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High Precision Current Measurement in Power Converters

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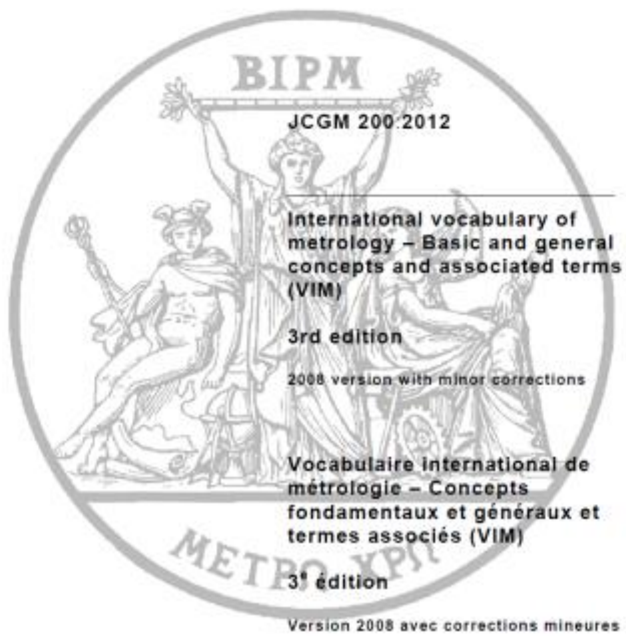
Metrology - some terms and definitions



Metrology - terms and definitions

- **Accuracy**

  Qualitative concept referring to the closeness of agreement between a measurement and:

  (i) The true value of the measurand (absolute accuracy)

  (ii) An accepted reference value (relative accuracy).

- **Uncertainty**

  Non-negative parameter characterizing the quantity values attributed to a measurand. It can be a standard deviation (or a multiple).

Both concepts include **Random** components and **Systematic** components.

Precision ≠ Uncertainty

Precision is the spread between measurements under the same conditions with no regard for the true value of the measurand.

Metrology - terms and definitions

The most common approaches to express uncertainty are:

- Represent each component of uncertainty by a **standard deviation**
- Combine the individual uncertainties to obtain a **combined uncertainty** using the “root-sum-of-squares” method: $\sigma^2 = \sigma_a{}^2 + \sigma_b{}^2$
- Multiply the combined uncertainty by a **coverage factor** k, to increase the **level of confidence**.

A coverage factor of k = 1, means 68.3% of the measurements are asserted to lie within the given uncertainty.

For a level of confidence of 95.5% corresponds a coverage factor k = 2.

Metrology - terms and definitions

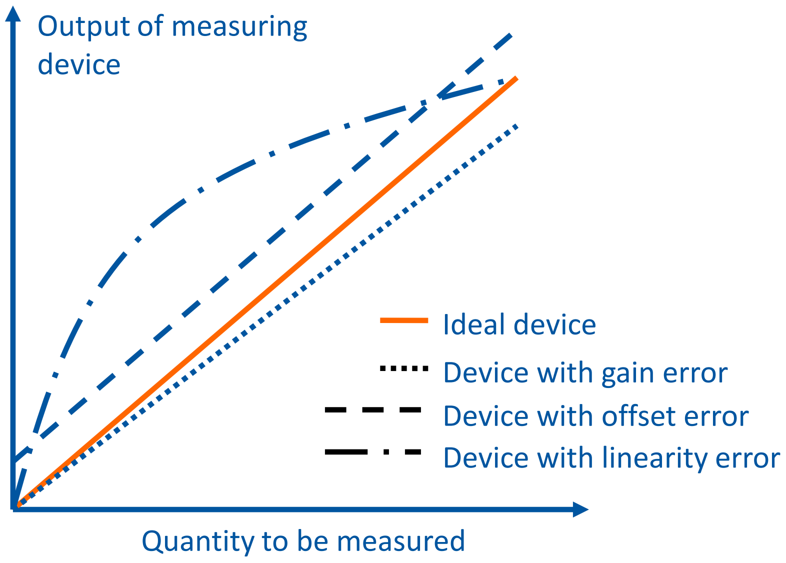
- In accelerator applications, a measurement's systems capability is often characterized in terms of **Gain** and **Offset** errors, **Linearity**, **Repeatability**, **Reproducibility** and **Stability**.

- **Repeatability** - closeness of agreement between s of successive measurements carried under the same conditions whilst **Reproducibility** is under changed conditions. In accelerators, this is often interpreted as different machine cycles.

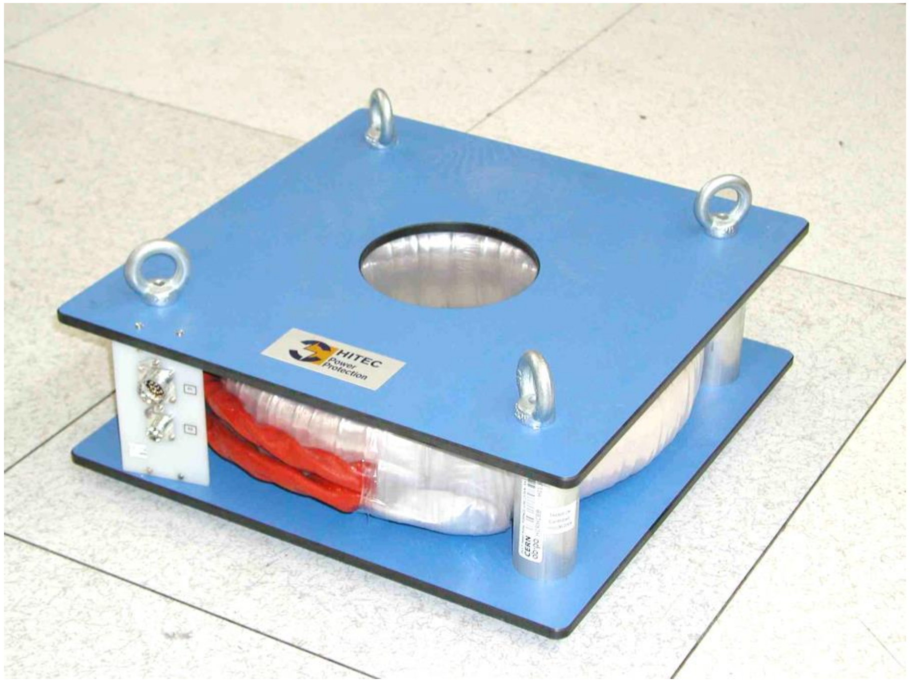
- The **Offset** and **Gain** errors refer to the systematic error at zero and full scale.

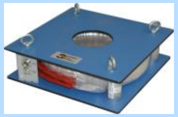
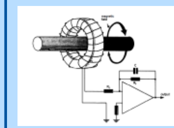
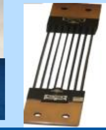
- **Linearity** describes a difference in the systematic errors throughout the measuring range.

- **Stability** can be defined as the change of measurement errors with time.

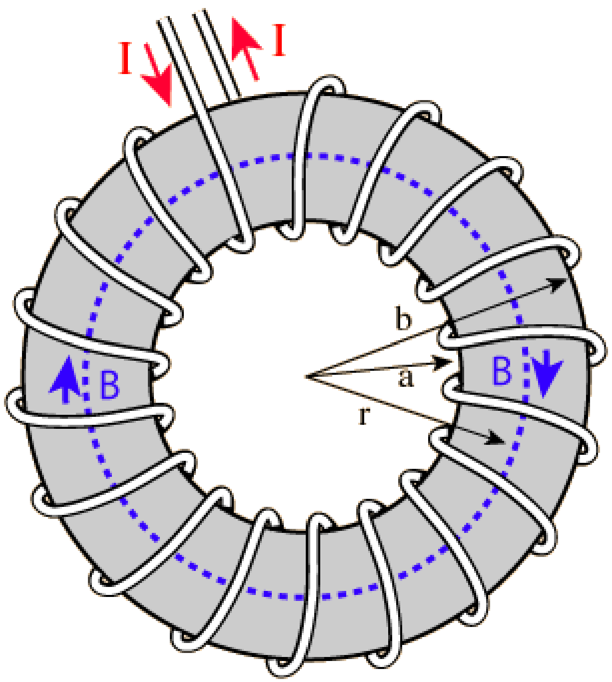


Current Measurement Devices



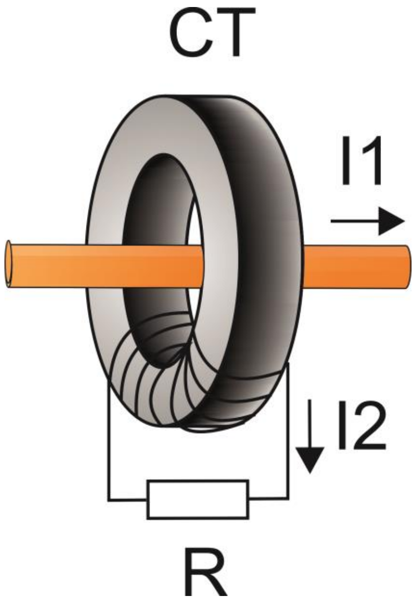
	DCCTs	Hall effect	CTs	Rogowsky	Shunts
	 		 	 	 
Principle	Zero flux detection	Hall effect	Faraday’s law	Faraday’s law	Ohm’s law
Output	Voltage and current	Voltage and current	Voltage and current	Voltage	Voltage
Accuracy	Best devices can reach a few ppm uncertainty	Best devices can reach 0.1% uncertainty	Typically not better than 1% uncertainty	Typically %, better possible with digital integrators	Can reach a few ppm for low currents, <% for high currents
Ranges	50A to 20kA	hundreds mA to tens of kA	50A to 20kA	high currents possible, up to 100kA	From <mA up to several kA
Bandwidth	DC ..kHz for the higher currents, DC up to couple hundred kHz for lower currents	DC up to couple hundred kHz	Typically 50Hz up to a few hundreds of kHz	Few Hz possible, up to the MHz	Up to hundreds of kHz with coaxial assemblies
Isolation	Yes	Yes	Yes	Yes	No
Error sources	**Magnetic** (remanence, external fields, centering) **Burden resistor** (thermal settling, stability, linearity, tempco) **Output amplifier** (stability, noise, CMR, tempco)	**Magnetic** **Burden resistor** **Output amplifier** **Hall sensor stability** (tempco, piezoelectric effect)	**Magnetic** (remanence, external fields, centering, magnetizing current) **Burden resistor**	**Magnetic** **Integrator** (offset stability, linearity, tempco)	Power coefficient, tempco, ageing, thermal voltages

Current Measurement Devices
- theory of operation -



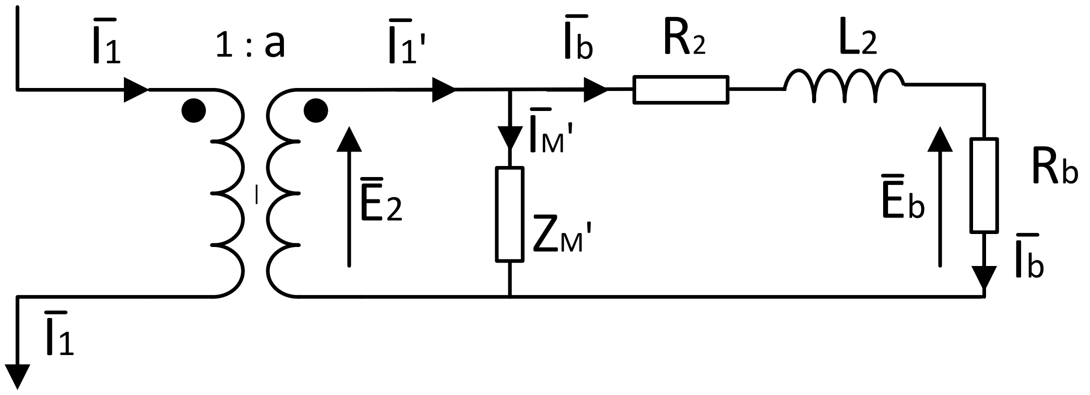
Current transformers

Current transformers are instrument transformers that produce, from an AC primary current, a proportional secondary current. The secondary winding is normally connected to a burden resistor to produce a measurable voltage signal.



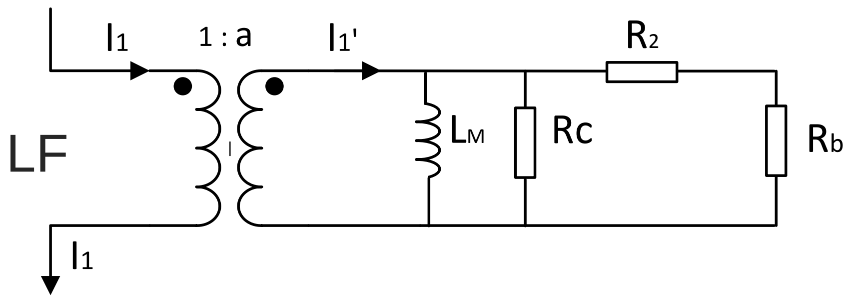
Current transformers

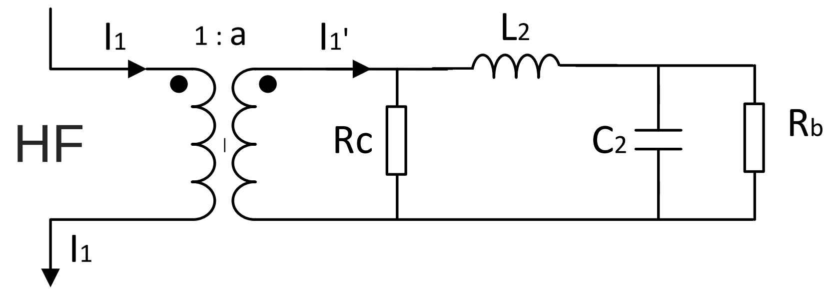
The simplified equivalent circuit, referenced to the secondary, of a current transformer is shown below:



- The **magnetizing current** causes an amplitude and phase error in the CT
- **Secondary leakage impedance** adds to the burden affecting the current distribution between I_M and I_b
- To improve accuracy => **magnetizing inductance** must be maximized and **leakage inductance** must be minimized (high μr, good winding distribution)

Current transformers - LF, HF models





$$f_{LF} = \frac{\omega_{LF}}{2\pi} = \frac{R_C || (R_b + R_2)}{2\pi L_M}$$

$$f_{p1} = \frac{\omega_{p1}}{2\pi} = \frac{1}{2\pi R_b C_2} \qquad f_{p2} = \frac{\omega_{p2}}{2\pi} = \frac{R_C}{2\pi L_2}$$

- To extend the CT's low frequency response **magnetizing inductance** should be maximized -> high permeability cores (silicon steel, nickel alloy)
- The high cutoff frequency is determined mostly by **leakage inductance** and **stray capacitance** which, with some approximations, give origin to two real poles

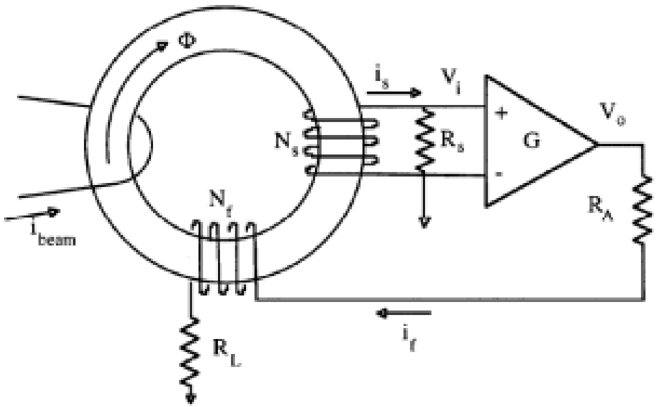
CTs - applications and limitations

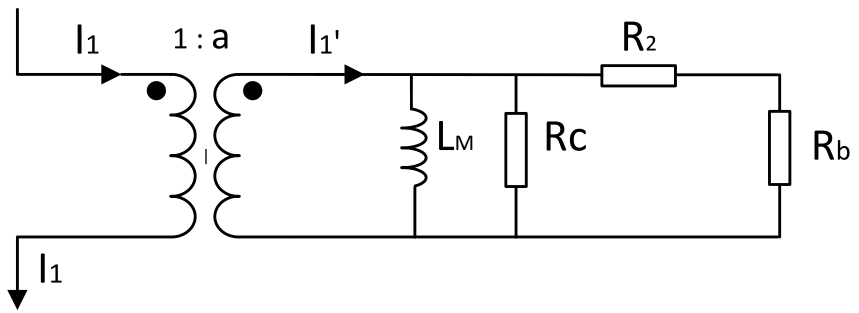
- CTs -> **% uncertainty** for AC and fast pulse current monitoring applications
- As the CT approaches **saturation**, magnetizing inductance decreases increasing the ratio error.
- External magnetic fields create a flux and therefore cause errors. External fields also put the CT closer to saturation - **magnetic shielding is crucial!**
- Limited LF response causes **droop** in pulse measurement applications

In the 60s, H.G. Hereward proposed an active current transformer circuit that used electronic feedback to extend the low frequency response of a CT and improve its accuracy.

Hereward transformer

- An active circuit senses the voltage across the burden and uses a **feedback loop** to produce a compensation current that keeps the **total flux in the cores** at zero.
- The compensation current is a fractional image of the primary current.
- The effect of the feedback is equivalent to increasing L_M by (A_L + 1), in which A_L is the open loop gain of the sensing amplifier => **improved accuracy**, **extended low frequency response**.

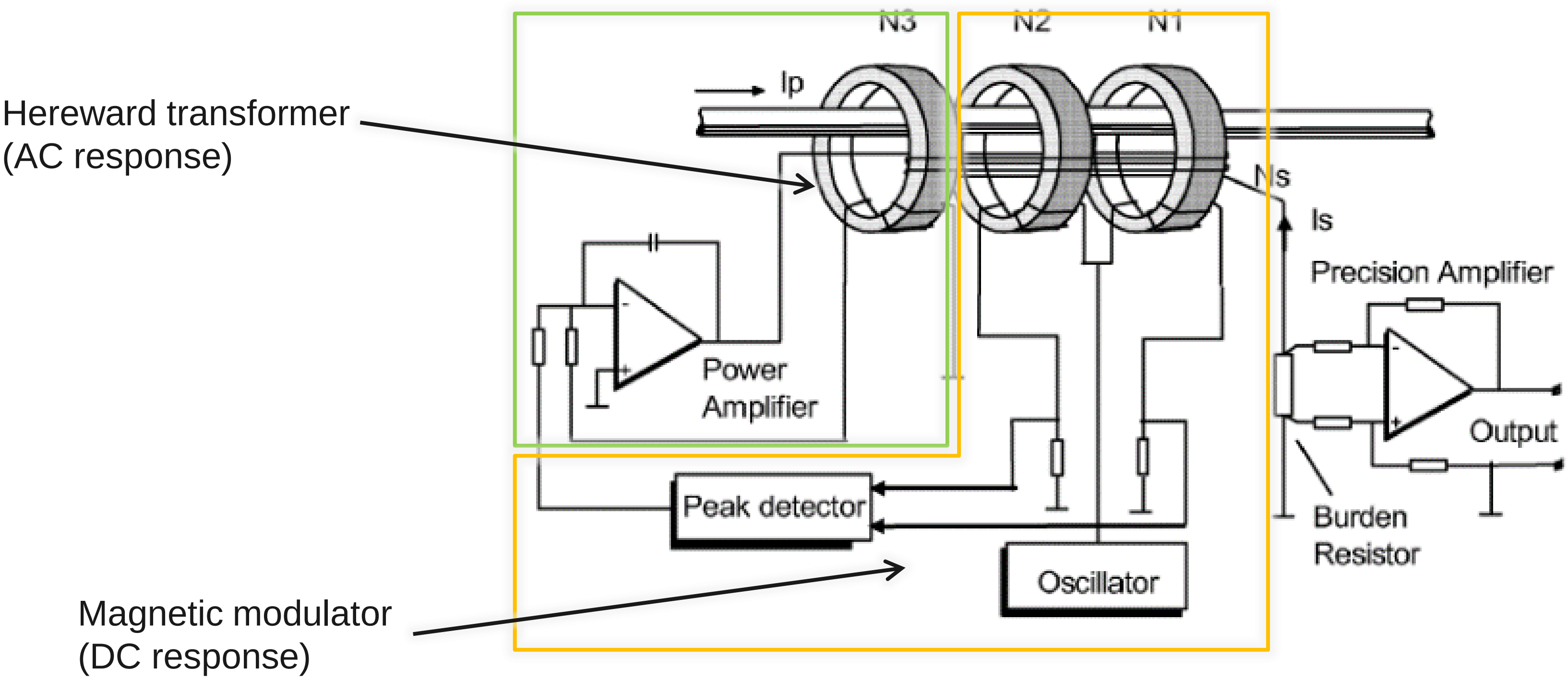




f_{LF} is reduced → $$f_{LF} = \frac{\omega_{LF}}{2\pi} = \frac{R_C||(\boldsymbol{R_b}+R_2)}{2\pi L_M}$$

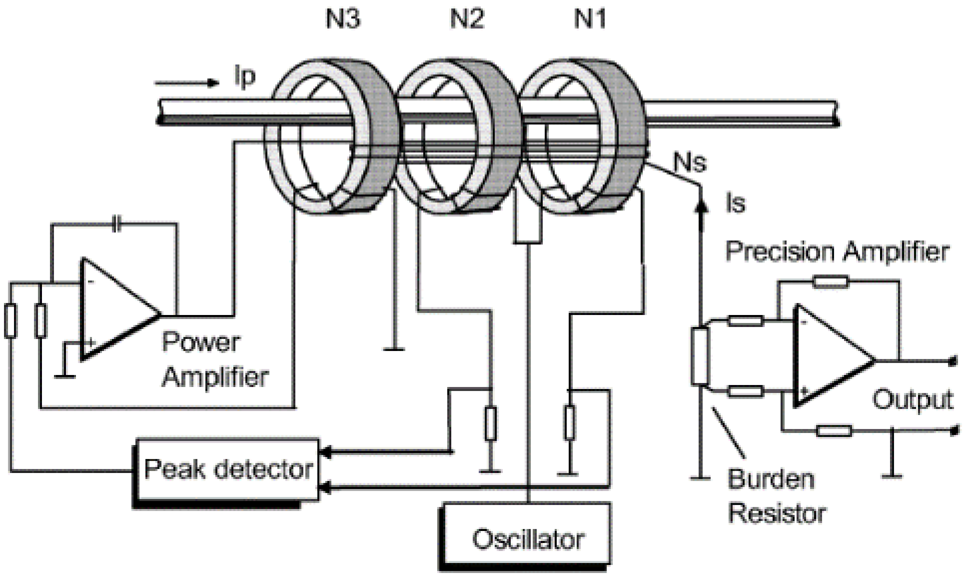
DCCTs

In the **DCCT** (Direct-Current Current Transformer) this principle is taken further and combined with the **magnetic modulator** principle (used since the 30's in fluxgate magnetometer) to provide an accurate measurement of currents ranging from DC to a few hundred kHz.



DCCTs - theory of operation

- The primary current generates a magnetic flux seen by three cores. A **magnetic modulator** drives two of the sensing cores in and out of saturation. Current peaks are unequal if there is a DC flux in the cores.
- The current peak asymmetry is measured and combined with the **AC component** measured by the third core. A control loop generates a compensation current that makes the total flux zero. This current is a **fractional image** of the primary current.



DCCTs – understanding sources of error

Errors in DC measurements with DCCTs can come from:

- **Magnetic head**

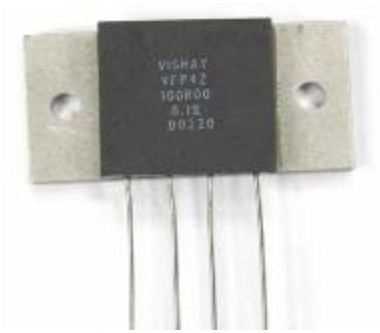
  Sensitivity to external magnetic fields, return bar, centering

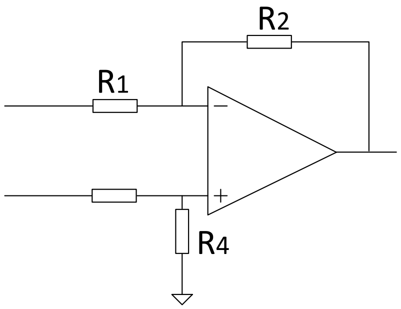
- **Burden Resistor**

  Gain error, settling at FS, stability at FS, linearity, gain TCR

- **Output difference amplifier circuit**

  Offset error, settling at zero, stability at zero, offset and gain TCR, noise, CMRR

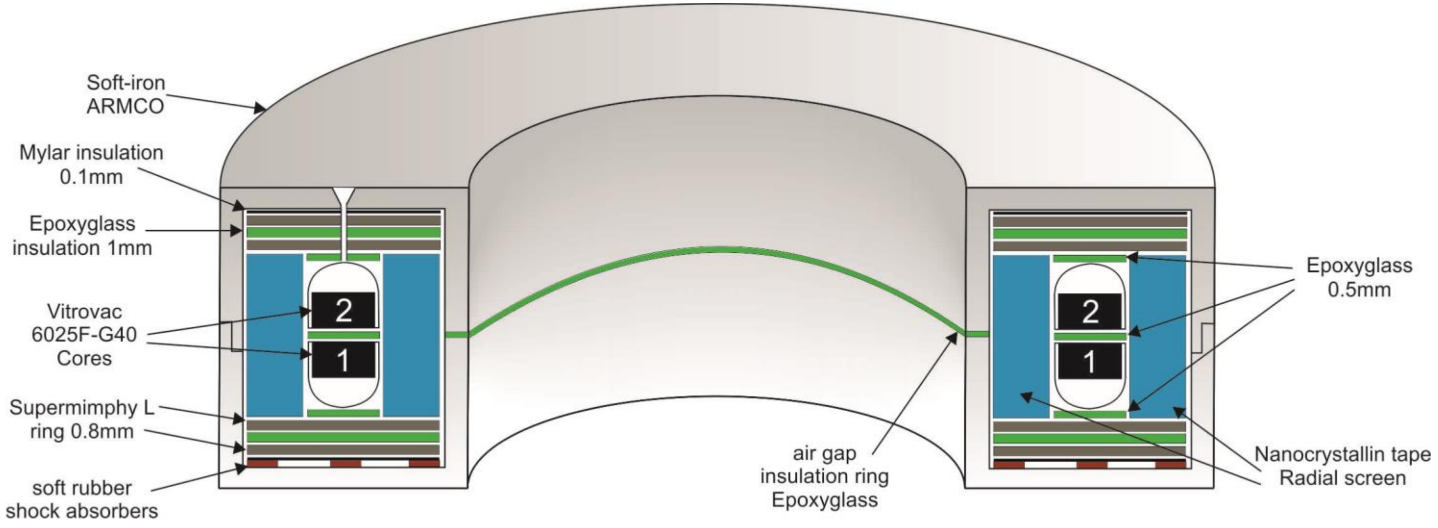




DCCTs - Magnetic head

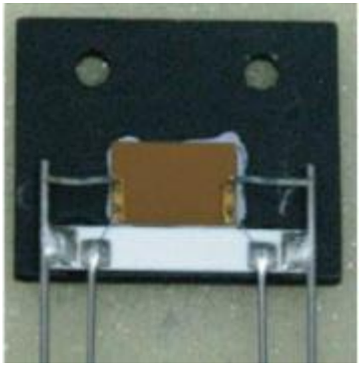
- **High permeability** tape-wound magnetic cores with **modulation windings**
- **Magnetic shielding** to protect the cores from external and leakage field
- Secondary windings

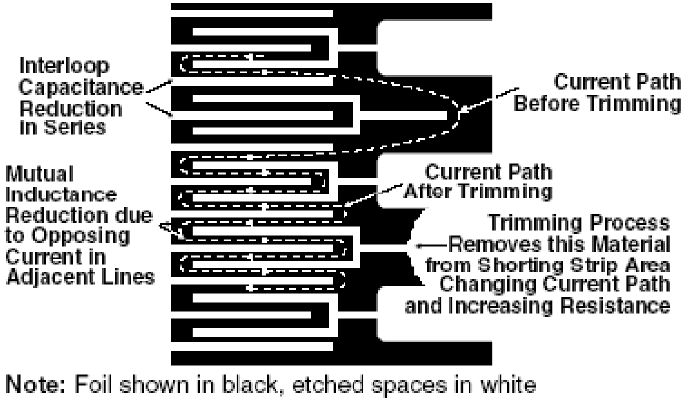
Other possible errors related to the magnetic circuit include offset and offset drift due to **remanence** as well as **modulation noise** due to poor matching of sensing cores.



DCCTs - burden resistor

- **4 wire** current sense resistor
- Basic accuracy requirement is **stability**!
- For power dissipation a **foil** is better than a **wire**. Common foil substrates are alumina and copper. A **film** deposited on a substrate is also a popular solution - thin film, thick film.
- **Tolerance and stability** do not always go together: processes that lead to tighter tolerance can result in degraded stability due to degraded power distribution and the creation of hotspots.





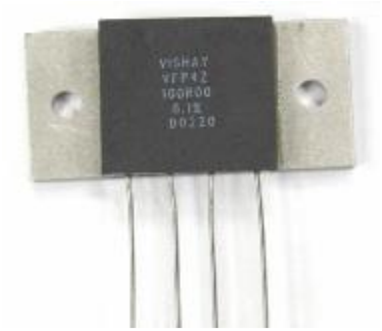
DCCTs - burden resistor

Well-known effects on resistance:

- Change of resistance with ambient temperature: **ΔT.TCR**
- Change of resistance with self-heating*: **P.θR.TCR**
- **Ageing**: causing long-term drift

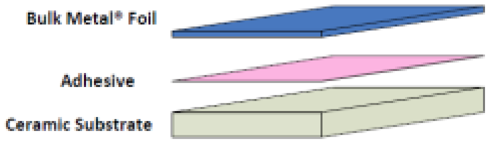
Less known effects:

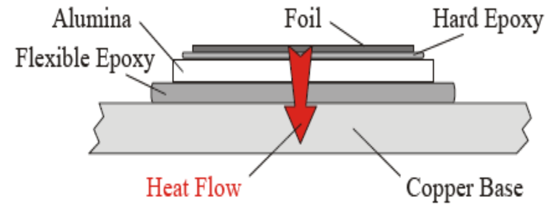
- **Power Coefficient of Resistance**: transient effect due to self heating*
- **Hysteresis** under power cycling
- **Humidity** absorption/ evaporation



* *Manufacturers treat these two effects together defining WCR as the total change in resistance due to self heating = P. WCR*

DCCTs - burden resistor

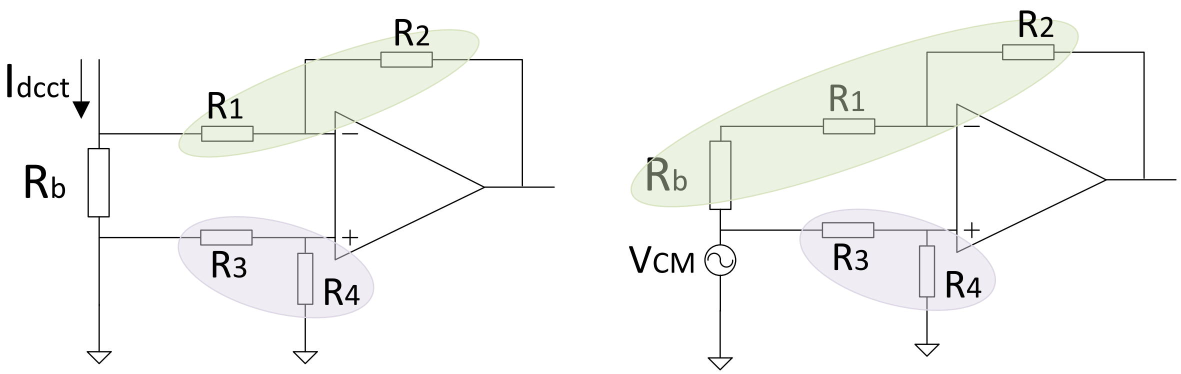




- **Bulk Metal Foil** resistor technology widely used in precision applications
- Rolled **metal foil** (NiCr) bonded to a **substrate**, usually Alumina.
- The foil/hard-epoxy/alumina combination is designed to give **zero TCR** to **ambient** changes of temperature: the foil TCR is compensated by **mechanical compression** due to the substrate's lower thermal expansion coefficient. Resulting TCR is close to zero.
- This works well when temperature changes occur in all layers equally. **However**, with dissipation in the foil, thermal gradients are different resulting in **over compression** of the foil and effective TCR turning more negative. The **Power Coefficient of Resistance** describes this effect.

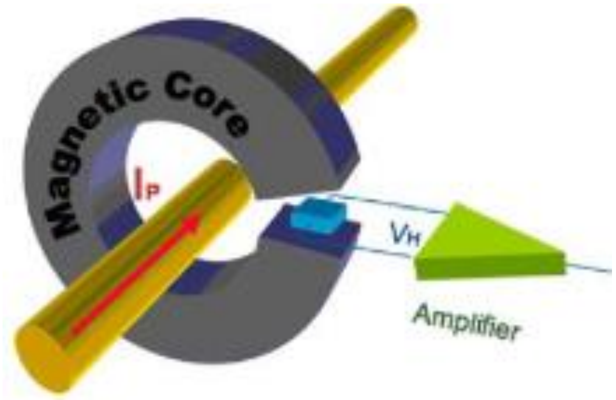
DCCTs – output amplifier

- **Difference amplifier** circuit normally used
- Some points to watch for:
  - Gain resistor **drift** – matched networks are a good solution
  - Common Mode Rejection
    - **Matching** of the gain ratios – matched networks are a good solution
    - Burden resistor affects matching of gain ratios
    - Gain adjustment can impact CMR – prefer **digital calibration**



Hall effect transducers

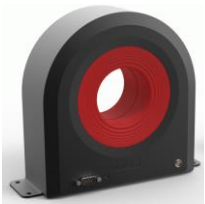
- **Hall effect current transducers**
  - **Open loop:** Hall probe placed in the air gap of a toroidal magnetic circuit. The magnetic flux generated by the primary current produces a hall voltage in the probe which is then amplified to produce the output signal.
  - **Closed loop:** Same principle but the Hall voltage voltage is used in a closed loop to generate a compensating current which is an image of the primary current



Hall effect transducers

- **Accuracy** – Closed loop models are better although limited to 0.1% uncertainty (1% for open loop models) mostly due to stability of the Hall probe. Sensitivity to EMI can also be an issue.
- **Bandwidth** – Core geometry, thickness of laminations, core material and hall chip impact the bandwidth of open loop probes, typically not better than 50kHz. Closed loop probes go up to 200kHz.
- **Output signal** - Closed Loop transducers generally provide a current output. Open loop usually provide an amplified voltage signal.

Current Measurement Devices Selection



Current measurement devices - selection

The choice of a current measuring device for a given application depends on various factors:

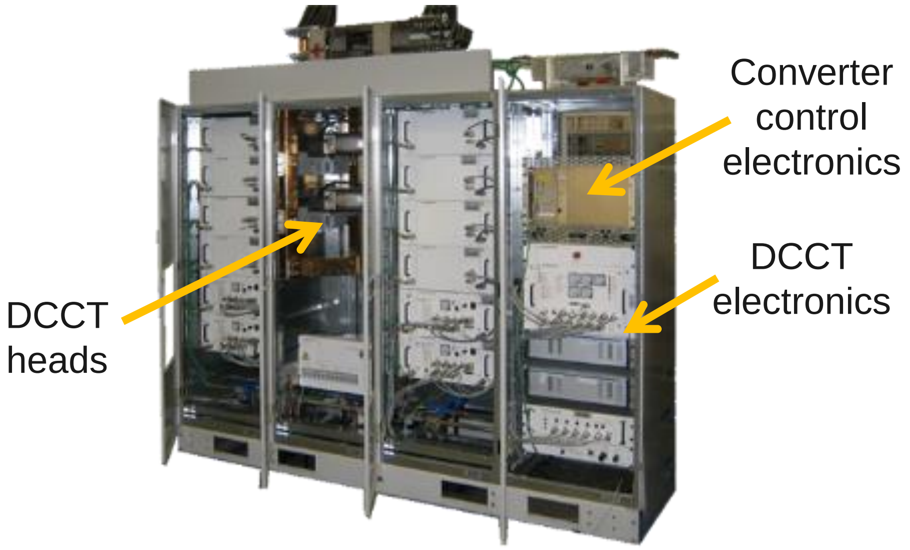
- **Type of application** (current range, bandwidth)
- Required **accuracy** (uncertainty)
- Required **output signal** (voltage, current)
- Need for **isolation** from primary current circuit
- **Reliability** (MTBF)
- **Installation** constraints
- **Availability** and **cost**

Current measurement devices - selection

High Current Applications: > 1kA

High Accuracy required

- **DCCTs -> high current dccts tipically better than 50ppm uncertainty**
  - Voltage outputs are mode common but current output are available with secondary currents ranging from 1A to 5A
  - Separated electronics and head: electronic chassis installed close to the converter control electronics minimizes transmission distances
  - Mains powered
  - Very good reliability
  - Higher cost, longer delivery times



Low Accuracy required

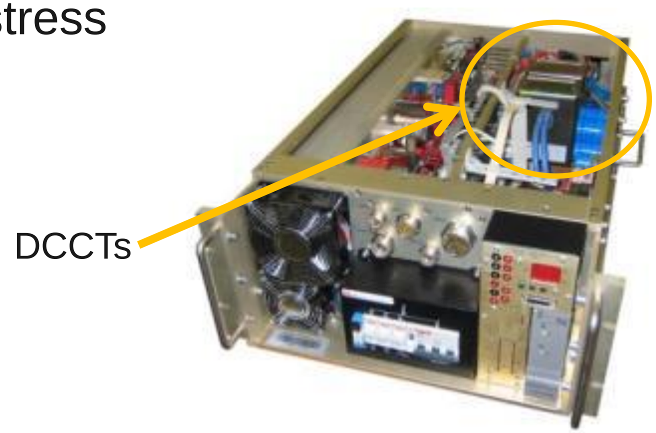
- **CTs, Hall Effect -> % uncertainty**

Current measurement devices - selection

Medium Current Applications: hundreds of Ampere

High to Medium Accuracy required

- **DCCTs -> available models offer better than 100ppm uncertainty**
  - Both voltage and current outputs available
  - Current output allows the designer to adapt the burden and amplifier choice and design to the required accuracy.
  - In most cases electronics and head are **integrated** and installed close to the power -> noisy environment, long distances -> **current** output can be a plus
  - DC powered, typically ±15V -> use **linearly** regulated voltages
  - Integration means higher density, more thermal stress
  - Lower cost, short delivery times



Low Accuracy required

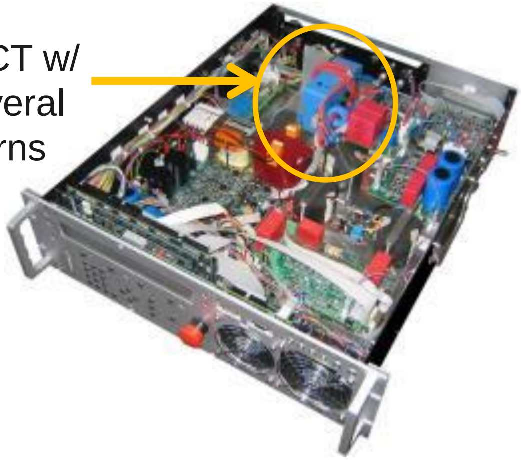
- **CTs, Hall Effect -> % uncertainty**

Current measurement devices - selection

Low Current Applications: < 100A

Medium, Low Accuracy required

- **Shunts, current sense resistors**
- **DCCTs -> tipically offer better than 200ppm measurement uncertainty**
  - Mostly current outputs available
  - Electronics and head are integrated
  - DC powered, typically ±15V -> use linearly regulated voltages when possible
  - In case higher accuracy is needed use a medium current DCCT with multiple primary turns
  - Some PCB mounted models



Low Accuracy required

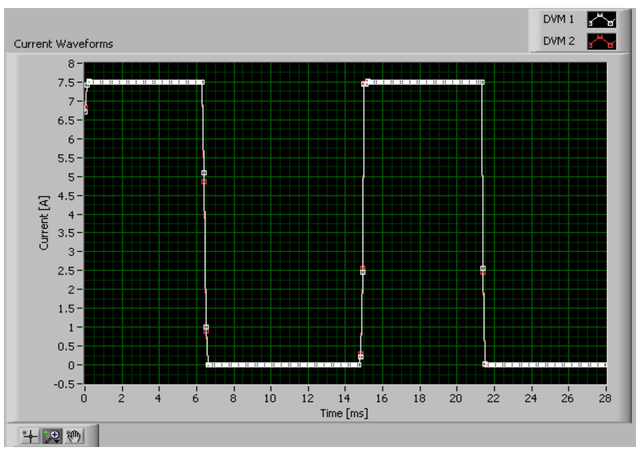
- **CTs, Hall Effect, Shunts -> % uncertainty**

Current measurement devices - selection

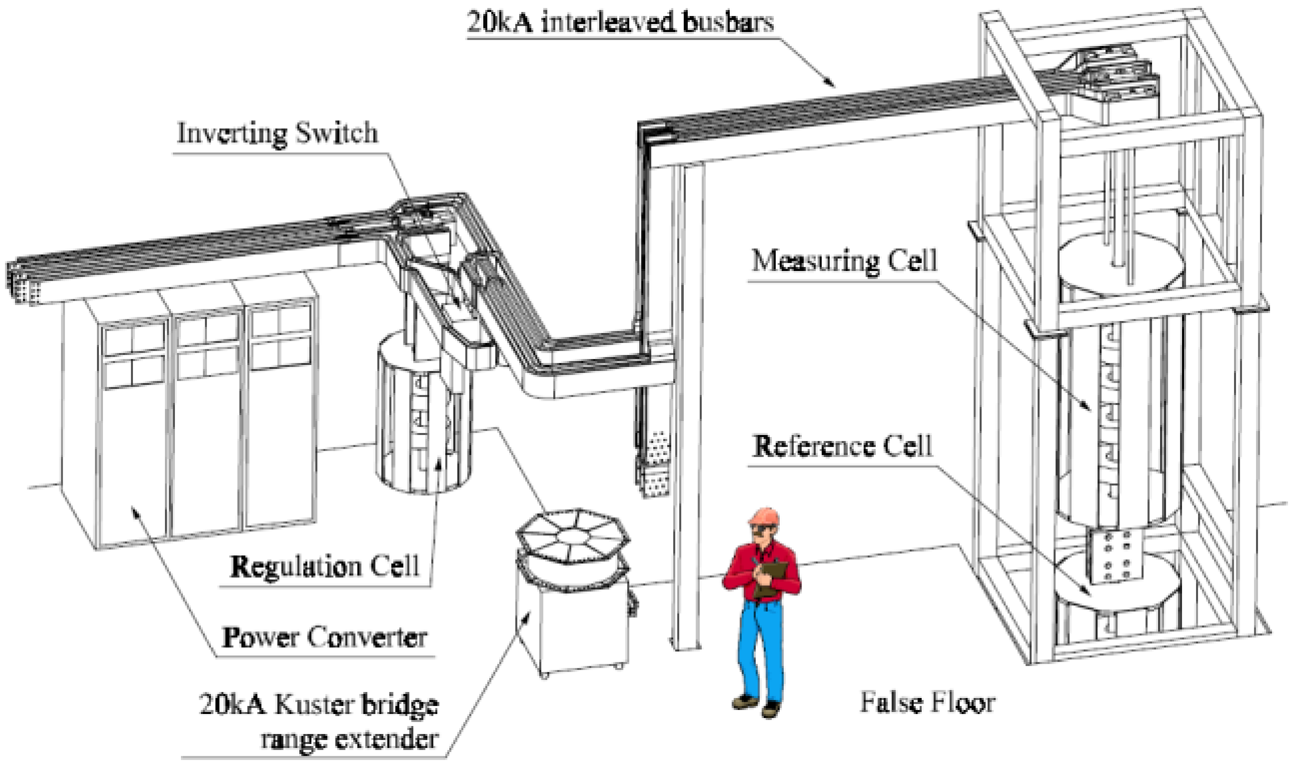
Fast Applications (>ms pulses)

If high acuracy needed

- **DCCTs**
  - DCCT **small signal bandwidth** can go up to few hundred kHz
  - **Modulation voltage noise** at the output of the DCCT and voltage induced in the primary can be a problem in fast applications
  - RMS noise given in datasheets for different frequency ranges but **crest factor** is normally quite high due to saturation peaks - **look at p-p instead**

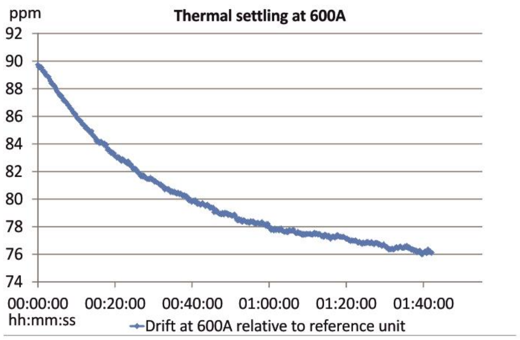


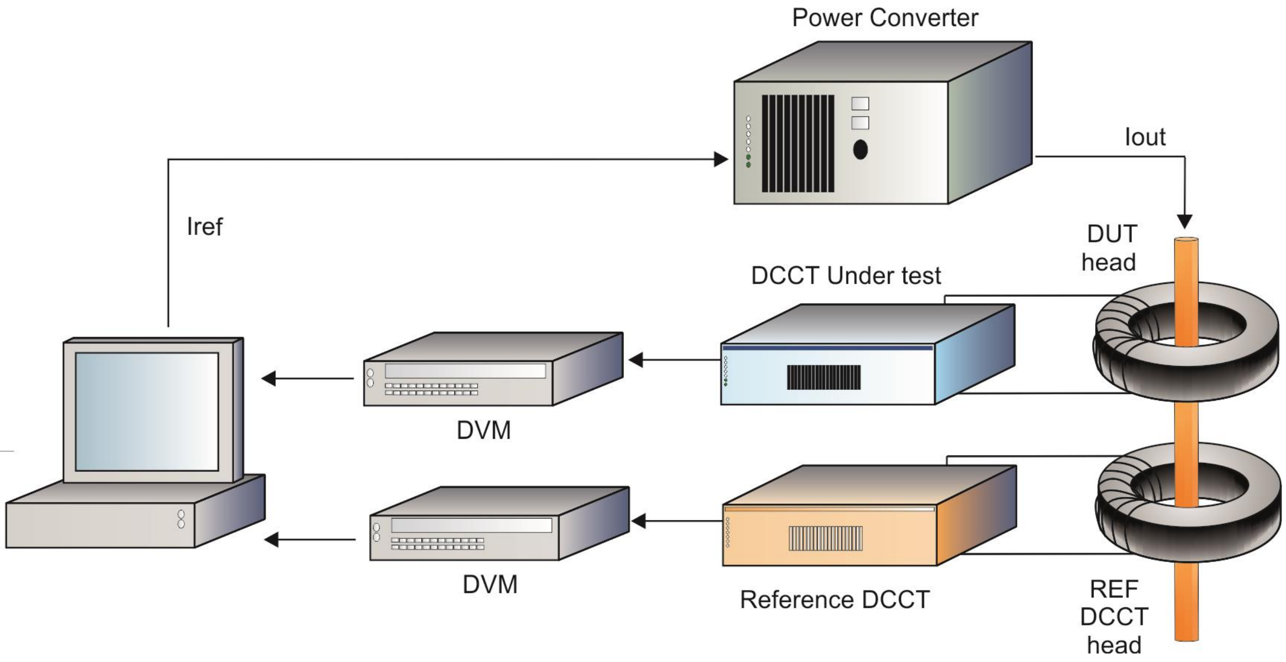
Test methods and calibration strategy



DCCTs – test and calibration methods

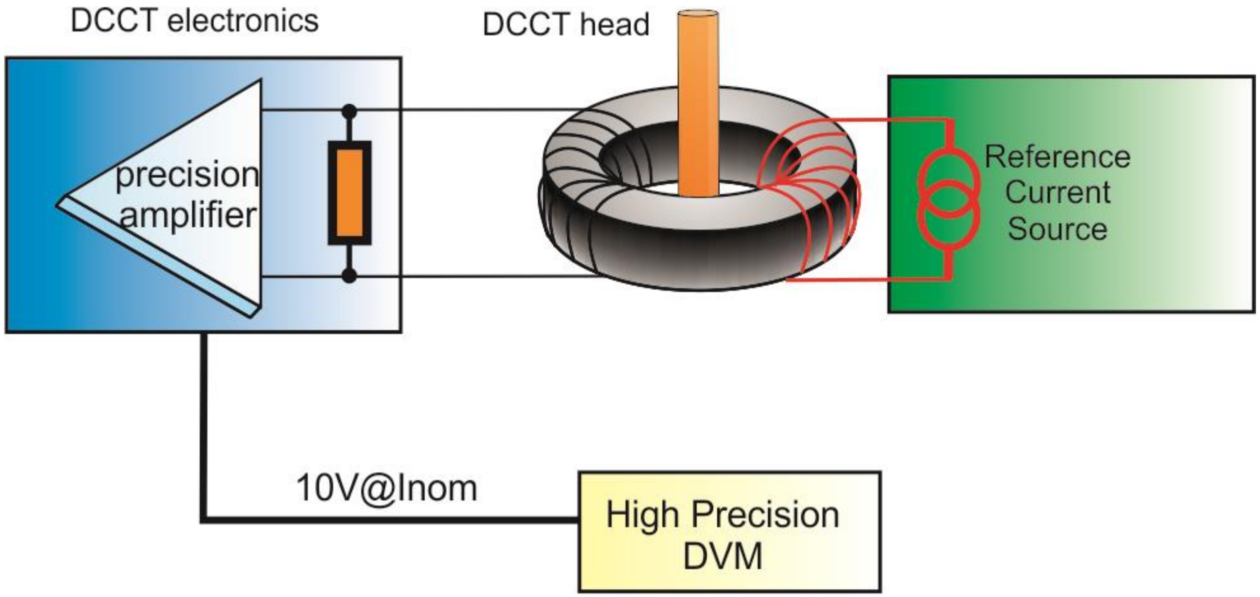
- **Reference device method** - the primary current is measured both by the DUT and by a reference device, which are then compared
- According to ANSI/NCSL Z540.3-2006, the performance of the reference device must be at least 4 times better than the DUT's.





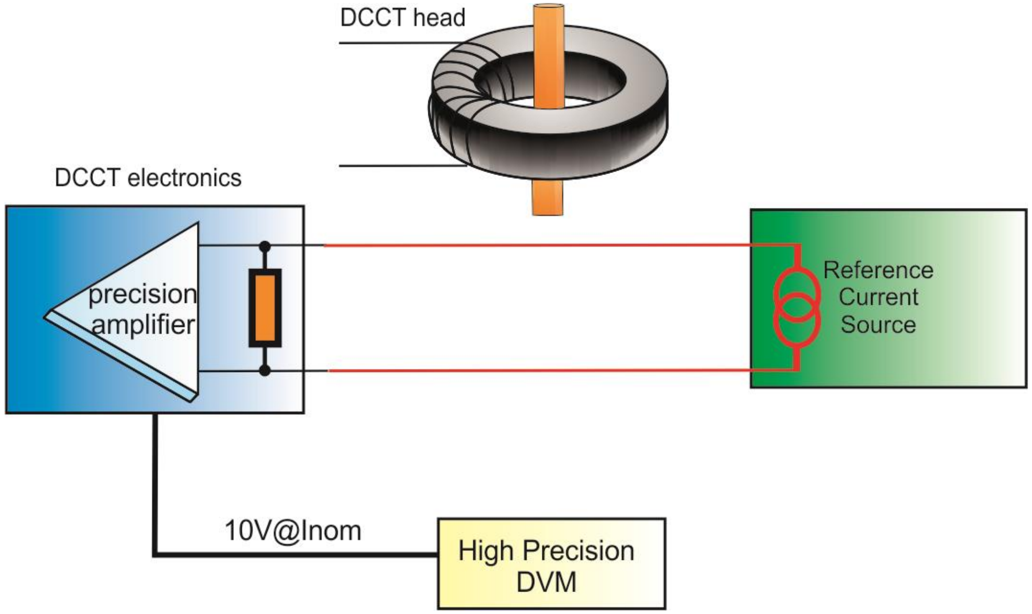
DCCTs – test and calibration methods

- **Reference current injected in an auxiliary winding** - a relatively small reference current is injected in an auxiliary winding with enough turns to simulate primary Ampere Turns.
- The auxiliary winding can be permanent or temporary



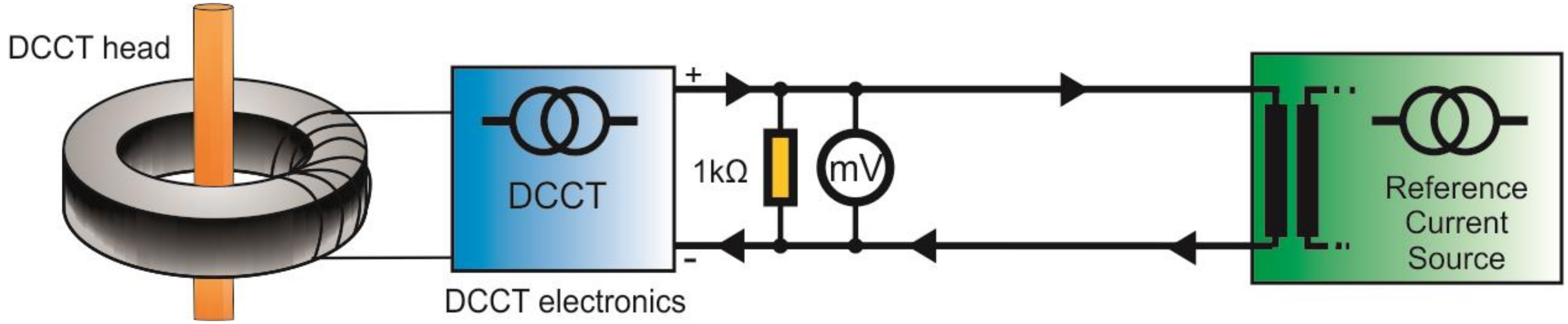
DCCTs – test and calibration methods

- **Reference current injected directly into the burden** resistor in place of the compensation current. This test allows us to understand which errors are caused by the burden and output amplifier.
- This method must be used with care as common mode voltages between the burden resistor ground and the precision amplifier ground depend on the point of connection of the current source low.



DCCTs – test and calibration methods

- **Reference current 'back-to-back'** with the DCCT current output - this test evaluates the quality of the current output of the DCCT which is normally much better than the voltage output.



Current measurement devices - calibration

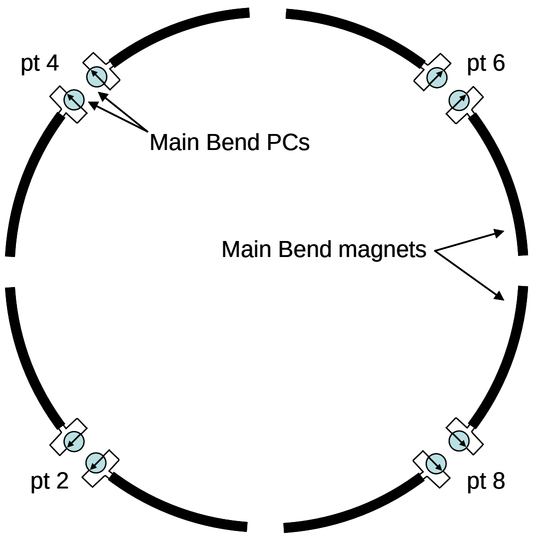
Do I need a Calibration strategy?

- Is **long term stability** an important requirement?
- What is the long term drift of my current measuring devices?
- Is there a need for **tracking** between different power converters?
- What is the impact of DCCT **replacement?**
  - Replacing a DCCT that has drifted can cause a jump seen by the machine
  - Calibrations can limit the size of this jump

Current measurement devices - calibration

The LHC case:

- Divided in 8 independent powering sectors, due to high stored energy.
- For the particles to see the same magnetic field the current must be the same in all sectors: the eight **power converter currents must track** each other!
- This is not the case for example for **corrector magnets,** whose currents are set independently with no special requirement for tracking and with relaxed stability



LHC corrector power supply: no DCCT calibration

LHC main quadrupole power supply: in-situ DCCT calibration system permanently installed

Current measurement devices - calibration

High and Very High Accuracy Applications

Requirements: < 10ppm relative accuracy, 50ppm yearly drift

- Calibration winding - requires suitable current source
- Calibration against reference units - requires suitable reference unit

Medium Accuracy

Requirements: < 100ppm relative accuracy, 1000ppm yearly drift

- Injection of reference current in burden resistor - requires suitable current source
- Calibration against reference units - requires suitable reference unit
- In some applications: no need for calibration

Low Accuracy

Requirements: % yearly drift

- Probably no need for calibration (some correctors)

CERN reference
Current source

Current measurement devices - test

High and Very High Accuracy

Requirements: < 10ppm measurement uncertainty

- High precision testbeds with reference units - chosen or modified DCCTs
- Installation and environment tests: centering, return bar influence, external magnetic field influence, Temperature Coefficient, EMC (voltage dips, burst test immunity, conducted noise)
- Performance Tests: Gain, Offset drift; Settling at Inom, Linearity, Noise, Repeatibility, Reproducibility, Settling at Zero

Current measurement devices - test

High and Very High Accuracy

Type tests or individual tests?

- Normally quantities are normally not very high: individual testing of all parameters is recommended.
- In addition, basic integration tests shall be performed when DCCT is installed in the converters, to validate EMC and performance.

Current measurement devices - test

Medium Accuracy

Requirements: < 100ppm measurement uncertainty

- Testbeds with reference units - chosen or modified DCCTs
- Installation and environment tests only on few units (**type tests)**
- Complete performance tests on few units (**type tests)** and sub set of performance tests on all units

Low Accuracy

Requirements: < 200ppm measurement uncertainty

- Test against reference device - DCCT, Shunt
- Performance tests on few units (**type tests**) and functional tests on all units

Current measurement devices - test

Characteristic	Criteria	Definition
Gain adjustment and resolution	Adjustable to 0 ppm error, Resolution of 0.1 ppm, Range ± 50 ppm	Resolution and adjustment range of output voltage, as a deviation from nominal output voltage, when measuring nominal primary current (assuming output offset has already been adjusted to zero).
Gain drift	< 0.5 ppm/24h < 1 ppm/month < 5 ppm/year	Maximum change in gain with time.
Gain initial error	< 25 ppm	Maximum gain error when delivered to CERN.
Gain temperature coefficient	< 1 ppm/°C	Maximum change in gain due to changes in ambient temperature.
Nominal output voltage	10.00000 V	Output voltage from the DCCT when nominal primary current is applied.
Output : supply voltage effect	< 0.5 ppm	Maximum permissible output voltage change, independent of primary current, due to variations in supply voltage.
Output impedance	< 10 milliOhms	Output impedance of the output signal.
Output load	> 10 kOhms, < 2 nF	Permissible loading of the output signal.
Output noise	< 2 ppm p-p, 5 Hz to 100 Hz < 10 ppm p-p, 100 Hz to 10 kHz < 30 ppm p-p, greater than 10 kHz	Output noise in the specified frequency ranges at any primary current.
Output offset: Adjustment and resolution	Adjustable to 0 ppm, Resolution of 0.1 ppm, Range ± 50 ppm	Range of values over which the offset may be adjusted, and resolution of the adjustment.
Output offset: Drift	< 1 ppm/24h < 2 ppm/month < 5 ppm/year	Maximum change in output offset with time.
Output offset: Initial error	< 5 ppm	Maximum offset error when delivered to CERN.
Output offset: Temperature coefficient	< 1 ppm/°C	Maximum change in output offset due to changes in ambient temperature.
Repeatability	0.5 ppm	Maximum dispersion in output voltage when repetitively returning to the same primary current. All other conditions unchanged.
Slew rate	> 20 V/ms	Maximum rate of change of output voltage.
Small signal bandwidth	> 10 kHz, at 1% amplitude	Small signal bandwidth for the stated primary current amplitude, from DC up to +/- 3 dB point, at any DC level.
Stability	< 0.5 ppm over 30 minutes	Deviation or scatter (DC to 5 Hz) of the output signal for a constant value of primary current (anywhere in the operating range) during a specified period of time - all operating conditions being held constant.

Current measurement devices - test

Characteristic	Criteria	Definition
Centre bar: Radial displacement sensitivity	< 1 ppm/cm from DCCT central axis	Effects of displacing the centre busbar radially from the geometric centre (but still parallel to central axis) of the head.
Minimum separation between DCCTs	< 0.1m	Minimum distance between two DCCT heads when mounted on the same primary busbar.
Overload current: Continuous	105% of nominal current	Maximum continuous primary overload current.
Reproducibility after saturation during power-up	2 ppm	Maximum deviation in output voltage from the previously measured value at any given current to the value found after switching on auxiliary power with nominal primary current already applied, and then returning to the same given current.
Reproducibility with auxiliary power cycle - no primary current	1 ppm	Maximum dispersion in output voltage when repetitively switching power off and on with no primary current.
Reproducibility with auxiliary power cycle - nominal primary current	2 ppm	Maximum deviation in output voltage when switching power off with nominal primary current, re-power with no primary current and returning to the nominal current.
Stabilisation time to specification after initial switch-on	30 minutes	Time from cold (stabilised at ambient temperature) switch on, to full performance.
Step response: Settling time	< 10 minutes for an error of 1 ppm	The settling time is the time taken for the output to come within (and stay within) a specified error following a step change of primary current from zero to nominal primary current.
Unipolar linearity	< 2ppm (for both polarities)	Unipolar linearity is a measure of the worst case deviation of the transfer function (output voltage versus primary current) of the DCCT, in one polarity, from an ideal straight line. The ideal straight line is determined by measuring the response of the DCCT to a range of primary currents from zero to nominal primary current in that polarity, and calculating the linear regression best-fit line for these points.
Immunity to external DC magnetic fields	10 mT	External magnetic field for which no influence is measurable in the output voltage.
Induced voltage into primary bar	< 200 µV p-p	Worst case voltage induced by the DCCT head into the single-turn open circuit primary busbar passing through the head.
Insulation resistance: Inter-winding	> 100 MOhm @ 500 V DC.	Minimum insulation resistance between any pair of windings.

Thank you For your attention!

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