CERN

Miguel Cerqueira Bastos
CERN, for POCPA-2016, Barcelona

High precision specification and test of power converters at CERN

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- Accuracy and uncertainty
- CERN power converter procurement strategy
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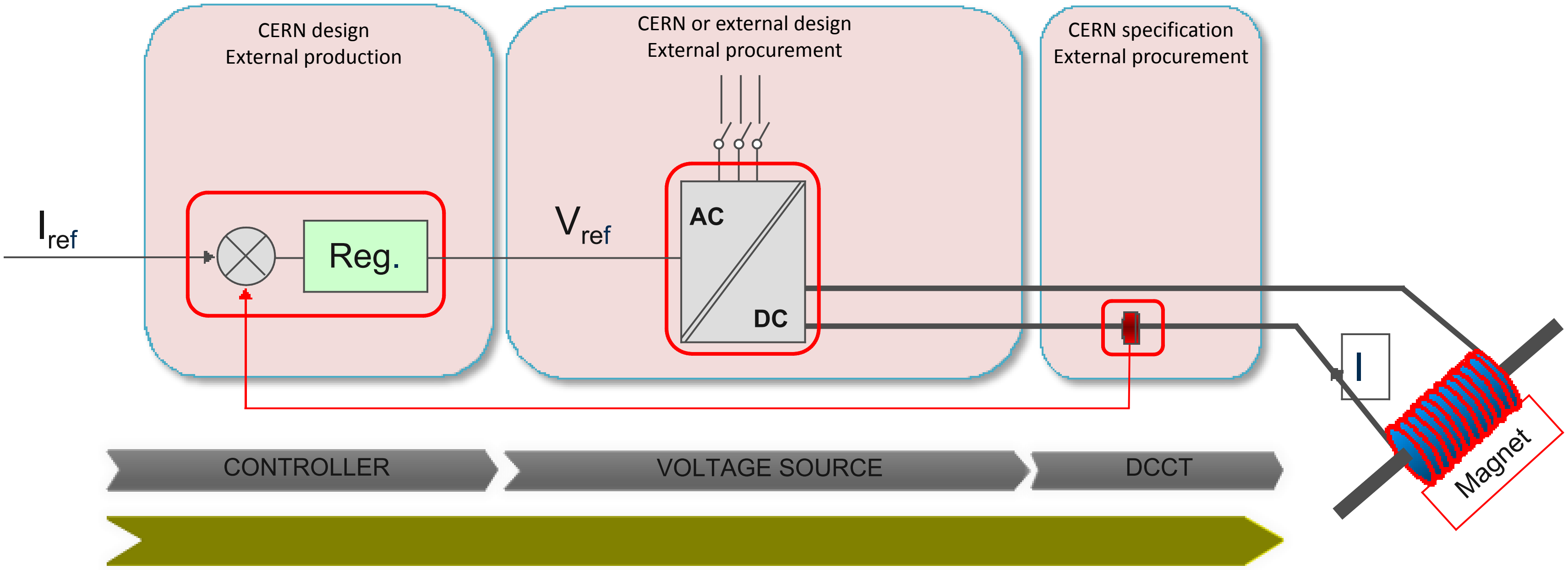
Accuracy and uncertainty

- This presentation uses ppm (part per million) of the converter nominal current
- "**Accuracy**" is a qualitative term: closeness of agreement between a test result and the accepted reference value
- "**Uncertainty**" is a non negative parameter that characterizes the dispersion of the quantity values
- For power converters
  - "**Accuracy**" can be used to characterize the Performance Class of converters
  - "**Uncertainty**" is the best term to numerically express the dispersion of the values of the current generated by the power converter

CERN procurement strategy



- The **Controller** is designed and produced by CERN
- The **Voltage Source** is designed/specified and procured by CERN
- The high-precision current sensors (**DCCTs**) are specified and procured by CERN

Specification of current source performance

- CERN does not procure current sources, only voltage sources
- Specification of current source is for internal CERN use:
  - A set of **requirements** for the **magnet current** is received from the physicists
  - A specification for the **power converter** (**current source**) can then be written
  - Based on the current source specification specifications for **DCCTs**, **controller** and **voltage source** can be written

Specification of power converter performance

- Often, a single requirement is given for magnet current performance, typically the acuracy class, eg “Precision: 100 ppm”, which can be insufficient
- Magnet current requirements are derived from beam performance parameters like **tune stability** for quadrupoles and **orbit variation** for correctors.
- As a consequence, important performance parameters are, in most cases **stability** (affected by **drift**) and **repeatibility** (affected by **noise**)

2.2 ELECTRICAL REQUIREMENTS

Table 1 — Circuits electrical requirements.

Parameter	Unit	LNR.MLSEA.0433
Total circuit Inductance	[mH]	1.7
Total circuit Resistance (cable not included)	[mΩ]	58
Total cable resistance	[mΩ]	95 Assuming 2x70m of UCA1S cable
Maximum operating current (Iop.max)	[A]	21.1
Minimum operating current (Iop.min)	[A]	0
Minimum ramping Time, from 0A to Iop.max or Iop.min.	[s]	1
Magnet applied common mode from operation configuration	[V]	None * *Magnet is not polarized vs ground by an external system
Required precision level given by operation at nominal current	[mA]	Maximum change of converter current of 5

Specification of power converter performance

- At least two parameters must be considered in the specification:
  - Maximum **Noise** (ppm pk-pk)
  - **Stability**, which can include:
    - Temperature dependant drift
    - Time dependant drift
- The conditions under which the requirements should be met must be specified:
  - **Bandwidth**
  - **Range of loads**
  - **Temperature range**
  - **Time frame** - often more than one time frame is given: 30min, 24h, 1 year

Specification of power converter performance

- Requirements given by the physicists can be assumed to be maximum limits
- To ensure compliance to those requirements, **maximum** values must be used in our specification
- When testing many converters, performance distribution will be gaussian, so in order to **guarantee** compliance, performance of all units must be **verified** and non compliant units **rejected**

- **Performance testing** is essential to ensure compliance with requirements
- Specification must allow for a good **margin** with respect to requirements, in order to minimize the number of rejected units
- Margins depend on application: cost, feasibility, effort, criticality

Specification of voltage source performance

- Procured in industry: a performance requirement specification must be written
  - The Voltage Source must undergo **acceptance tests to validate performance!**
- Important specification parameters:
  - **Output noise**: frequency domain, time domain

7.3.4.2 Output voltage frequency-domain noise

The Power Supply conducted noise emissions measured at the output terminals shall be lower than the mask level shown in Figure 20, both for differential and dissymmetrical mode noise, regardless of the Power Supply state or output power and voltage levels while running. Quasi-peak measurement is required for all the measures in the range.

7.3.4.3 Output voltage time-domain noise

The Power Supply differential and dissymmetrical voltages measured in time-domain shall not be greater than 150 $mV_{peak\text{-}peak}$, in all the operating conditions and all the loads described in §7.3.1. The time-domain ripple measurement shall be performed as shown in Figure 21 (the FFT module is not needed in this case)

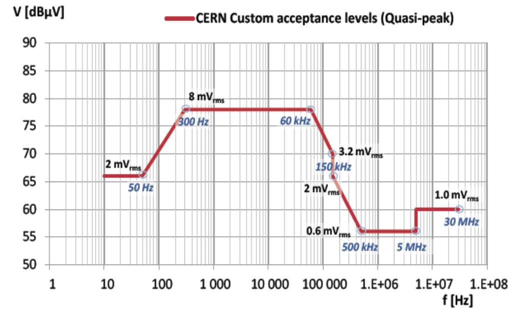


Figure 20: Output RMS voltage mask (differential and dissymmetrical mode).

More on this a few slides ahead!

Specification of voltage source performance

- **Controllability:** Resolution, regulation uncertainty, gain error

7.3.3.1 Uncertainty and controllable range

The voltage loop regulation shall deliver the same performance under any operating conditions (e.g. variations in the load, in the AC mains).
Desired ratio between the reference signal and the output quantity is $V_{OUT} / V_{REF} = 5$.
Non linearity typically due to down time and low level gain variation shall be compensated or eliminated.
The static V_{OUT} / V_{REF} function shall be continuous in the whole controllable range.
Slope error and uncertainty levels for the voltage regulation are shown in Table 13, and in Figure 15.

Description	Value	Detail
DC output voltage regulation uncertainty (including gain, T drift, DC offset, …)	±1 % of V_{NOM}	Uncertainty of the DC output voltage level
Static V_{OUT} / V_{REF} slope error	±10 % of V_{OUT} / V_{REF}	First derivative error on the V_{OUT} / V_{REF} ratio

Table 13: Voltage regulation uncertainties.

- **Load:** Load range

7.3.1 Loads specification

The Power Supply shall be stable under the possible loads combinations (resistance R in series with inductance L) reported in Table 11.

R	L
Ω	H
[0.01; 1]	[0; 0.2]

Table 11: Load range.

- **Dynamics:** Step response, Slew rate, Bandwidth

Specification of voltage source performance

- Specification of voltage source must take into account the current loop design and the expected range of loads, because:
  - Power converter noise below the **current loop bandwidth** is mostly determined by the current loop
  - Power converter noise above the **current loop bandwidth** is mostly determined by the **load** and the voltage source noise
- So, two different frequency ranges must be considered for the specification:
  - Below the current loop BW
  - Above the current loop BW

These two ranges normally overlap but we will ignore the overlap in this presentation, for sake of simplicity

Specification of voltage source performance

Limitations of the present specification

- Frequency domain limits are based on existing EMC standard *IEC-478-3** extended below 9kHz by CERN: not adapted to load and to performance requirements
- Time domain specification intended to cover for occasional spikes but not adapted to the load and to performance requirements
- **How to adapt the voltage source specification to reach the desired current performance ?**

** IEC-478-3 › Stabilized power supplies, d.c. output. Part 3: Reference levels and measurement of conducted EMI*

Specification of voltage source performance

Voltage noise specification: A proposal...

1. Requirement for maximum current noise in time domain ($I_{max\ p\text{-}p}$)
2. Consider the fastest load from specified range of loads: worst case !
3. Test/Measurement BW based on performance requirements and load:

E.g. FS voltage perturbations ($\mathbf{R_{load}*I_{nom}}$) and **< 1ppm** current noise

⟶ BW should be **6x decades** above the **load frequency ω_0**

Specification of voltage source performance

Calculating the noise limits profile in frequency domain:

4. Current noise is assumed to be white and gaussian. A flat current noise density in A/$\sqrt{Hz}$ can be calculated over the BW

5. The current noise density can be scaled to voltage by dividing it by the DC gain of the load transfer function (1/R)

6. A 20dB/decade shaping must be considered above the current loop BW, as the voltage perturbation attenuation by the load **increases** with frequency

7. A -20db/decade shaping is considered below the current loop BW (1 integrator) as the voltage perturbation attenuation **decreases** with frequency.

Note: A good approximation for the current loop BW is $I_{BW} = 10 \times \omega_0$

Specification of voltage source performance

Consider fload = 1Hz (L = 0.15H, R = 0.1R), on (200A, 50V) and required $I_{max\ noise}$ = 10ppm$_{p\text{-}p}$

1. $I_{max\ noise}$ = 10ppm$_{p\text{-}p}$, white gaussian noise, crest factor = 3 ⟶ $I_{max\ noise}$ = 1.5ppm$_{rms}$ (300µA$_{rms}$)
2. BW = 100 kHz (5 decades in order to ensure 100dB attenuation ⟶ 10ppm)
3. The load considered above is the fastest load for the application: f_{load} = 1Hz
4. Current noise density: 950 nA/$\sqrt{Hz}$ (300µA$_{rms}$/$\sqrt{100kHz}$)
5. Voltage noise density: 9.5µV/$\sqrt{Hz}$

6.,7. Response shaped at -20dB/decade below 10Hz and 20dB/decade above and combined with limits from *IEC-478-3* extended by CERN

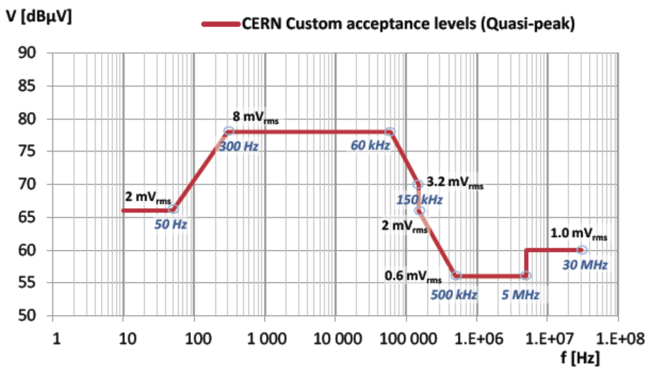
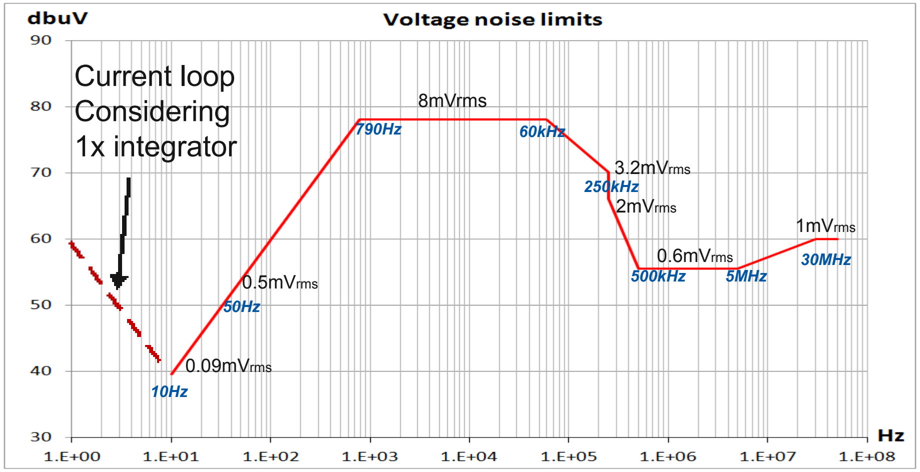


Figure 20: Output RMS voltage mask (differential and dissymmetrical mode).

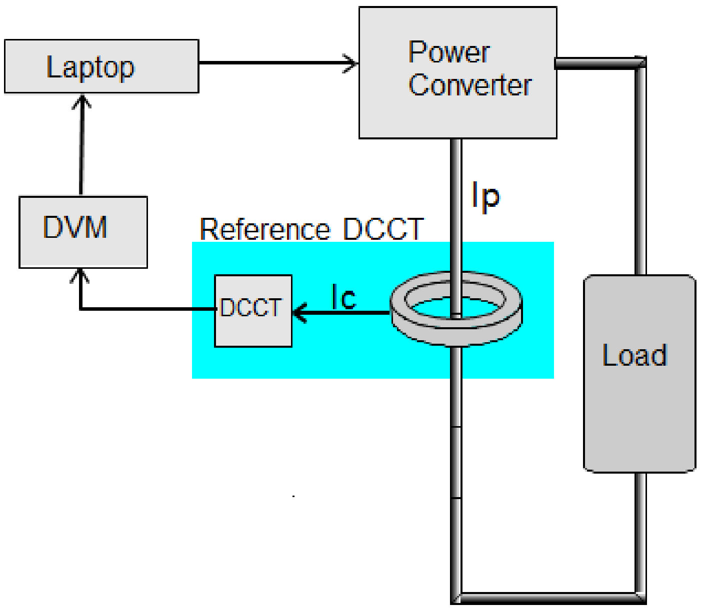


Power converter performance testing

- **Voltage source** performance tests
  - In addition to functional and EMC tests, performance tests must be carried out
  - Some of these tests can be performed at the factory
- **Power converter** performance tests
  - After integration of **voltage source** + **controller** + **DCCT** and tuning of current loop
  - Requires a test bed with a test load, **reference DCCT**, high precision DVM
  - Test load must have similar time constant as worst case final load

Power converter performance testing

- Reference DCCT connected to the output of the converter
- Reference DCCT assumed perfect, i.e. uncertainty negligible with respect to the target uncertainty of the converter
- Above a certain frequency the reference DCCT noise will be dominant (as PC noise is attenuated by the load) so DCCT baseline noise must be measured



Power converter performance testing

Typical power converter tests performed at CERN are listed below.

BW and time frame for the measurements depend on the application

1. Noise at zero or Imin

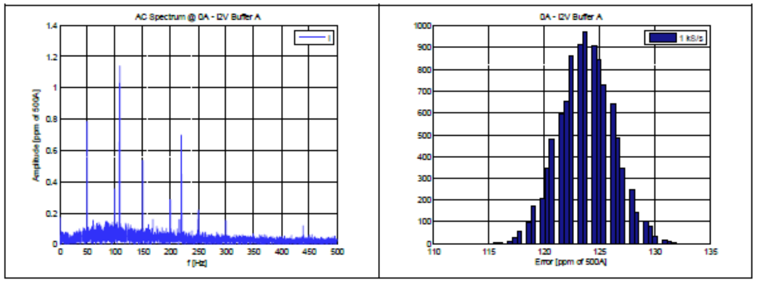
2. Stability at zero or Imin

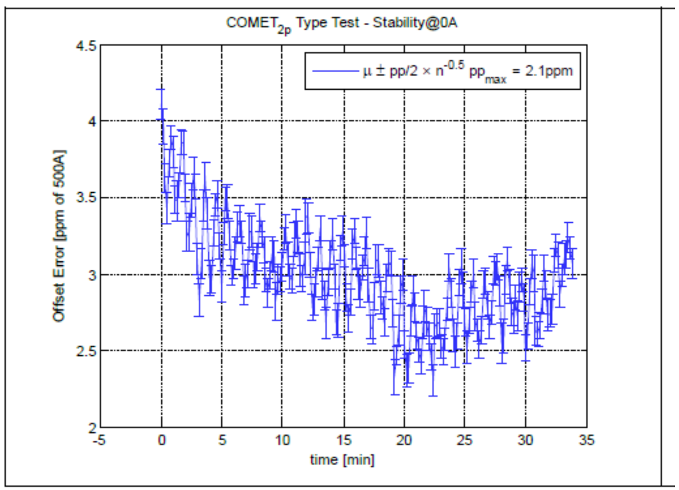
7.1.1. Noise at Zero

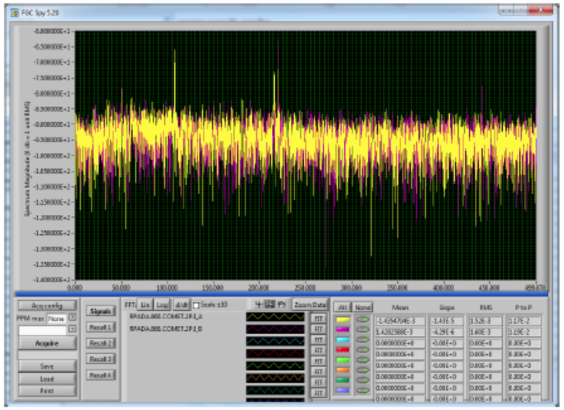
Performed on the internal DCCT A at I=0A @1ksps: 20.4 ppm pp FS

An Idle Tone can be observed around 108 Hz with an amplitude greater than 1ppm.

Idle Tones will be discussed in more detail in 9.6.

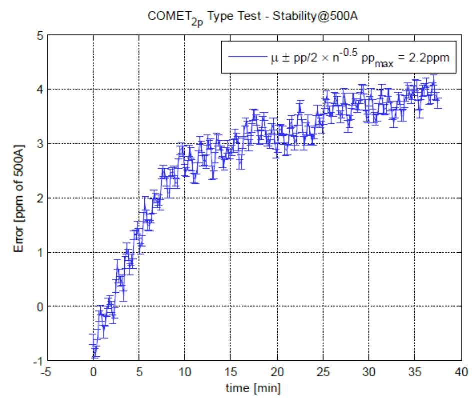






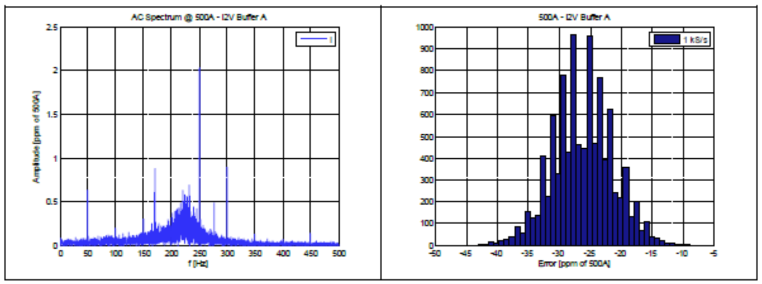
Power converter performance testing

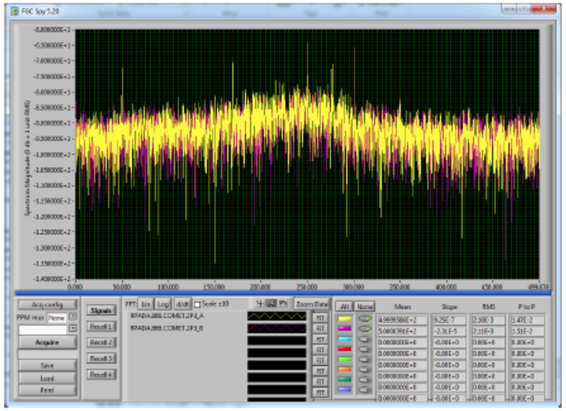
4. Linearity
5. Reproducibility at Inom
6. Noise at Inom
7. Stability at Inom



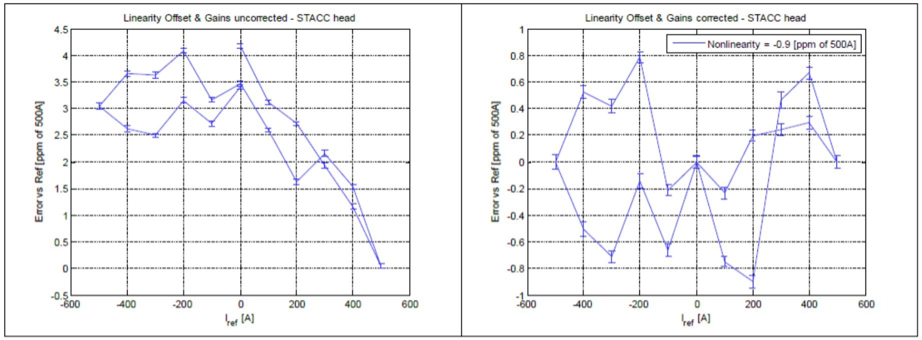
7.1.2. Noise at Ipos

Performed on the internal DCCT A at I=500A @1ksps: 40.1 ppm pp FS





The spectral line at 250 Hz is not present (or barely visible) for value of current less than 400A.



Power converter performance testing

- After the tests a **performance "datasheet"** of the converter can be prepared
- The datasheet states the **worst case** expected performance for each parameter
- The table below show the results from a set of performance tests, **stability** and **noise** can be used to prepare a datasheet

	Desired Performance	Measured Performance
Noise at zero (1ksps)	30 ppm p-p (*)	20.4 ppm p-p
LF Noise at zero	5 ppm p-p	3.4 ppm p-p
Stability at zero	5 ppm p-p	1.7 ppm p-p
Offset error	10 ppm	3 ppm
Noise at Ipos (1ksps)	30 ppm p-p (*)	40.1 ppm p-p
LF Noise at Ipos	5 ppm p-p	2.6 ppm p-p
Stability at Ipos	20 ppm p-p	1.1 ppm
LF Noise at Ineg	5 ppm p-p	2.2 ppm
Stability at Ineg	20 ppm p-p	2 ppm p-p
Gain error at Ipos	20 ppm	4 ppm
Gain error at Ineg	20 ppm	-5.5 ppm
Repeatability	5 ppm p-p	4 ppm p-p
Linearity	5 ppm	-0.9 ppm Corrected

Conclusions

- Magnet current performance requirements are often a single value
- A power converter performance requirement specification must contain at least **stability** and **noise** requirements for a given BW, load, temperature, time
- Based on the power converter specification a DCCT, controller and voltage source performance requirement specification can be written
- **Performance tests** are essential to guarantee performance within requirements
- A **performance "datasheet"** of the converter can be prepared based on the performance test results