This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation program.

Harmonic analysis of non-sinusoidal waveforms during no-load loss measurement of power transformers

Gu Ye

Gert Rietveld

gye@vsl.nl

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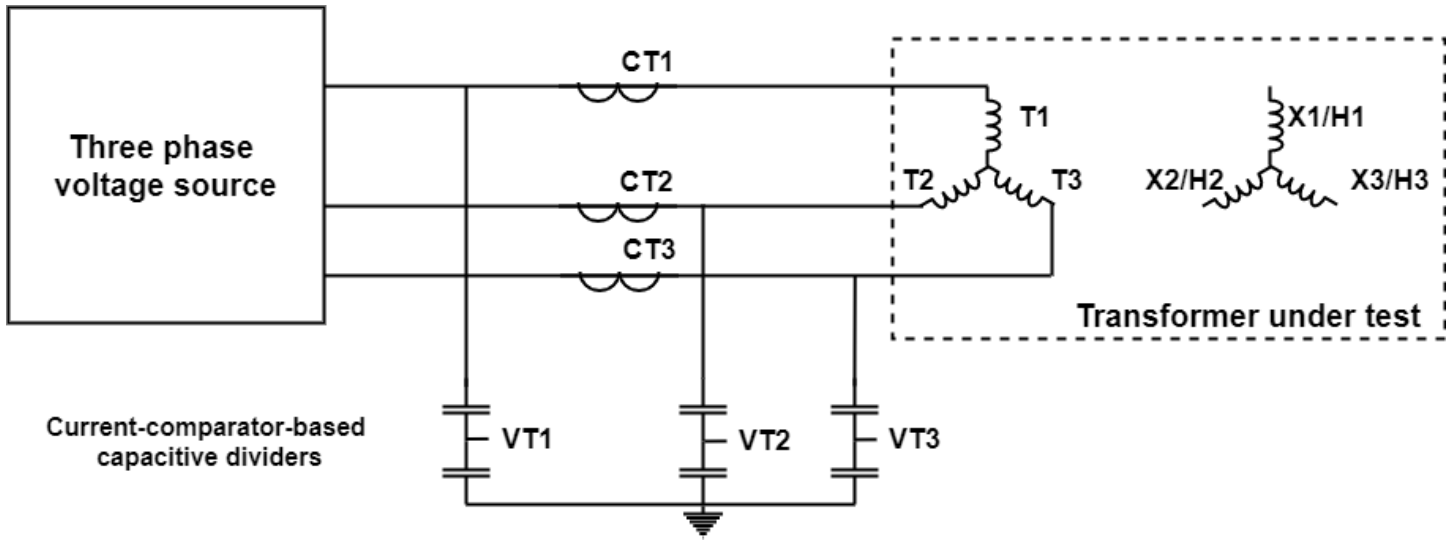
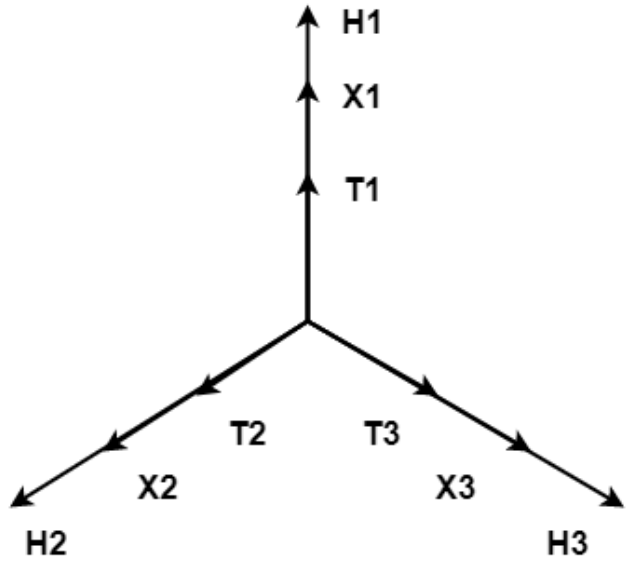
No-load loss (NLL) tests of power transformers





Voltage [kV]	Connection
380	H1, H2, H3
138	X1, X2, X3
10.6	T1, T2, T3
Power [MVA]	600/600/45

- 60 Hz
- Y/Y connections
- 10.6 kV auxiliary winding for testing
- Measurements are performed with 70, 80, 90, 95, 100, 105, 110 and 115 % of the rated voltage

Correction of the measured NLL losses

- Yokogawa WT3000
- Record 1002 points
- A 100 ms acquisition period
- 10 kSa/s sampling rate

$$IEEE:\ \mathrm{P}_0 = \frac{P_m}{P_1 + kP_2}, k = \left(\frac{V_{rms}}{V_{avg-rms}}\right)^2$$

$$IEC: \mathrm{P}_0 = P_m(1+d), d = \frac{V_{avg-rms} - V_{rms}}{V_{avg-rms}}$$

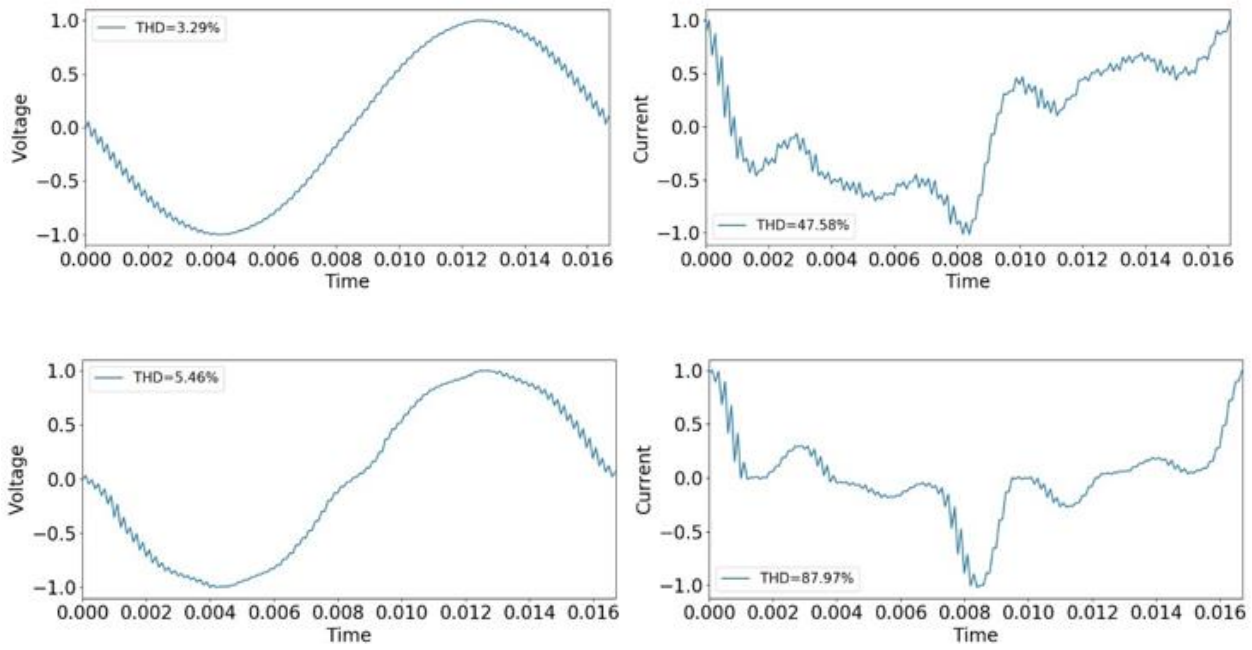
$$\%\text{correction} = \frac{|P_0 - P_m|}{P_m} \cdot 100\%$$

With

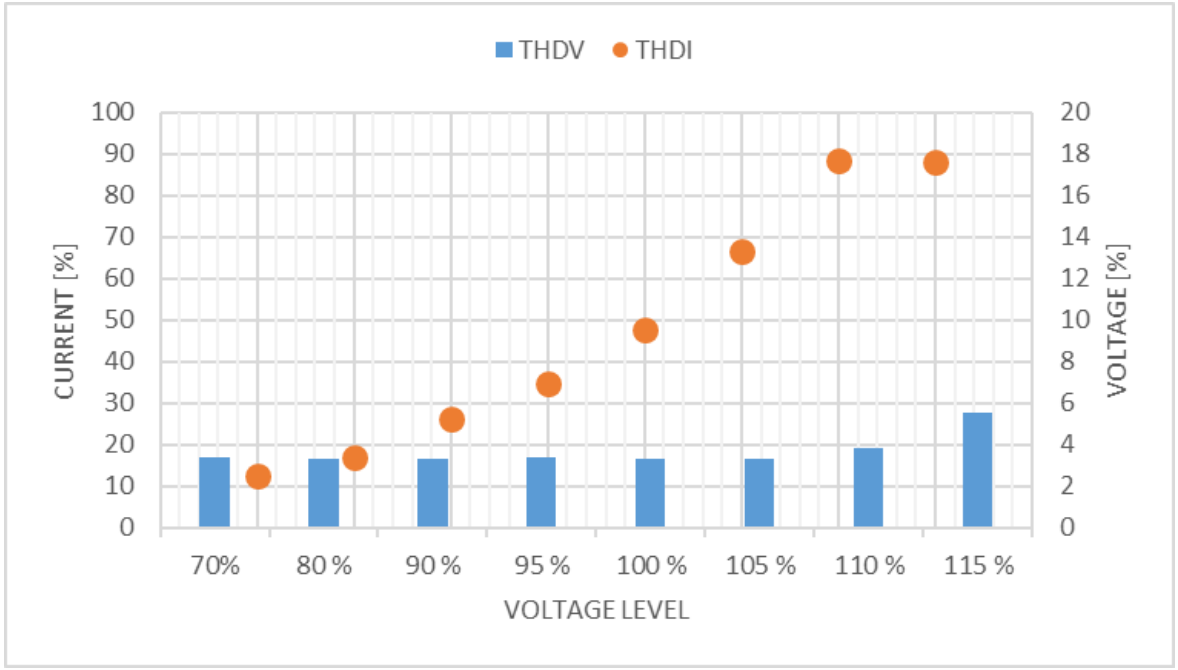
$$V_{avg-rms} = \left(\frac{2}{T}\int_0^{\frac{T}{2}} V_{ex}(t)dt\right) \cdot \frac{\pi}{2\sqrt{2}}$$

Measurement results

- Voltage and current waveforms during the NLL measurements for test voltages equal to 100 % and 115 % U_{rated}

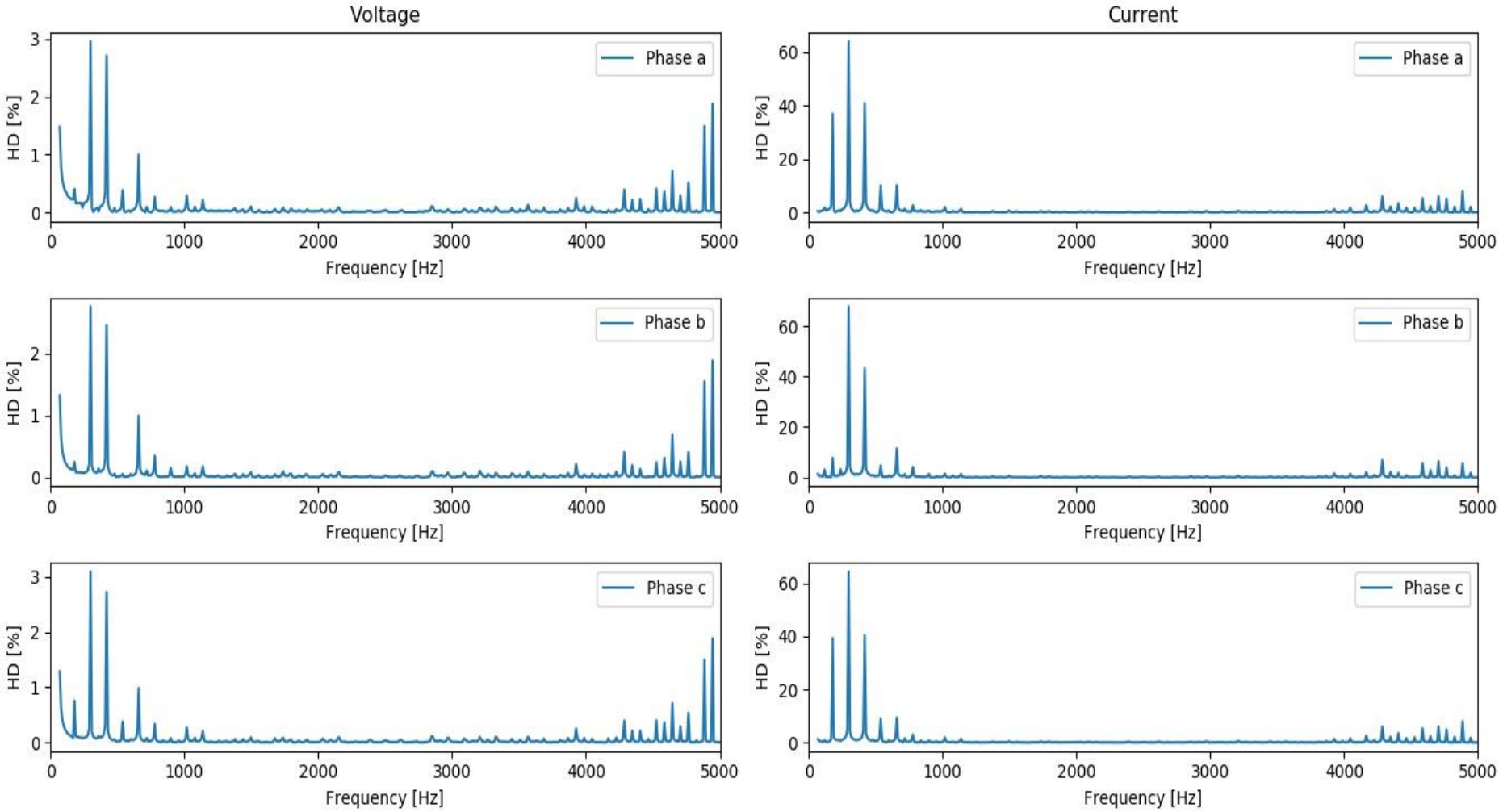


- THD values of varying voltage levels calculated up to 5 kHz



Dutch Metrology Institute

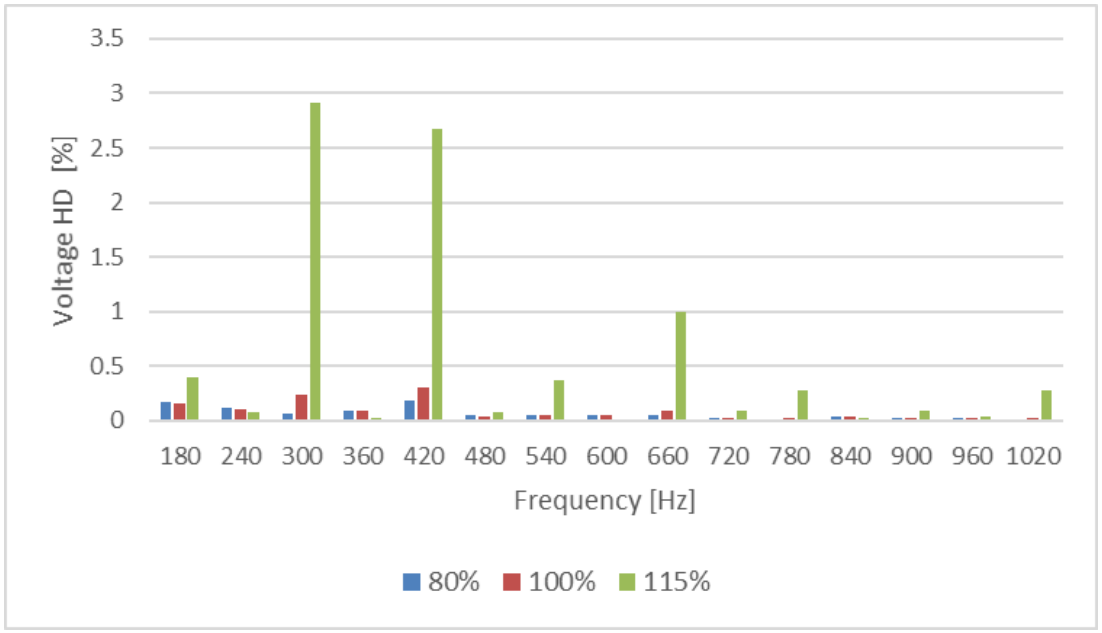
Measurement results at 115 % U_{rated}

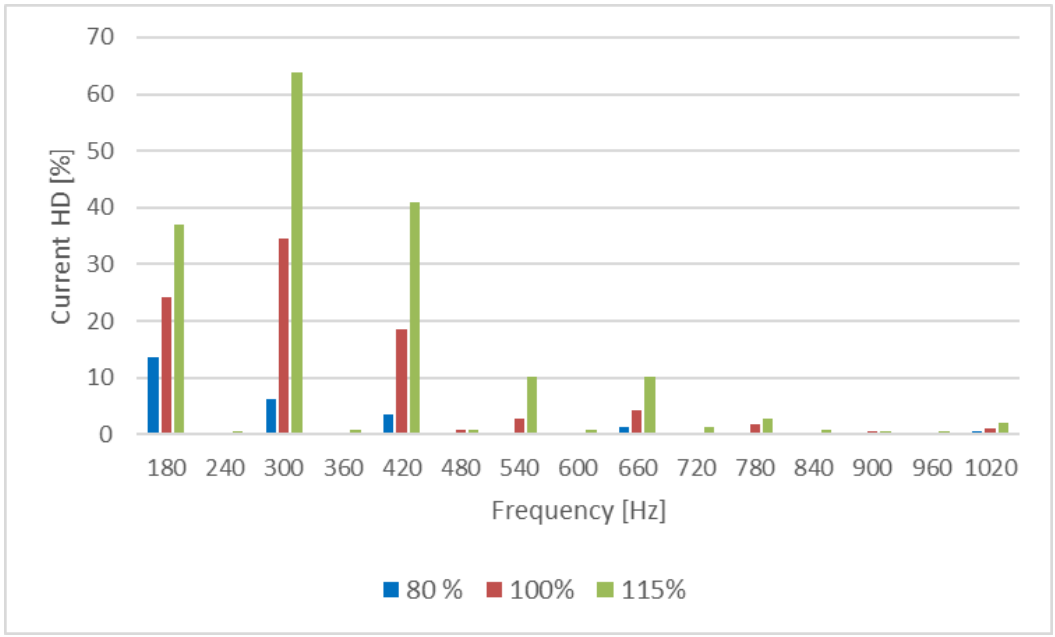


- High-frequency ripple (4.5 kHz - 5 kHz) from the source
- The 3rd, 5th, 7th, 9th and 11th harmonic voltage components are dominant

Measurement results

- Harmonic distortion of voltage and current for 80 %, 100 % and 115 % U_{rated}

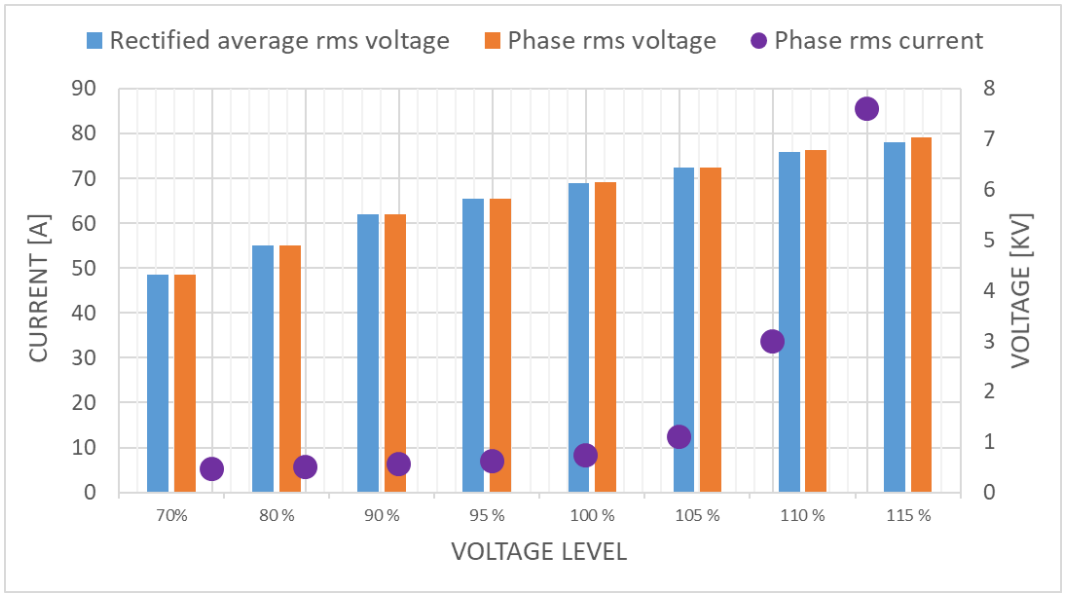


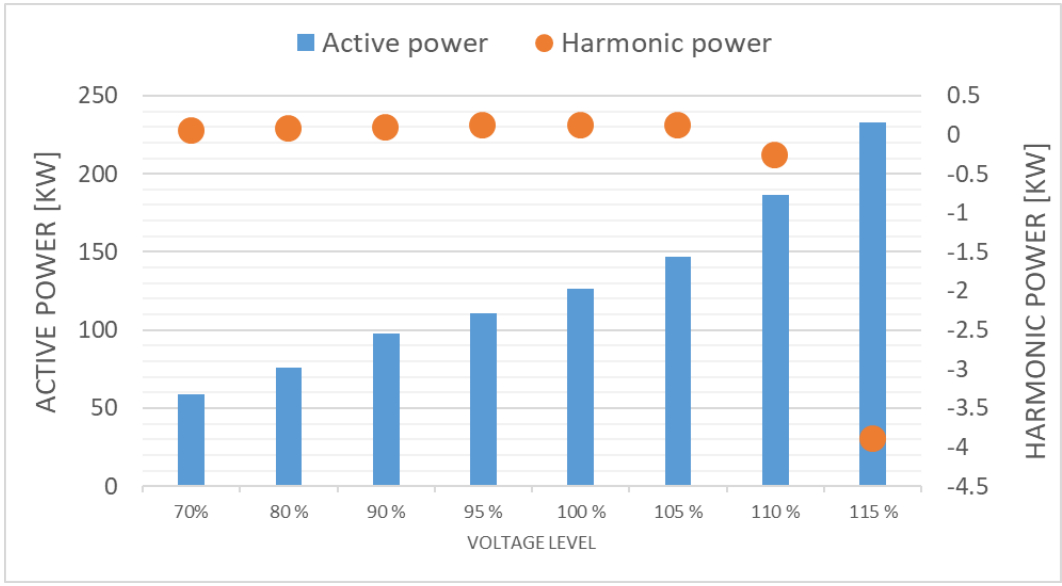


- The distortion of 115 % case is higher than the lower voltage levels since the current are much more distorted combined with a non-negligible output impedance of the generator.

Measurement results

- Active power and Harmonic power





- For 115 % case, the harmonic power is about 1.6 % of the total active power (4 kW) and *generated* by the transformer (negative sign).
- The 5th and 7th harmonic power are the most dominant ones, followed by the 3rd harmonic
- For other voltage levels, the harmonic power values are lower than 0.1 %.

Discussions

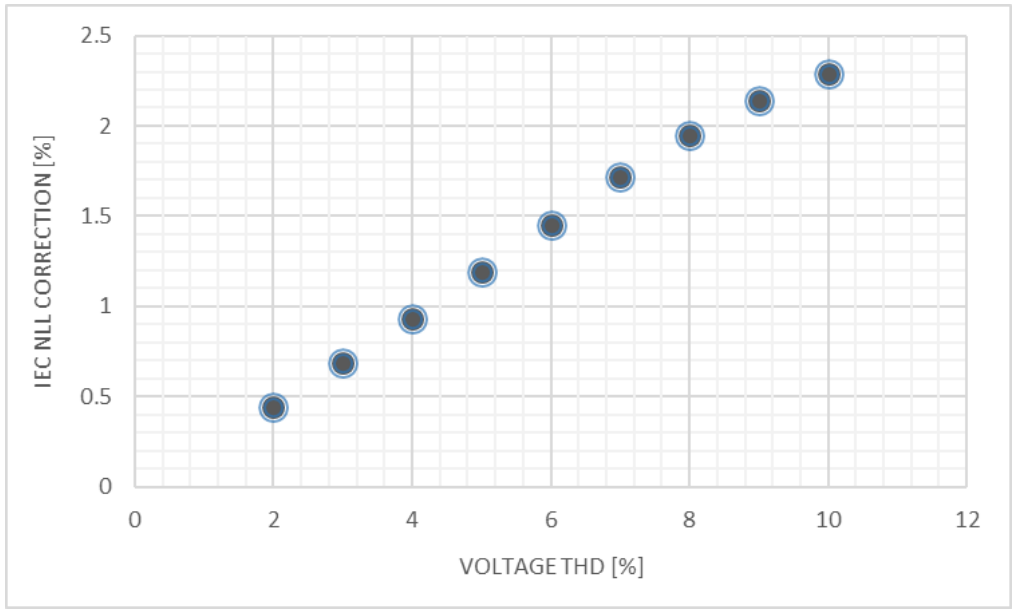
Loss measurement system (LMS) bandwidth

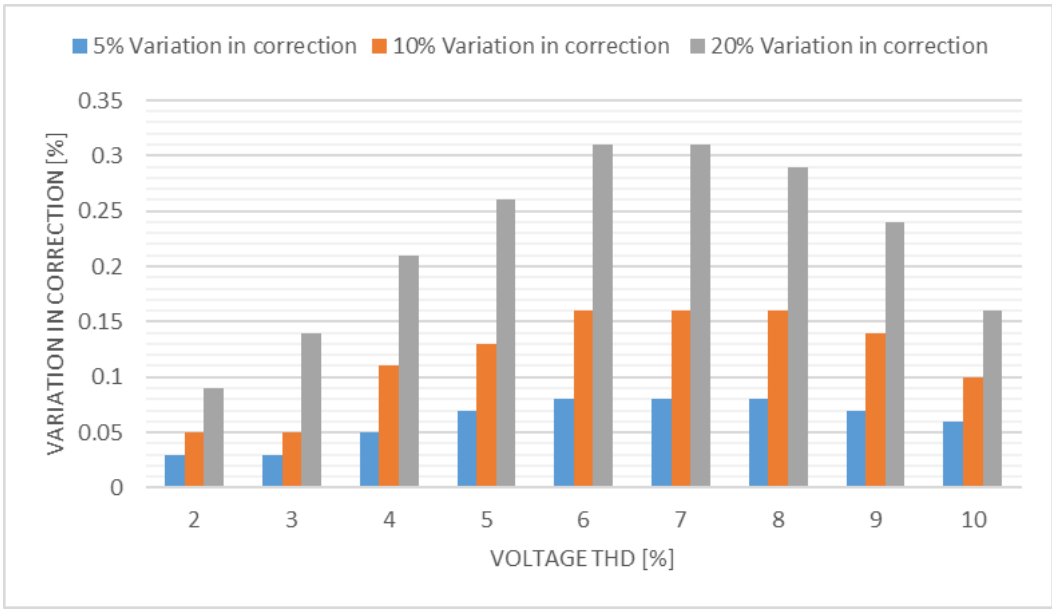
- The bandwidth of CCB capacitive voltage divider is within 0.01 % for frequencies up to 300 Hz.
- With the highest relevant harmonics up to 420 Hz in the present test, even a conventional VT can be used since the previous study shows that the voltage transformer is still accurate to 5 % in ratio up to 1 kHz.
- Current transformers have no problems within 1 % up to 1 kHz. Above 1 kHz, it has a minor impact on harmonic power since the voltage at the same frequencies are very low based on the present measurements
- The present (sampling) power meters are sufficiently accurate for loss measurements, with a deviation of at most 0.1 % with voltage THD up to 29 %.

Conclusion: accuracy < 10 % for the harmonic power losses up to 1 kHz

Discussions

- Impact of non-sinusoidal waveforms on LMS accuracy

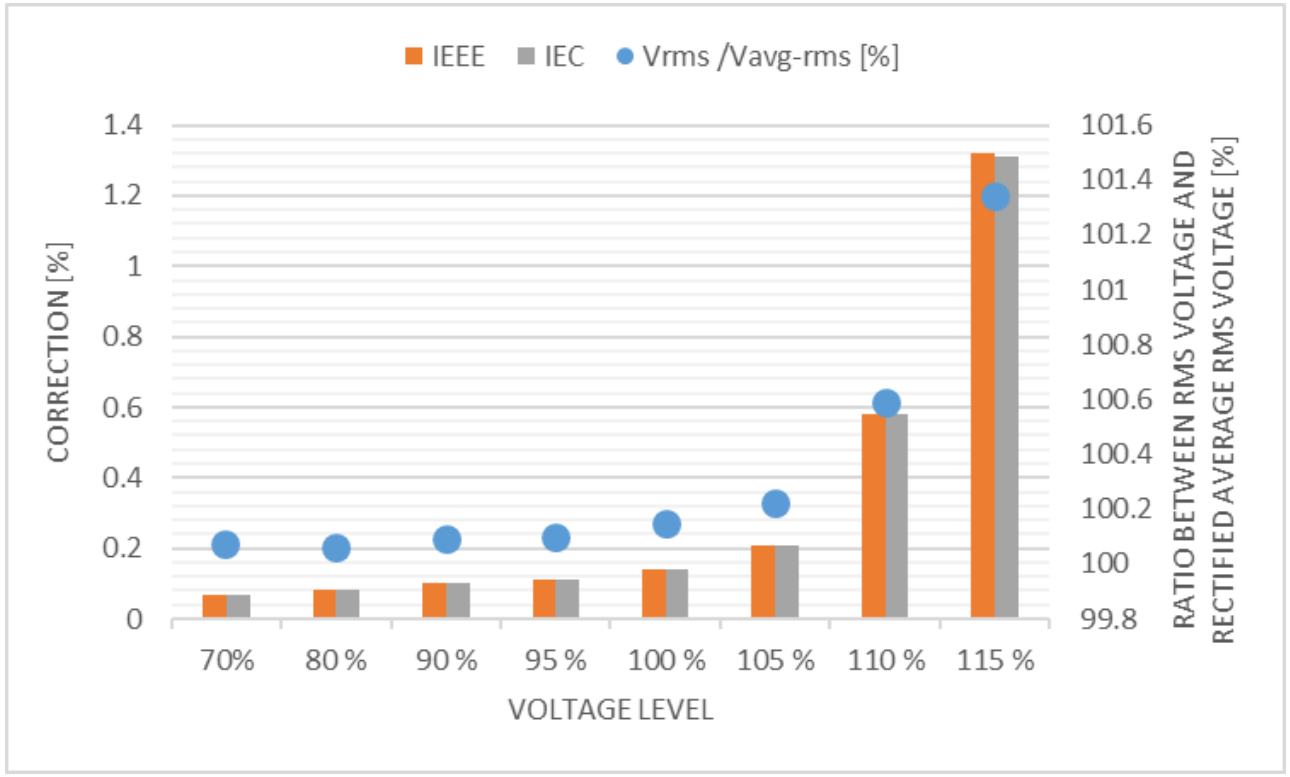




- With less than 5 % error in the voltage THD, the maximum 1.3 % IEEE/IEC correction values in the present NLL measurements will be accurate to 0.1 %.

Discussions

- Impact of non-sinusoidal waveforms on LMS accuracy



- Results of IEC and IEEE are very close.
- The maximum correction percentage is 1.32 % for 115 % voltage level.
- The minimum is less than 0.1 % for 70 % voltage level.

Summary

Harmonic analysis during NLL measurement of power transformers achieves:

- Accuracy: < 10 % for the harmonic power losses up to 1 kHz
- the maximum correction: ≈1.3 % (THD of 5.5 %), < 0.1 % (THD of 3.3%)
- Impact of measurement error: < 0.1% (5 % THD error), < 0.2 % (10 % THD error)
- Harmonic power: ≈ +0.1% (up to 105 % U_{rated}),
  -0.3 % (110 % U_{rated}) and -1.6 % (115 % U_{rated}) – generation!

THANK YOU!

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