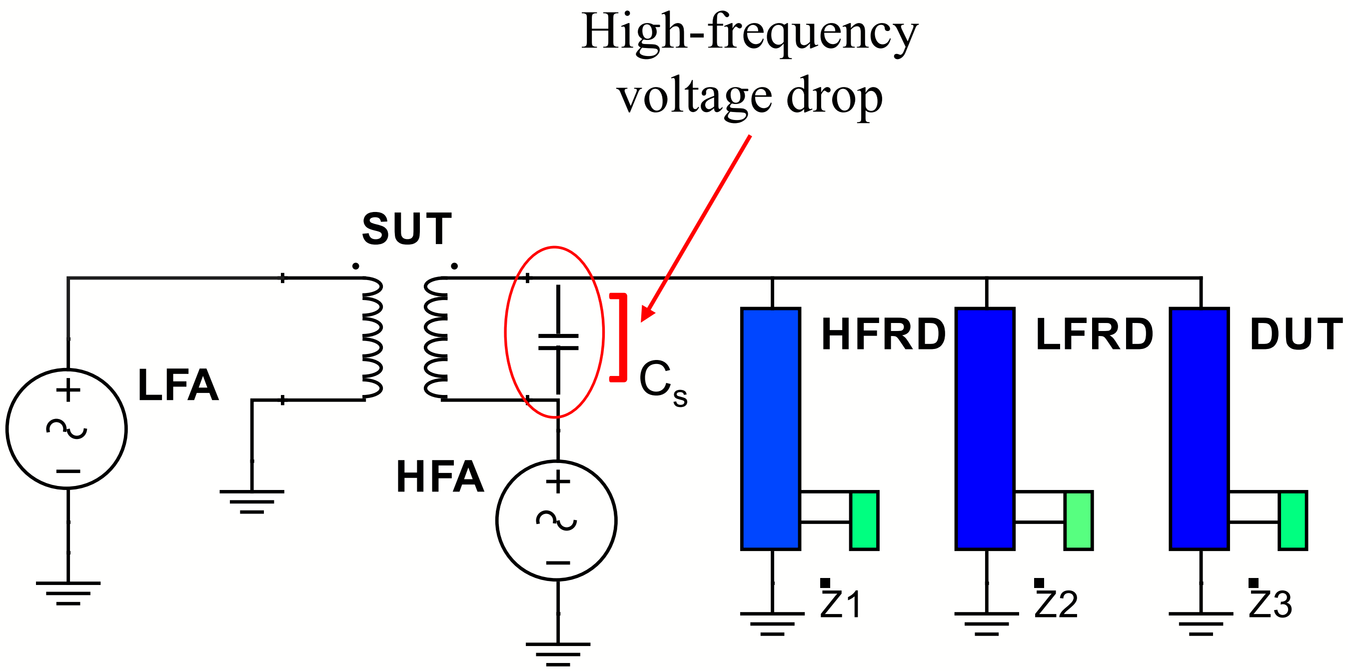
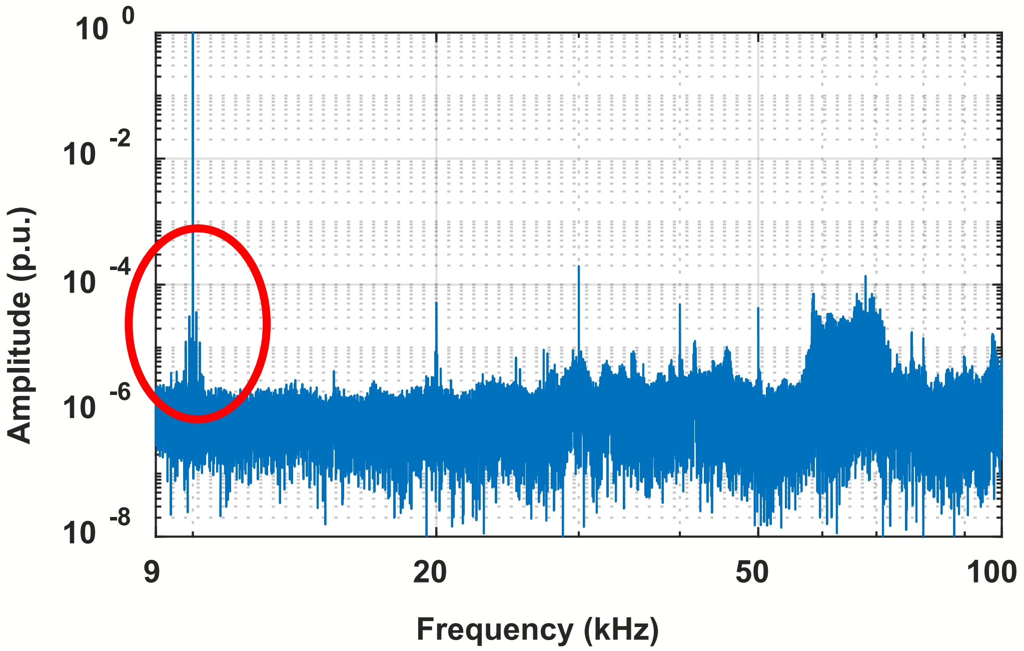
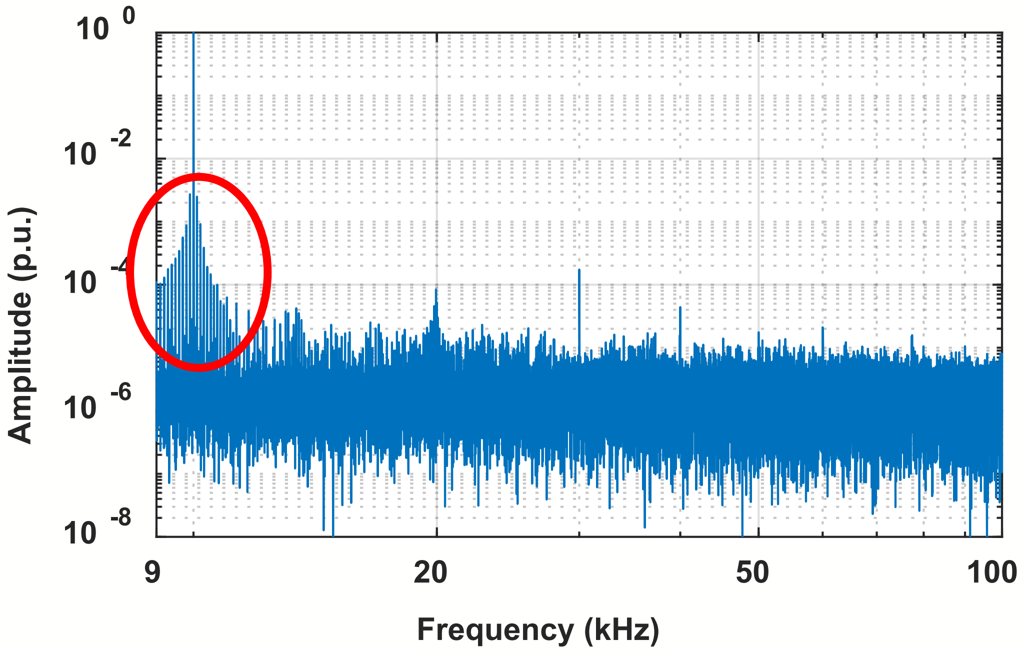



| | |
|---|---|
| **LFA** | Low-Frequency Amplifier |
| **HFA** | High-Frequency Amplifier |
| **SUT** | Step-Up Transformer |
| **LFRD** | Low-Frequency Reference Device |
| **HFRD** | High-Frequency Reference Device |
| **DUT** | Device Under Test |

# Input spectrum ($f_{hf} = 10\ kHz$)




# Output spectrum ($f_{hf} = 10\ kHz$)



# More details later….

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