CERN

Miguel Cerqueira Bastos
CERN, for POCPA-2016, Barcelona

High precision specification and test of power converters at CERN

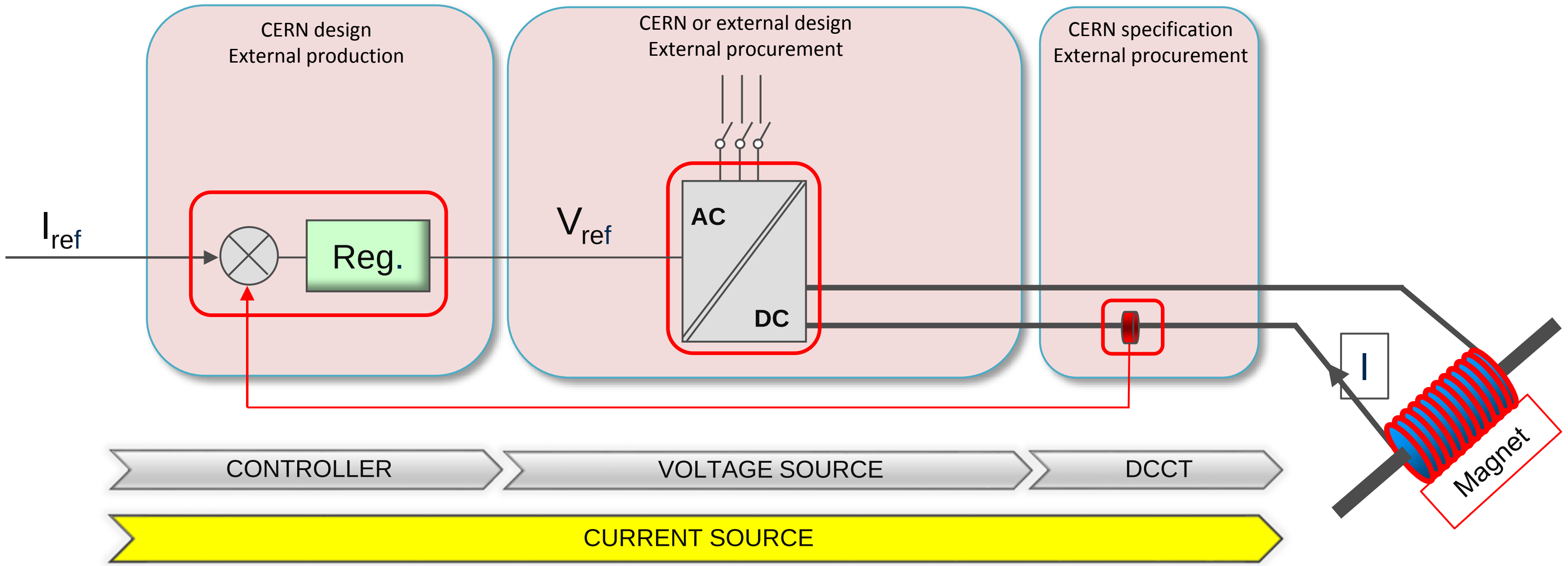
Contents

- Accuracy and uncertainty
- CERN power converter procurement strategy
- Specification of power converter performance
- Specification of voltage source performance
- Power converter performance testing
- Conclusions

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 a **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 are used
- 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

- In case of a CERN design, CERN is responsible for the performance
- In case of an external design, performance requirements must be specified
  - 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)

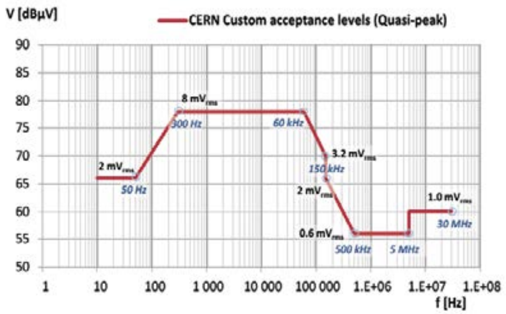


Figure 20: Output RMS voltage mask (differential and dissymmetrical mode).

More on this
a few slides ahead!

Specification of voltage source performance

- **Uncertainty and Controllability:** Resolution, 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 specification:** 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.

- **Dynamic specification:** Step response, Slew rate, Bandwidth

Specification of voltage source performance

- Specification must ensure the required performance can be reached:
  - For the required **range of loads**
  - For the expected **current regulation loop** (target BW, target uncertainty)
- Two different frequency ranges must be considered for the specification:
  - Within the **current loop BW**
    Current noise is mostly determined by the current regulation loop
  - Above the **current loop BW**
    Current noise is determined by the voltage source noise and by the load.

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 our load and requirements
- Time domain specification intended to cover for occasional spikes but not targeted for the load and the requirements of the application
- **How to adapt our voltage source specification to allow us to reach the required performance on the current loop?**

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

Specification of voltage source performance

A proposal…discussion ongoing…

Conditions:

1. Requirements for maximum current noise in time domain:
   Maximum p-p noise and test/measurement BW

2. Test/ Measurement BW depends on performance requirements:
   To obtain **<1ppm** current noise for voltage perturbations **up to R_{load}*I_{nom}**
   BW should be **6x decades above ω_0**

3. The load shall be the fastest from specified range of loads: worst case !

Specification of voltage source performance

A proposal...discussion ongoing...

Calculation:

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

5. Noise density can be scaled to voltage, by dividing it by the DC gain of the LR circuit transfer function (1/R)

6. Finally the a -20dB/decade attenuation is considered, in order to obtain the voltage noise density profile required for the desired current noise

7. Below the current loop BW (a good assumption is I_{BW} = 10 x ω_0), the voltage noise depends on the current loop. A 20dB shaping is assumed (1 integrator)

Specification of voltage source performance

For f_{load} = 1Hz (L = 0.15H, R = 0.1R), 200A, 50V converter with 10Hz current loop

1. Max current noise = 10ppm p-p, gaussian → I_{noise} ~ 1.5ppm$_{rms}$ (300 µArms), crest factor = 3
2. BW = 100kHz (5 decades, in order to ensure 100dB attenuation → 10ppm)
3. Worst load is L = 0.15H, R = 0.1R, f_{load} = 1Hz
4. Current noise density: 300nA rms
5. Voltage noise density: 3µV rms

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

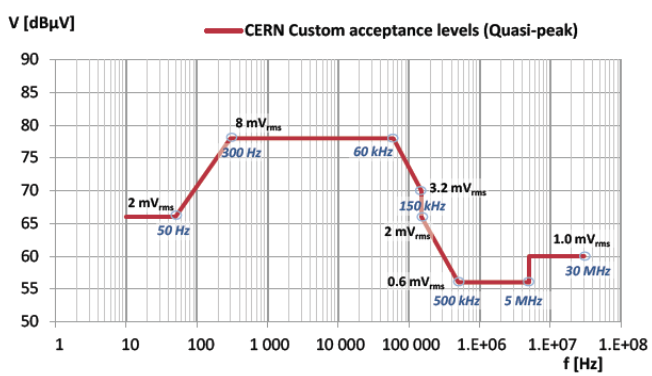
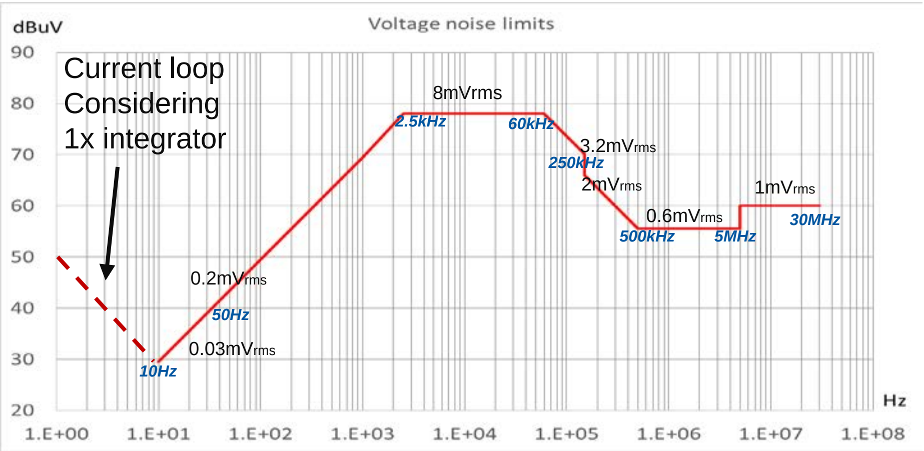


Figure 20: Output RMS voltage mask (differential and dissymmetrical mode).



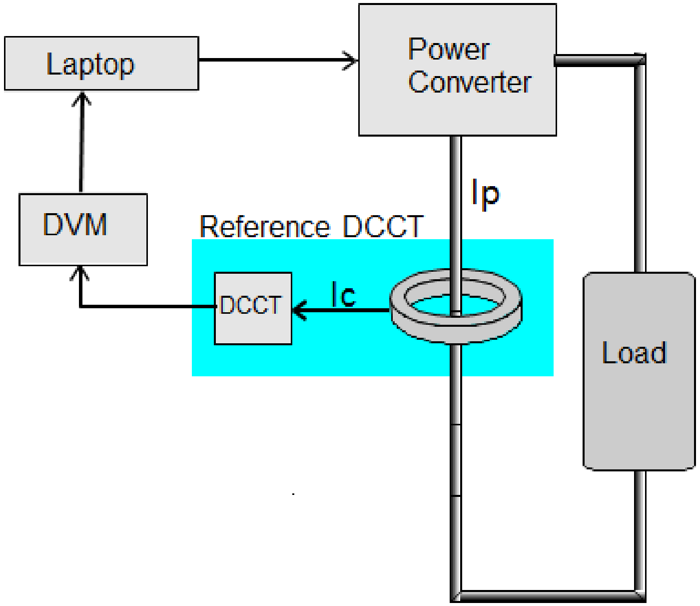
This results in tighter performance limits for the voltage source, down to 0.03mVrms (600ppm of 50V) at 10Hz... Difficult to measure !!

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
  - Performed after integration of controller + DCCT and tuning of current loop
  - Test bed with 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



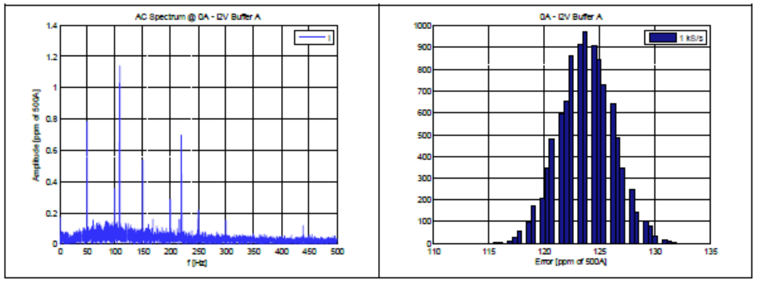
Power converter performance testing

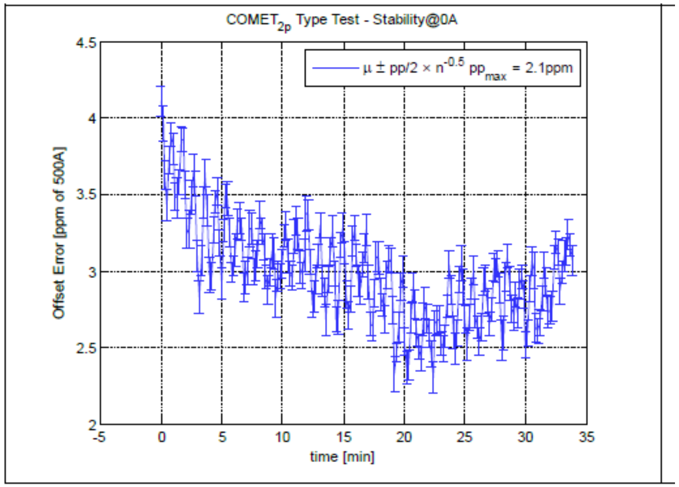
Typical power converter tests performed at CERN are listed below. BW and time frame for measurements depend on the application

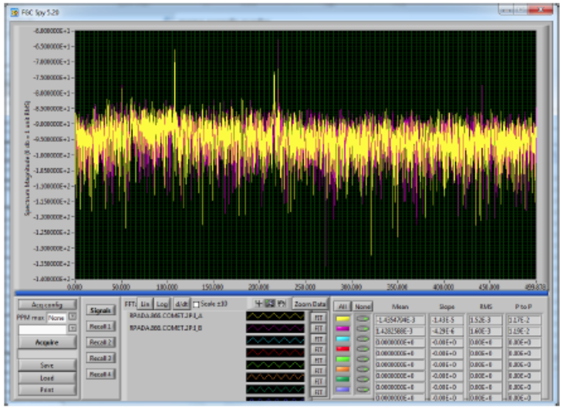
1. LF Noise at zero or Imin
2. Noise at zero or Imin
3. Stability at at zero or Imin

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

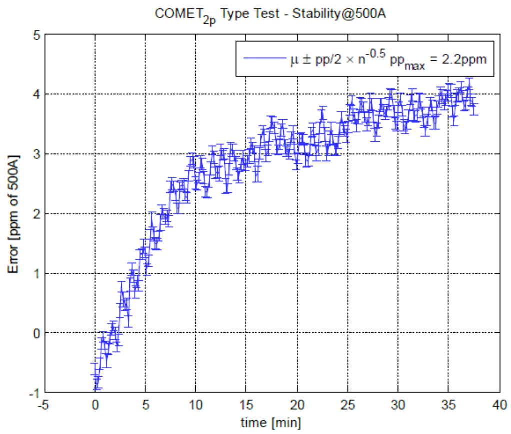
4. LF Noise at Inom

5. Noise at Inom

6. Stability at Inom

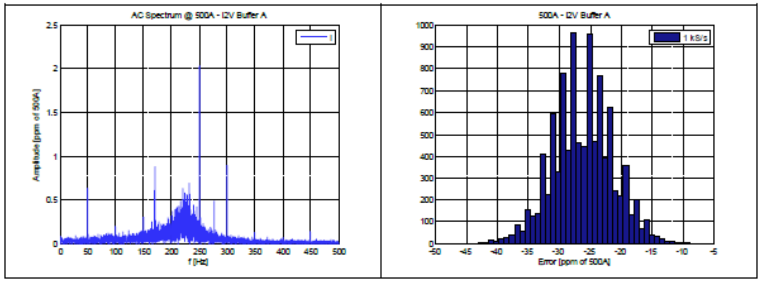
7. Linearity

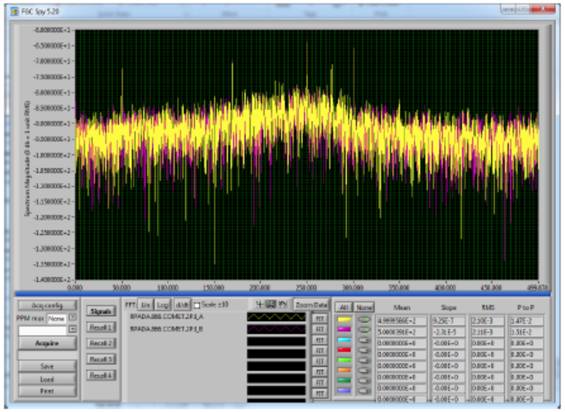
8. Reproducibility at Inom



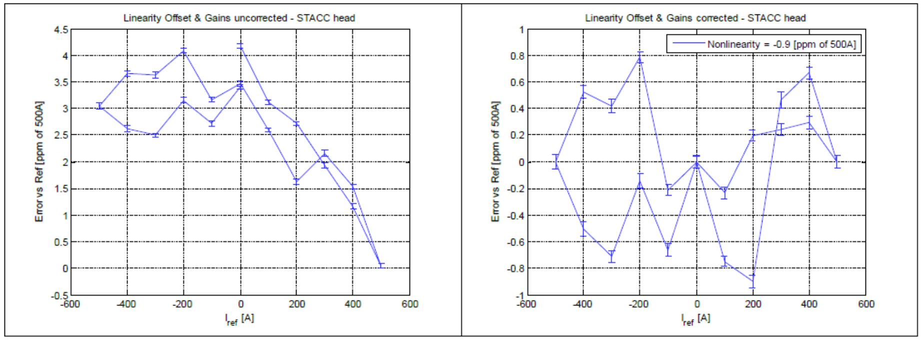
7.1.2. Noise at Ipos

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

- A **performance "datasheet"** of the converter, which describes what can be expected from the power 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 incomplete
- 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 written based on the performance test results