Current Transformers with nanocrystalline cores
Exact power value

\[ P_{true} = U \cdot I \cdot \cos \phi \]

Measured power value including errors

\[ P_{meas} = U \cdot I \cdot (1 - F(I)) \cdot \cos (\phi + \phi(I)) \]

Error

\[ \Delta P \% = \frac{P_{meas} - P_{true}}{P_{true}} \cdot 100 \]
Power Measurement
Functional principles of current transducers

- Shunt resistor
  - D complex joining technology
  - D no galvanic separation
  - D low output voltage
  - D output drifts over time

- Hall Effect sensor
  - with flux concentrating pole pieces
  - with gapped laminated core
  - D high offset, high T-drift
  - offset ≠ extensive compensation

- Pickup coil sensor
  - „Rogowski-Coil“ (no core)
  - gapped laminated core
  - with gapped ferrite core
  - D low output signals
  - D needs integrator

- Current transformer
  - with ferrite core
    - with optimised toroidal VAC core
  - C secure galvanic separation
  - C high dynamic range
  - C insensitive to external magnetic fields (closed core)
  - D high susceptibility to external magnetic fields for field-detecting measurement methods (≠ shielding)

Dominant technology
Differentiation by material

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Material:

- **permeabilities** \( \mu = \mu_s + i \cdot \mu'' \)
- **core losses** \( \delta \), \( \tan \delta = \frac{\mu''}{\mu_s} \)
- **saturation induction** \( B_{\text{sat}} \)

Current ranges

Errors
Current range:

\[ I_{\text{max rms}} \approx \frac{\omega \cdot N_{\text{sec}}^2}{\sqrt{2}} \cdot \frac{\hat{B}_{\text{sat}} \cdot A_{\text{Fe}}}{R} \]

\[ R = R_{\text{Cu}} + R_B \]

Primary current range increases with

\[ \hat{\gamma} \text{ higher saturation induction } B_{\text{sat}} \]

\( \uparrow \) crystalline, amorphous and nanocrystalline cores (\( B_{\text{sat}} > 1 \text{T} \)) superior to ferrites (\( B_{\text{sat}} \approx 0.4 \text{T} \))

\[ \hat{\gamma} \text{ increased core cross section } A_{\text{Fe}} \]

\( \uparrow \) drawbacks: higher cost, bigger component, \( A_{\text{Fe}} \uparrow \Rightarrow R \uparrow \sim \sqrt{A_{\text{Fe}}} \)

\[ \hat{\gamma} \text{ decreased winding resistance } R_{\text{Cu}} \]

\( \uparrow \) exhaust available winding space

Mostly \( R_{\text{Cu}} \gg R_B \), with \( R_{\text{Cu}} \sim N_{\text{sec}}^2 \Rightarrow R \sim N_{\text{sec}}^2 \), increasing \( N_{\text{sec}} \) does not extend primary current range.
Toroidal Core CTs – CT design

Errors

\[ \varphi(I) \approx \arctan \left( \frac{R}{\omega L} \right) \]

Amplitude error:
\[ F(I) \approx -\sin \delta \cdot \frac{R}{\omega \cdot L} \]

\[ FOM = \frac{R}{\omega \cdot L} \approx \frac{\rho_{Cu}}{\mu} \]

Errors improve with
- Higher permeability \( \mu \)
  \( \mu \uparrow \Rightarrow L \uparrow \), crystalline, amorphous, nanocrystalline cores (\( \mu > 100000 \)) superior to ferrites (\( \mu < 15000 \))
- Lower core losses (amplitude error)
  
  \( \Downarrow \) amorphous and nanocrystalline cores superior to crystalline cores and ferrites
- Decreased winding resistance \( R_{Cu} \)
  \( \Downarrow \) exhaust available winding space

\[ \omega = 2\pi \cdot f \]

\[ R = R_{Cu} + R_B \]
High-perm crystalline (C), amorphous (AM) and nanocrystalline (NC) cores

- Phase error $\phi$ [°]
- Amplitude error [%]

- Crystalline ULTRAPERM 10
- Amorphous VITROVAC 6025 F
- Nanocrystalline VITROPERM 500 F

AM, NC: no load dependence of phase error
AM, NC: Low amplitude errors

Easy error compensation requires independence of $L$, $\tan \delta$ on load and temperature + stable production processes with low tolerances for $\mu$ and $\tan \delta$. 

Losses!
Toroidal Core CTs - Material selection: Non-DC-tolerant CTs

- Material selection:
  - Non-DC-tolerant CTs

- Accuracy:
  - Primary current
  - High
  - Medium
  - Too low

- High current range + low errors:
  - Amorphous high-µ VITROVAC
  - Nanocrystalline high-µ VITROPERM
  - 80%NiFe ULTRAPERM
  - 50%NiFe PERMENORM
  - 3% SiFe TRAFOPERM

Current Transformers with nanocrystalline cores
Toroidal Core CTs – CT design

Maximum unipolar current

\[ \hat{I}_{DC\max} = \frac{\pi}{\mu_0} \cdot \frac{\hat{B}_{sat} \cdot l_{Fe}}{\mu} \]

Unipolar current range increases with

- higher saturation induction \( B_{sat} \)
  - crystalline, amorphous and nanocrystalline cores (\( B_{sat} > 1T \)) superior to ferrites (\( B_{sat} \sim 0.4T \))

- lower permeability \( \mu \)
  - low \( \mu \)  \( \Downarrow \) low \( L \)  \( \Downarrow \) generally higher amplitude and phase errors

- increased core length \( l_{Fe} \)
  - higher cost, bigger component
Low-perm nanocrystalline core

Phase and amplitude errors have to be compensated; compensation easy, if errors do not vary with temperature and load

basically no load and temperature dependence

 fácil compensation
Toroidal Core CTs - Material selection: DC tolerant CTs

Accuracy:
- very high
- high
- medium
- too low

Primary current ~ unipolar current

High unipolar current range + low errors

- Amorphous low-µ VITROVAC
- new low-µ VITROPERM variants
- Nanocrystalline low-µ VITROPERM
- low-µ ferrite

50%, 80% Ni-Fe, 3% SiFe
Further development of material basis:

- New low-µ nanocrystalline VP alloys
  - smaller cores (OD)
  - nanocrystalline material

Design of application-specific and customer-specific components:

- Integration of CT for e.g. 3 phase applications into 1 component
  - easier assembly

Customer-specific designs
Integrated seamless primary conductor

- radial through ID of core
- connection to meter base through blades

- optimized core geometry (ID smaller)
- less expensive copper bar

Picture to visualize concept

cost savings