Residual Magnetism

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AGENDA

> What is Residual Magnetism

> Ways to Reduce Remanence

> Determining the residual magnetism in a field test

> Summary

Significance of Residual Magnetism

It has been said that one really knows very little about a problem until it can be reduced to figures.

One may or may not need to demagnetize, but until one actually measures residual levels of magnetism, one really doesn't know where he or she is.

One has not reduced the problem to figures.

R. B. Annis Instruments, Notes on Demagnetizing

Physical Interpretation of Residual Magnetism

- **When excitation is removed from the CT, some of the magnetic domains retain a degree of orientation relative to the magnetic field that was applied to the core. This phenomenon is known as residual magnetism.**

- **Residual magnetism in CTs can be quantitatively described by amount of flux stored in the core.**

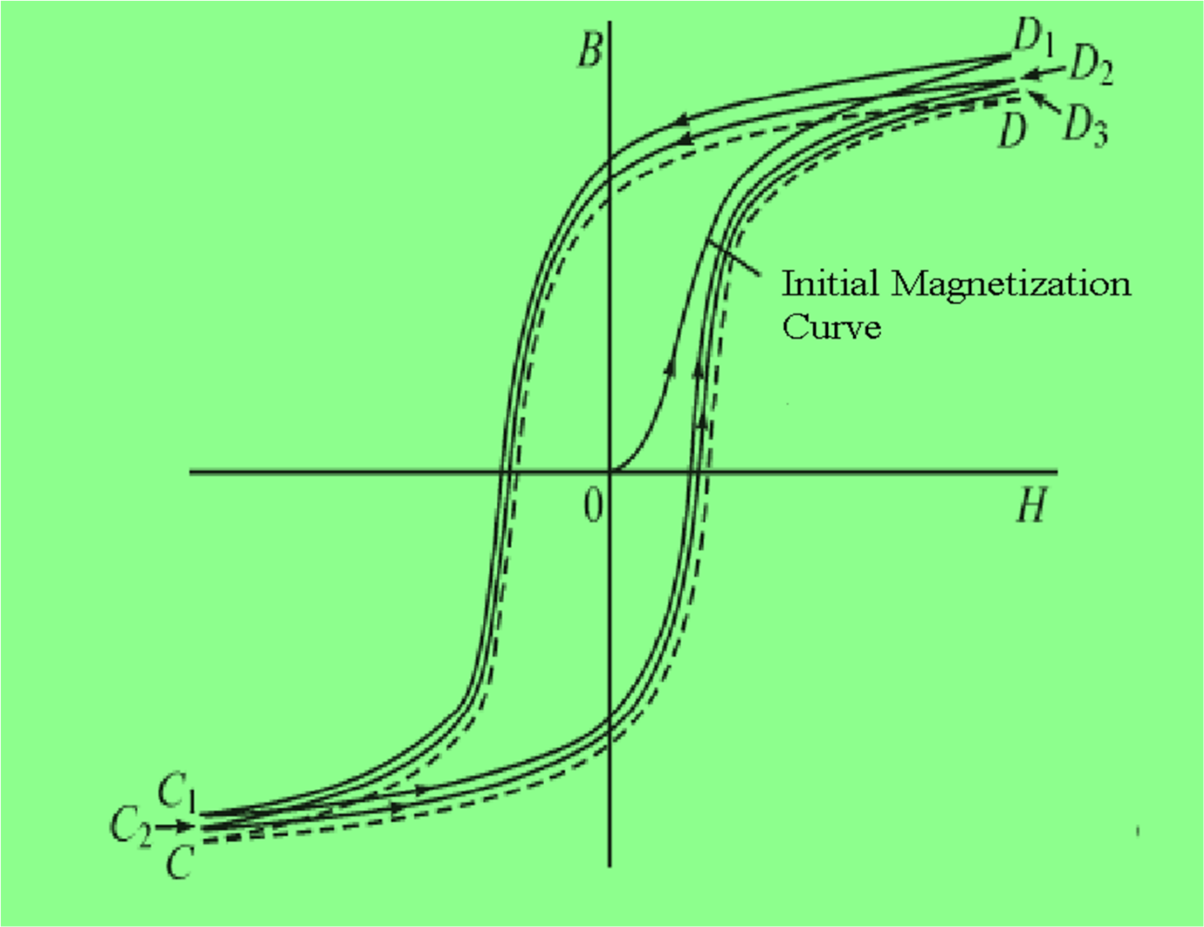
$$\Psi(t) = \int_0^t V_C(\tau)\,d\tau + \Psi_{res}$$

Significance of Residual Magnetism

WHY DO I CARE????

Bottom Line: If the CT has excessive Residual Magnetism, it will saturate sooner than expected.

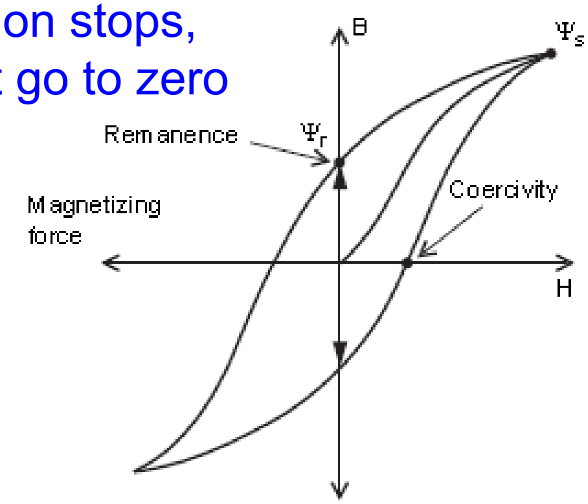
Magnetization Process and Hysteresis



*Picture is reproduced from K. Demirchyan et.al.,
Theoretical Foundations of Electrotechnics

Remanence Flux (Residual Magnetism)

When excitation stops,
Flux does not go to zero



Remanence factor (K_r):

$$K_r = 100 * \frac{\Psi_r}{\Psi_s}$$

Ψ_r = remanent flux

Ψ_s = saturation flux

K_r = remanence factor in %

Remanence is dissipated very little under service conditions. Demagnetization is required to remove the remanence.

*Source: IEEE C37.100-2007

Residual Remanence and Remanence Factor

• **Saturation flux (Ψs)**

that peak value of the flux which would exist in a core in the transition from the non-saturated to the fully saturated condition and deemed to be that point on the B-H characteristic for the core concerned at which a 10 % increase in B causes H to be increased by 50 % (IEC 60044-1, 2.3.6)

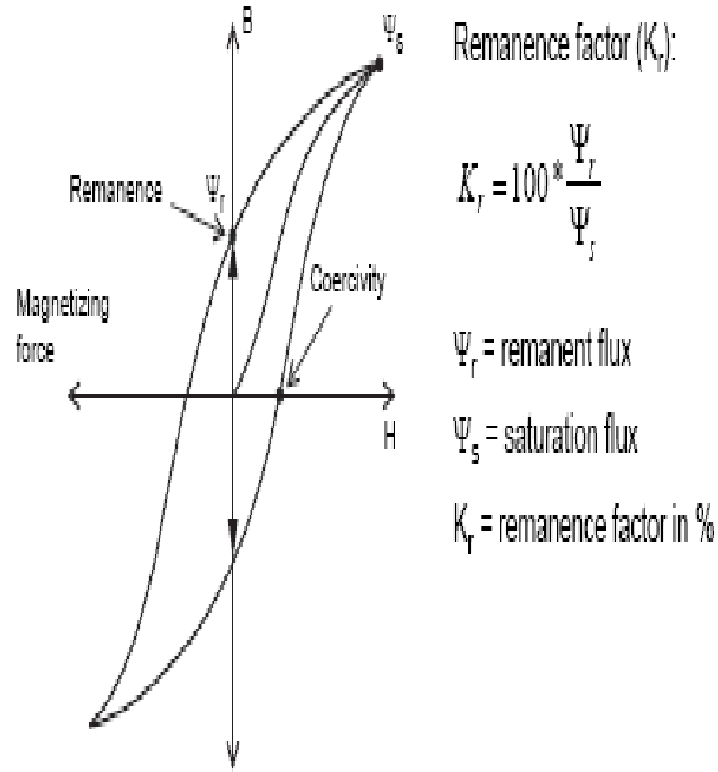
• **Remanent flux (Ψr)**

that value of flux which would remain in the core 3 min after the interruption of an exciting current of sufficient magnitude to induce the saturation flux (Ψs) (IEC 60044-1, 2.3.7)

$$M_r = \frac{\Psi_{res}}{\Psi_S} * 100\%$$

• **Remanence factor (Kr)**

the ratio Kr = 100 × Ψr / Ψs, expressed as a percentage
(IEC 60044-1, 2.3.8).



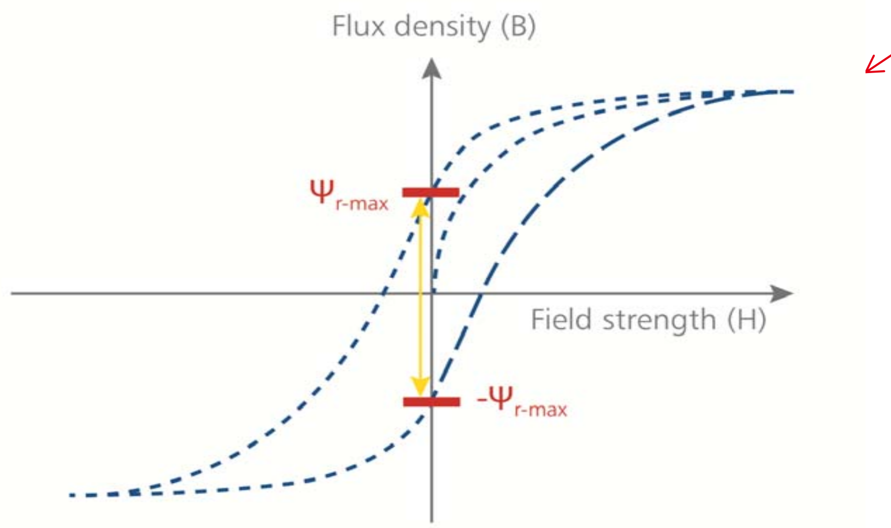
• **Residual remanence (Mr)**

the ratio Mr = 100 × Ψres / Ψs, expressed as a percentage.

* Picture from *CT-Analyzer User Manual*

Residual Magnetism

- Maximal Remanence Flux $\Psi_{r\text{-}max}$ (physically)
  - the flux which remains after magnetization of the core to **total saturation** and **removal** of this magnetizing current

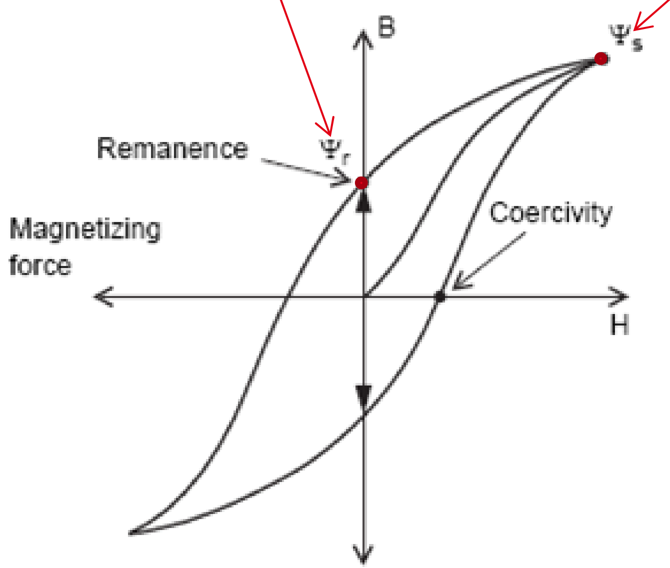


- **When** is the “total saturation” achieved? **How** defined? or **Specified**?

Residual Magnetism

- **Remanence Flux Ψ_r (IEC 60044-1)**
  that value of flux which would remain
  in the core after the interruption
  of an exciting current of sufficient magnitude
  to induce the saturation flux Ψ_s

- **Saturation flux Ψs (IEC 60044-1)**
  that peak value of the flux which would exist
  in a core in the transition from the non-saturated
  to the fully saturated condition (➔ Knee point)



Remanence factor (K_r):

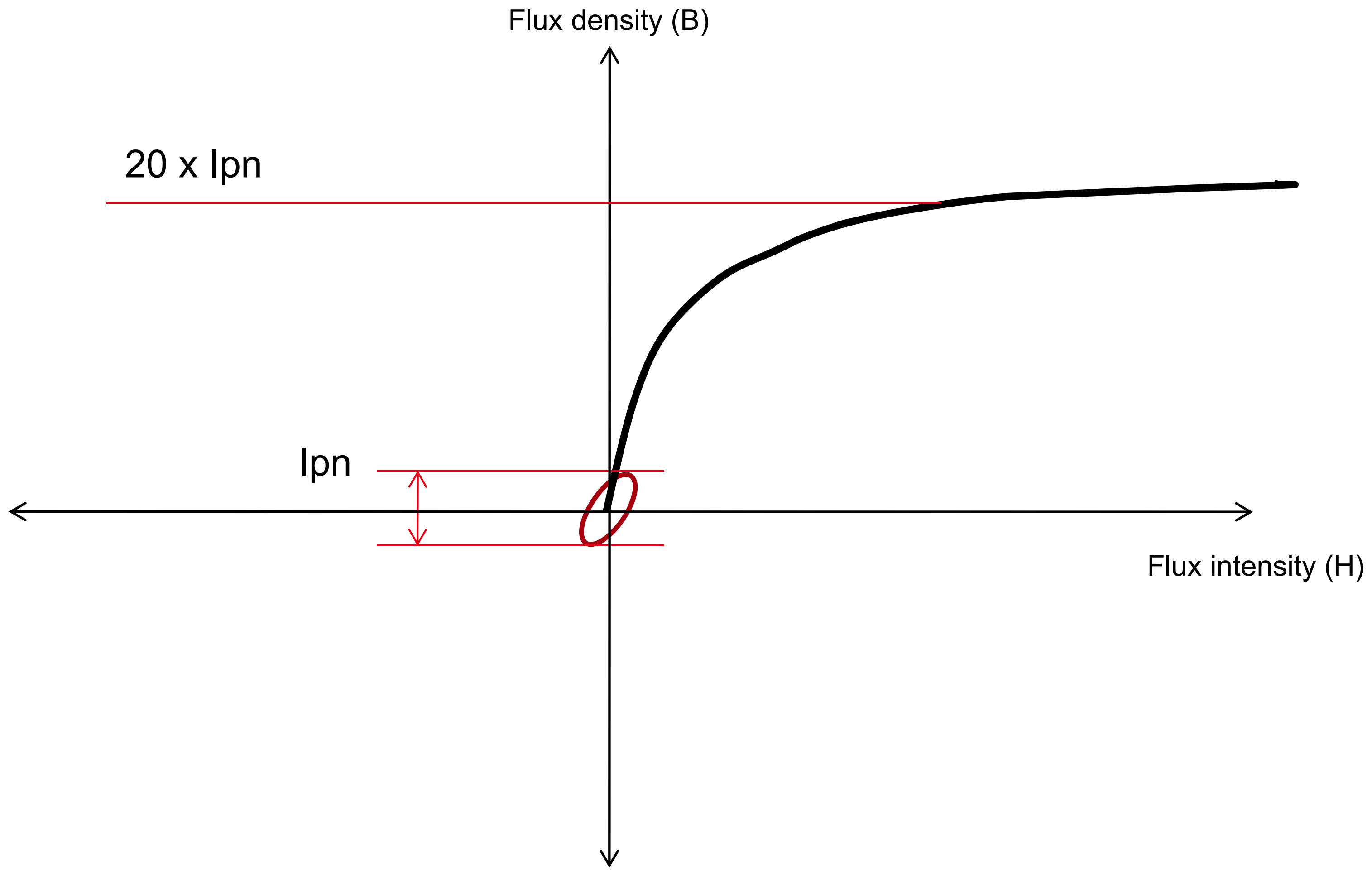
$$K_r = 100 * \frac{\Psi_r}{\Psi_s}$$

Ψ_r = remanent flux

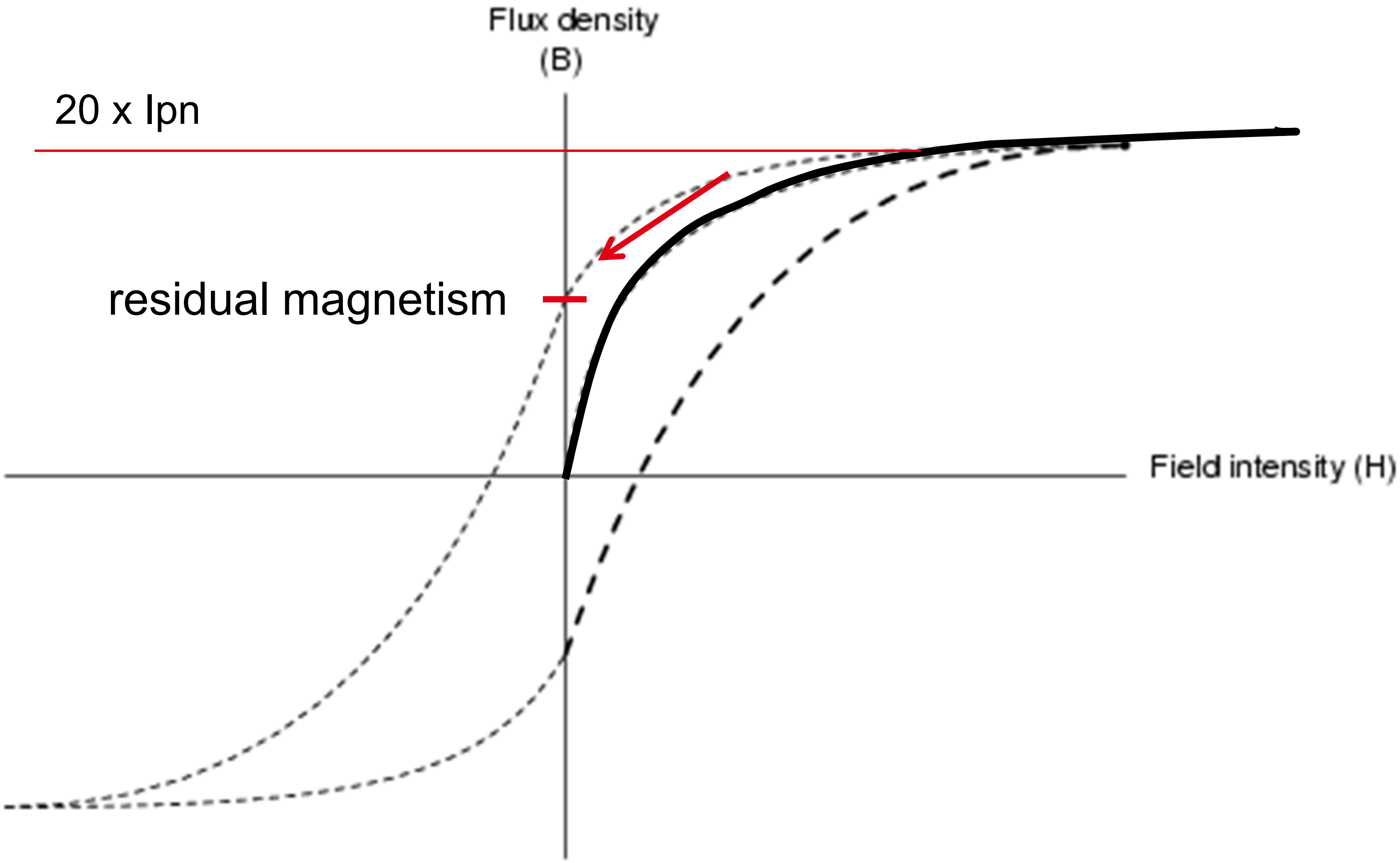
Ψ_s = saturation flux

K_r = remanence factor in %

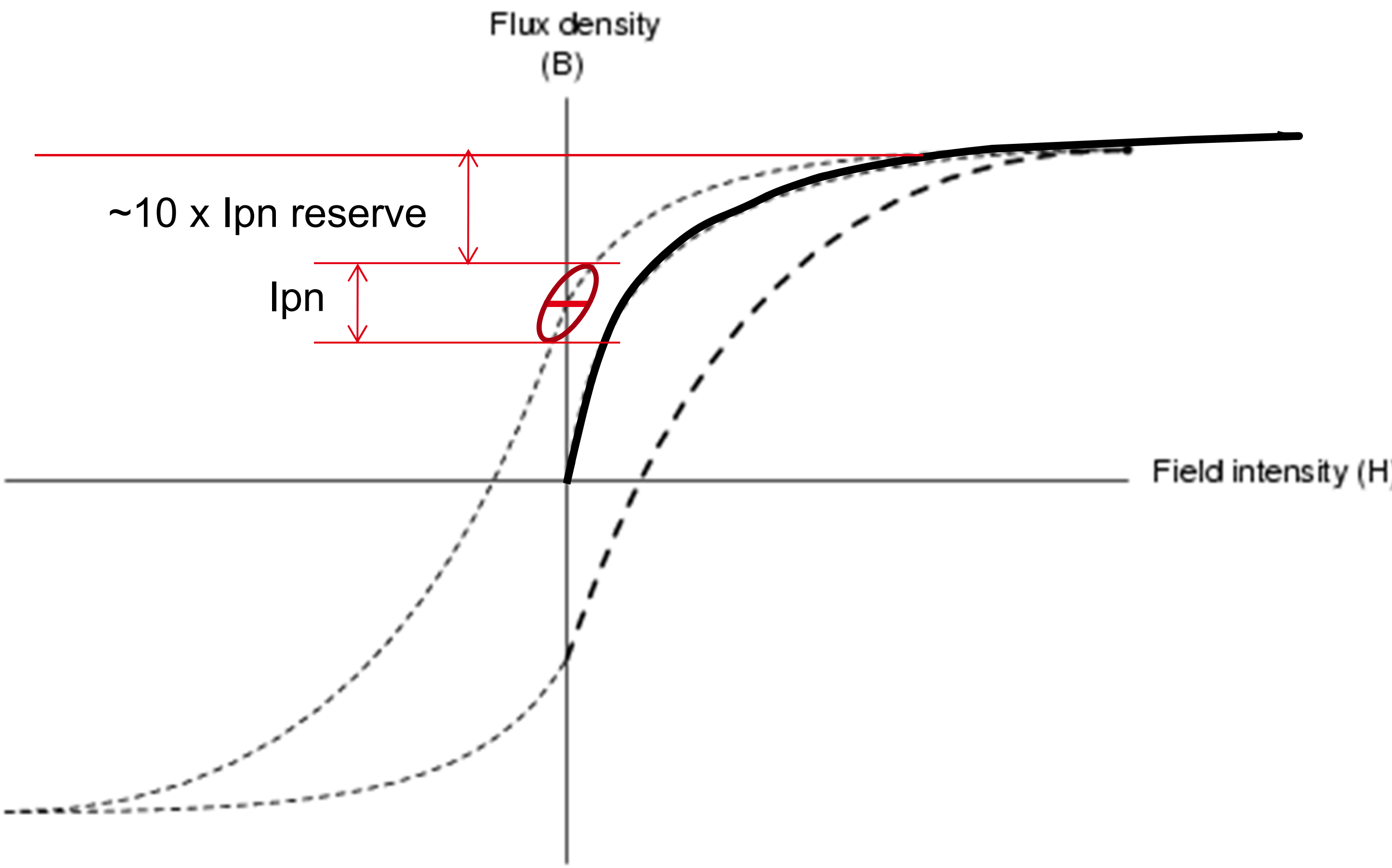
Residual Magnetism



Residual Magnetism



Residual Magnetism

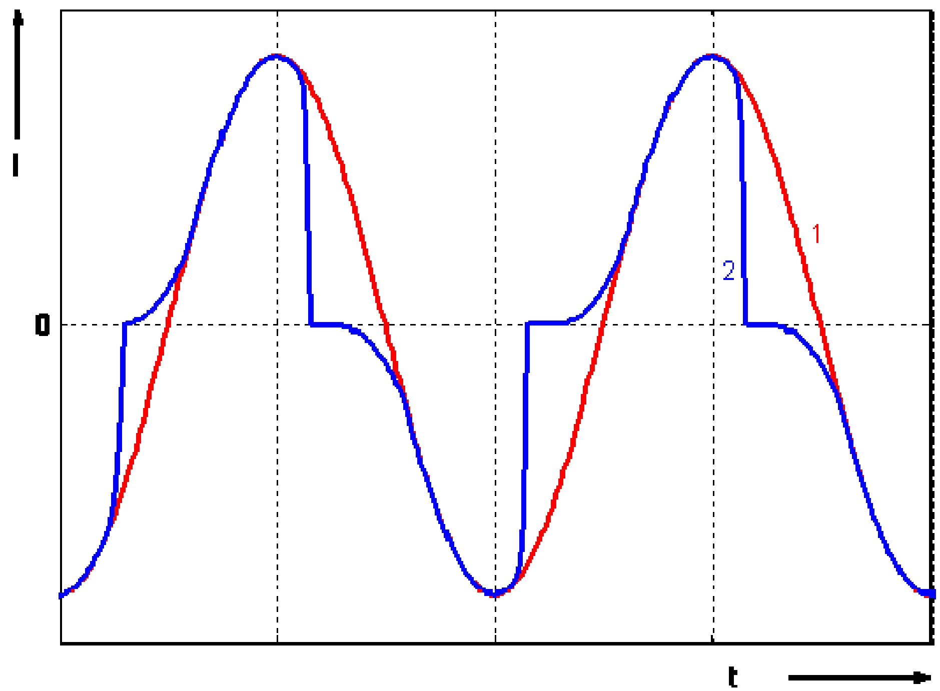


Residual Magnetism

1 I_p`Current of an ideal current transformer

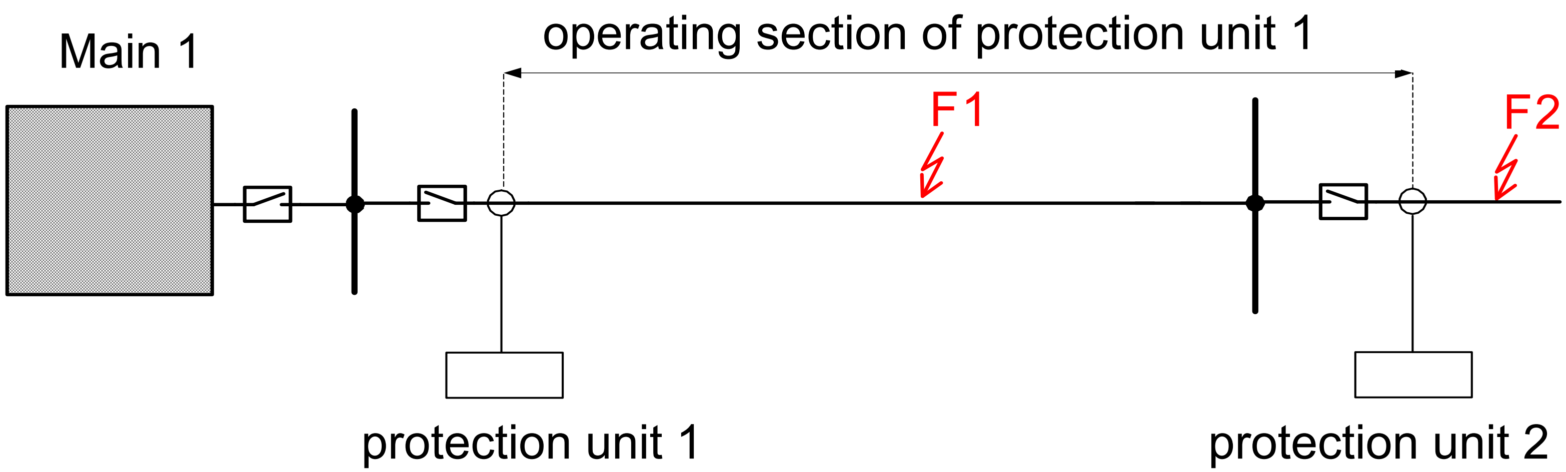
2 I_s Current of a saturated current transformer

The difference $I_\mu = I_p' - I_s$ is the current floating through the saturated inductance.



Residual Magnetism

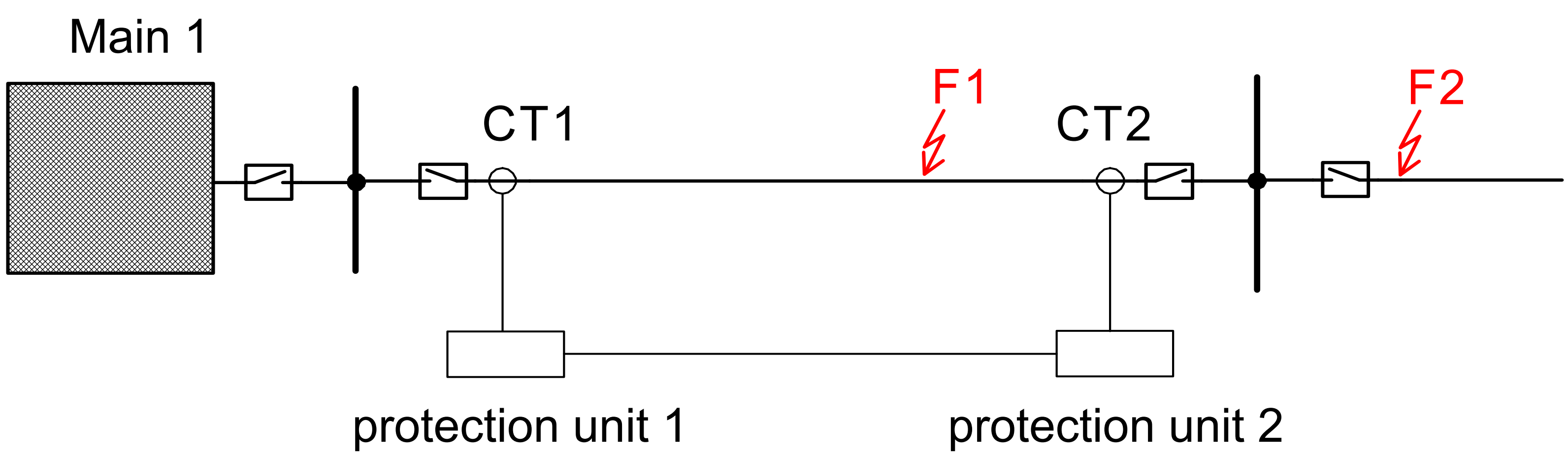
- Impact due to residual remanence with “Over Current Protection” and “Distance Protection”



- ➔ failure to operate
- ➔ unwanted operation

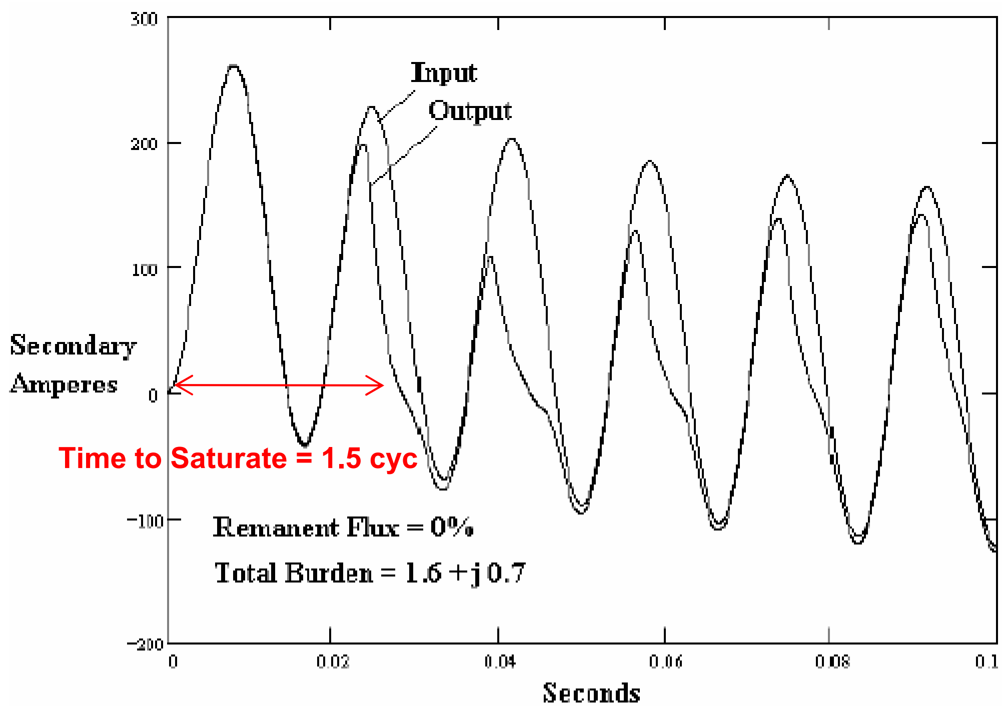
Residual Magnetism

- Impact due to residual magnetism with “Differential Protection“



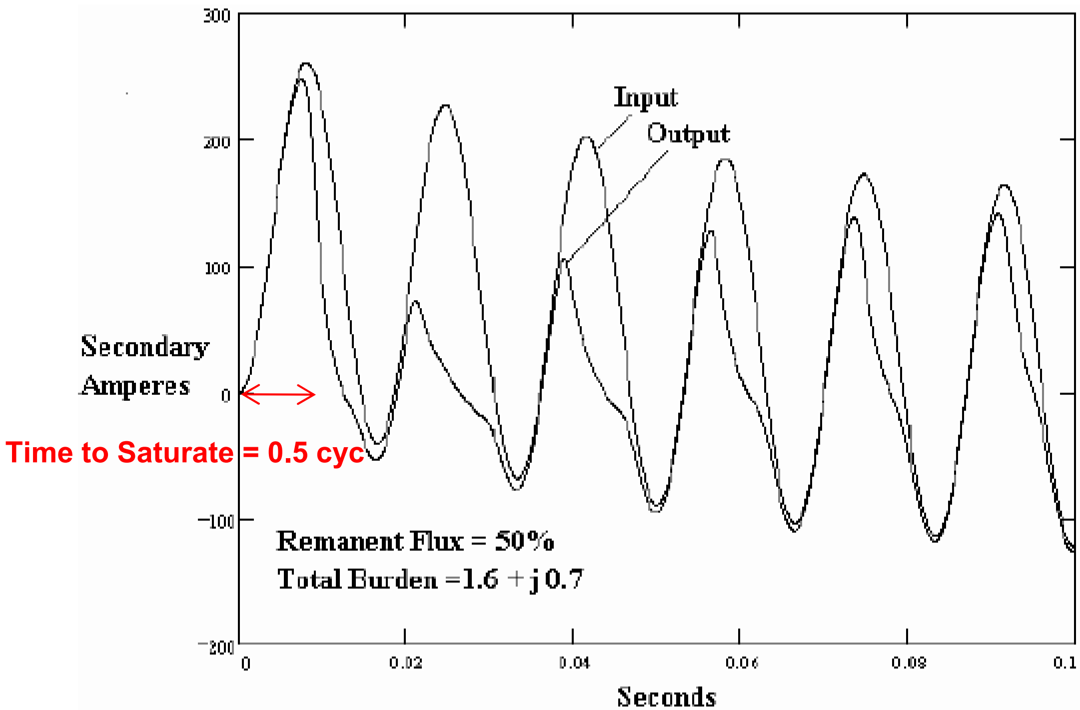
- ➔ no impact on inner failure
- ➔ unwanted operation in case of outer failure

Effect of Remanence (0%)



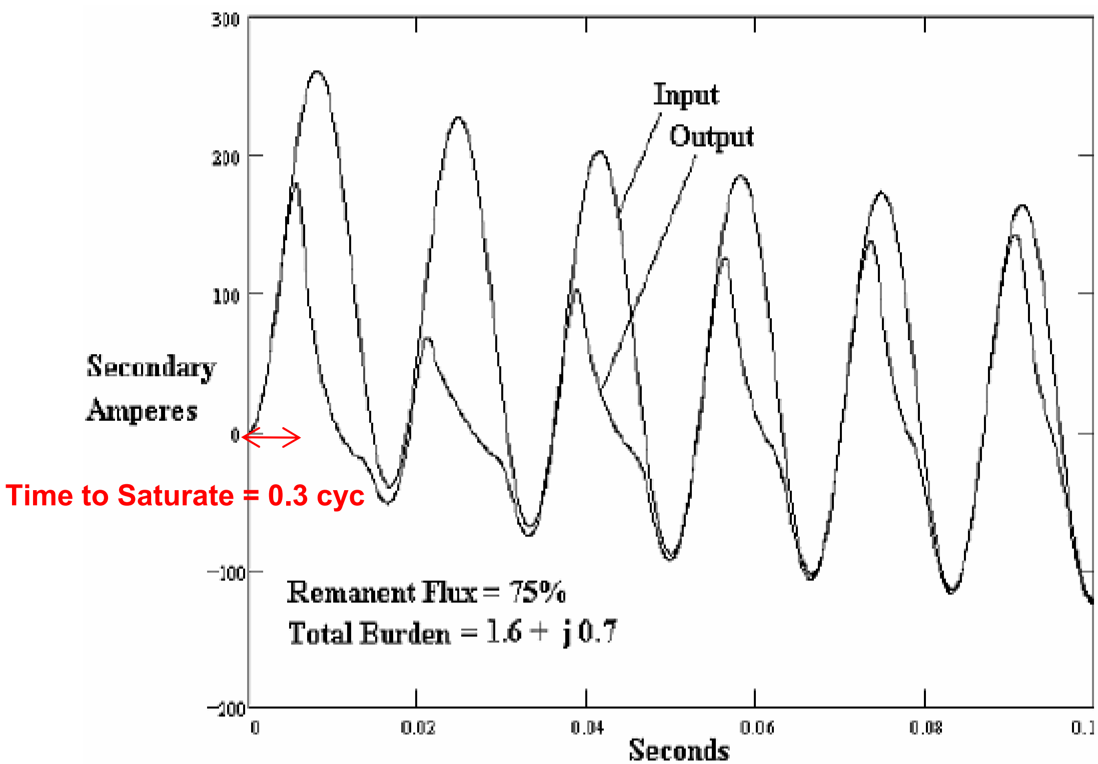
1200:5A
C800 CT
24,000A Ifault
X/R = 19

Effect of Remanence (50%)



1200:5A
C800 CT
24,000A Ifault
X/R = 19

Effect of Remanence (75%)



1200:5A
C800 CT
24,000A Ifault
X/R = 19

Effect of Remanence

- Remanence as much as 80% of saturation flux can be expected
- Can significantly reduce the burden capability of the CT

Table C.1—Remanent flux survey on 230 kV system

Remanent flux % of saturation	Percentage of CTs
0–20	39
21–40	18
41–60	16
61–80	27

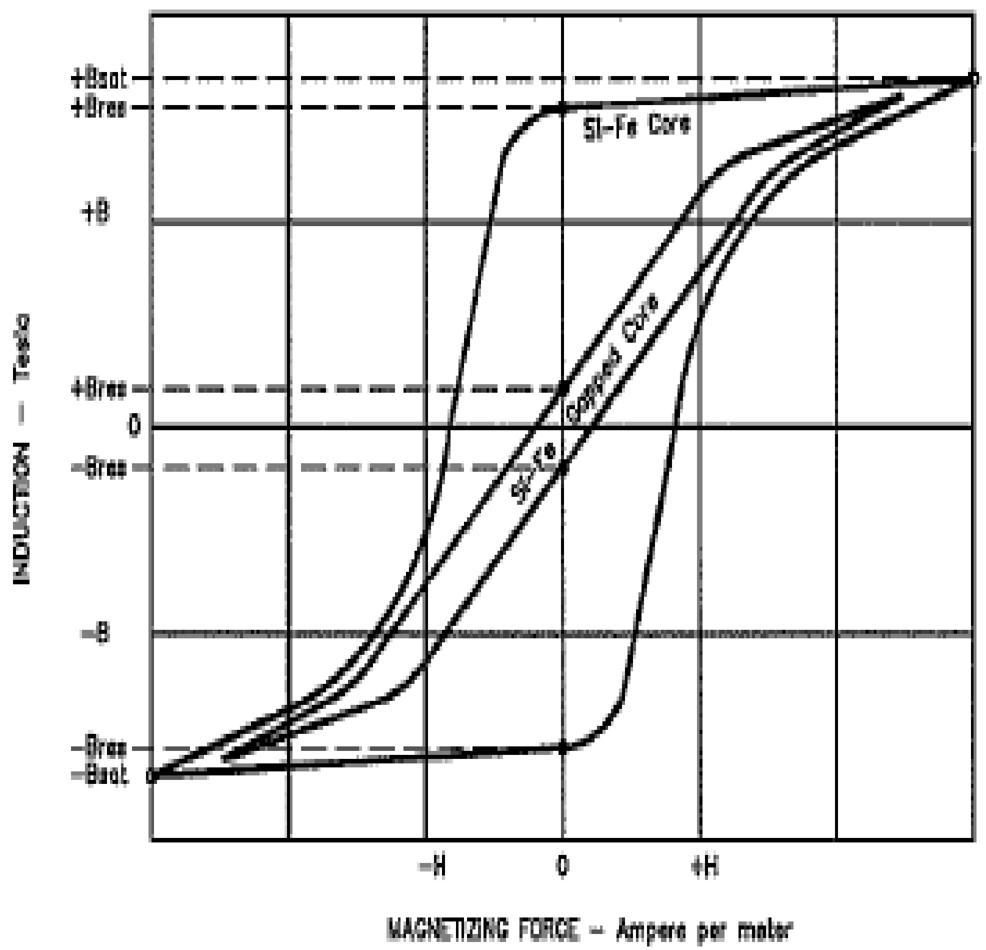
*Source: IEEE C37.100-2007

Ways to Reduce Remanence

- Use different grade of steel for core (hot-rolled instead of cold-rolled steel reduces up to half the max. remanence)
- Use Gapped Core CT (TYP Class)

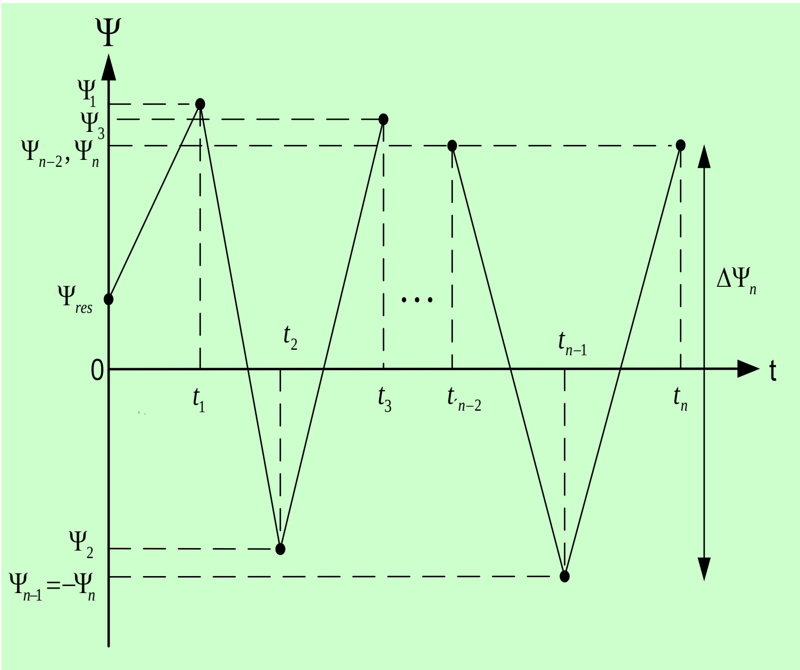
Reduction of Residual Magnetism

- Hot-rolled steel can reduce the residual magnetism to 40-50% of saturation flux
- Use of air-gapped core: higher exciting current and lower saturation levels;
- Drawbacks: larger and more expensive cores, lower accuracy
- Used when stable relay operation is critical for system security



* Picture from *Electric Power Transformer Engineering*, ed. by James H. Harlow

Residual Flux Measurement: Cumulative Method



Magnetic flux variation under rectangular magnetization

$$\begin{cases} \Psi_1 = \Psi_{res} + \Delta\Psi_1 \\ \Psi_2 = \Psi_1 + \Delta\Psi_2 \\ \Psi_3 = \Psi_2 + \Delta\Psi_3 \\ \ldots \\ \Psi_{n-1} = \Psi_{n-2} + \Delta\Psi_{n-1} \\ \Psi_n = \Psi_{n-1} + \Delta\Psi_n \end{cases}$$

$$\Psi_n = \Psi_{res} + \sum_{i=1}^{n} \Delta\Psi_i = \Psi_{res} + \sum_{i=1}^{n} \int_{t_{i-1}}^{t_i} U_C(\tau)d\tau = \Psi_{res} + \int_{t_0}^{t_n} U_C(\tau)d\tau$$

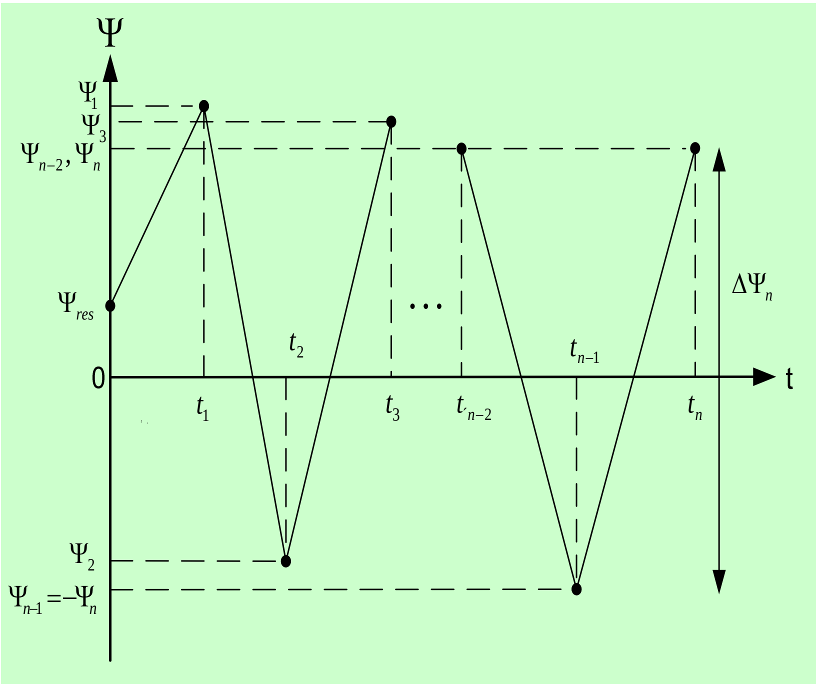
$$\Psi_{res} = -\int_{t_0}^{t_{n-1}} U_C(\tau)d\tau - \frac{1}{2} * \int_{t_{n-1}}^{t_n} U_C(\tau)d\tau =$$

$$-\left[\int_{t_0}^{t_{n-1}} U_{CT}(\tau)d\tau - R_{CT} * \int_{t_0}^{t_{n-1}} I_{CT}(\tau)d\tau\right] - \frac{1}{2} * \left[\int_{t_{n-1}}^{t_n} U_{CT}(\tau)d\tau - R_{CT} * \int_{t_{n-1}}^{t_n} I_{CT}(\tau)d\tau\right]$$

U_{CT} - terminal voltage I_{CT} - terminal current R_{CT} - secondary winding resistance

U_C - core voltage Ψ - interlinked (core) flux Ψ_{res} - residual flux

Residual Flux Measurement: Averaging Method



Magnetic flux variation under rectangular magnetization

$$\Delta\Psi_1 = \left|\int_0^{t_1} U_C(\tau)d\tau\right| = \left|\int_0^{t_1} U_{CT}(\tau)d\tau - R_{CT} * \int_0^{t_1} I_{CT}(\tau)d\tau\right|$$

$$\Delta\overline{\Psi} = \frac{1}{n-1}\sum_{i=2}^{n}\left|\Delta\Psi_i\right| =$$

$$\frac{1}{n-1}\sum_{i=2}^{n}\left|\int_{t_{i-1}}^{t_i} U_{CT}(\tau)d\tau - R_{CT} * \int_{t_{i-1}}^{t_i} I_{CT}(\tau)d\tau\right| =$$

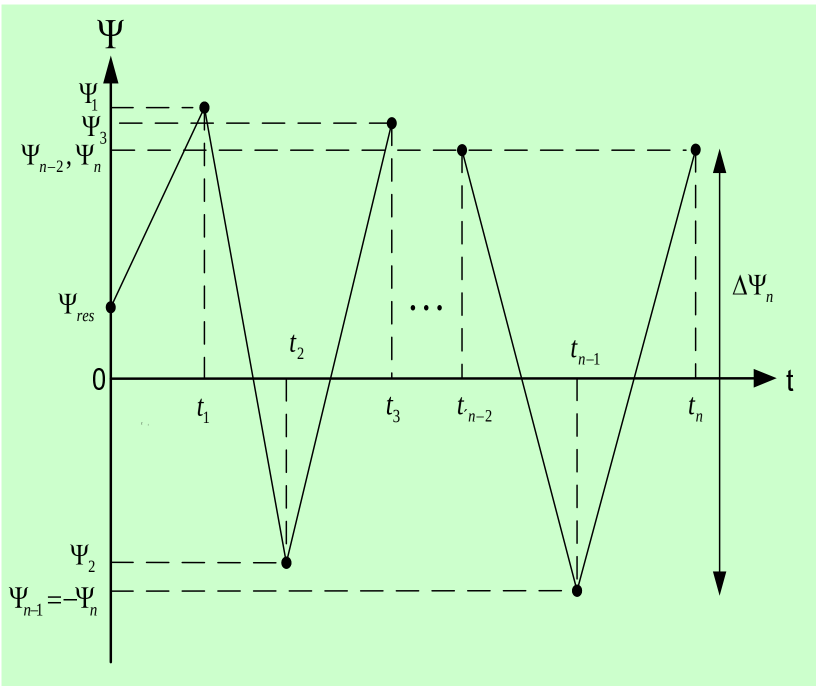
$$\frac{1}{n-1}\sum_{i=2}^{n}\left|\int_{t_{i-1}}^{t_i} U_{CT}(\tau)d\tau\right| - R_{CT} * \left(\frac{1}{n-1} * \sum_{i=2}^{n}\left|\int_{t_{i-1}}^{t_i} I_{CT}(\tau)d\tau\right|\right)$$

$$\Psi_{res} \approx \left|\Delta\Psi_1 - 0.5 * \Delta\overline{\Psi}\right|$$

U_{CT} - terminal voltage I_{CT} - terminal current R_{CT} - secondary winding resistance

U_C - core voltage Ψ - interlinked (core) flux Ψ_{res} - residual flux

Hysteresis Loop Symmetry Condition



Magnetic flux variation under rectangular magnetization

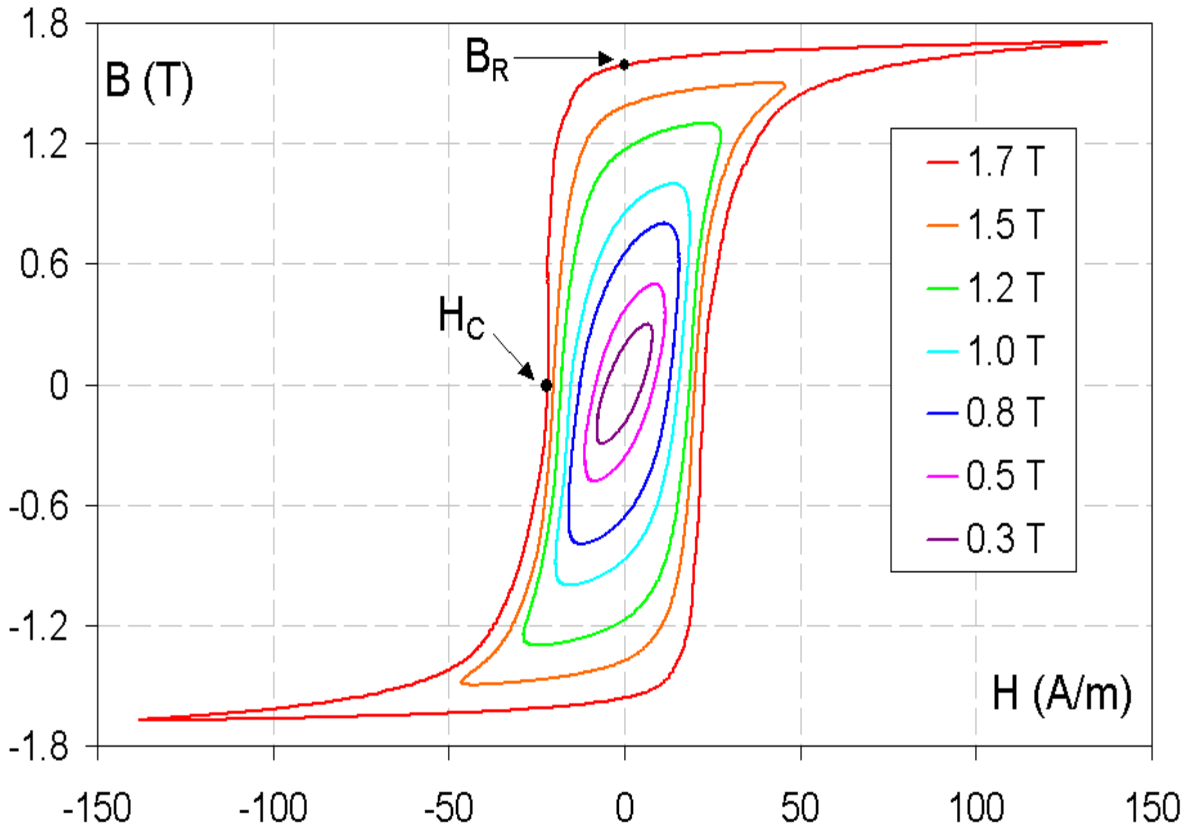
$$\Delta\Psi_{n-1} = -\Delta\Psi_n$$

$$\left| \int_{t_{n-1}}^{t_n} I_{CT}(\tau)d\tau \right| = \left| \int_{t_{n-2}}^{t_{n-1}} I_{CT}(\tau)d\tau \right|$$

$$\left| \int_{t_{n-1}}^{t_n} U_{CT}(\tau)d\tau \right| = \left| \int_{t_{n-2}}^{t_{n-1}} U_{CT}(\tau)d\tau \right|$$

U_{CT} - terminal voltage I_{CT} - terminal current Ψ - interlinked (core) flux

Residual Remanence and Remanence Factor (2)



Family of hysteresis loops for grain-oriented electrical steel

* Picture from [Wikipedia]

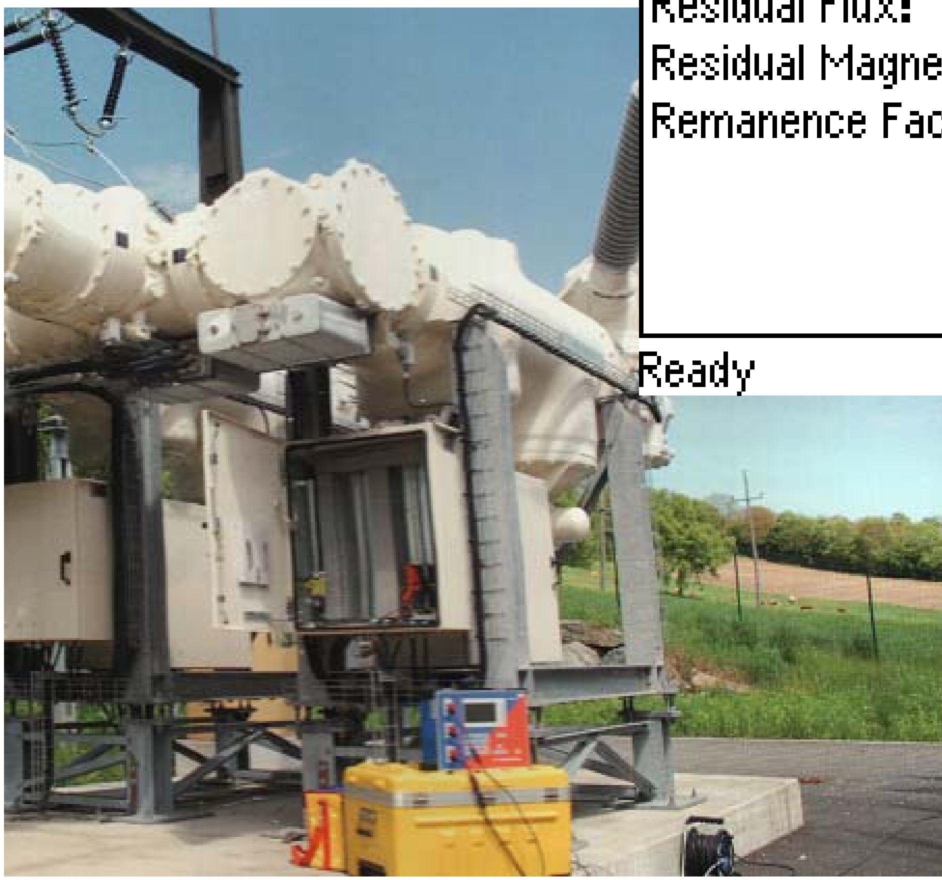
Residual Flux Measurement: Implementation Issues

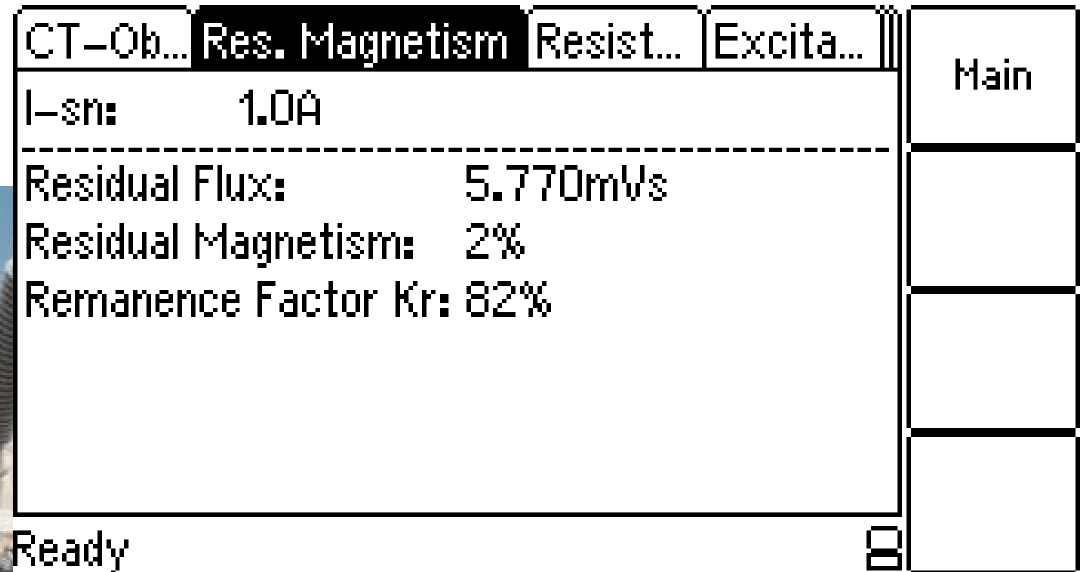
- **To determine residual flux it is essential to calculate voltage and current time integrals taken over measurement duration.**

- **If calculation of these integrals can be made real-time (i.e. simultaneously with input sampling), there is no need to store input data of current and voltage channels.**

- **Thus, even if saturation process is very long, it will still be possible to calculate residual flux, which allows applying this method to residual remanence measurement for both CTs and transformers.**

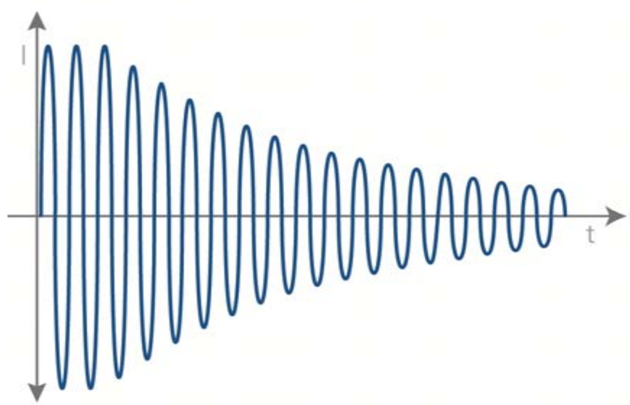
CTA Residual Magnetism Card

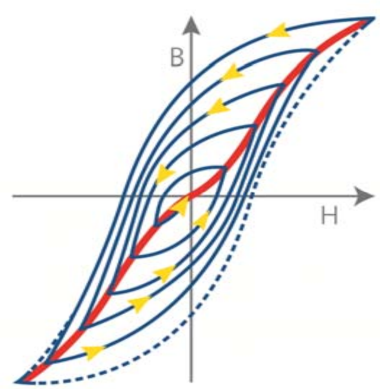




Residual Magnetism

- Demagnetization process
  - **by applying minimum the same electrical force as the force caused the magnetization effect.**





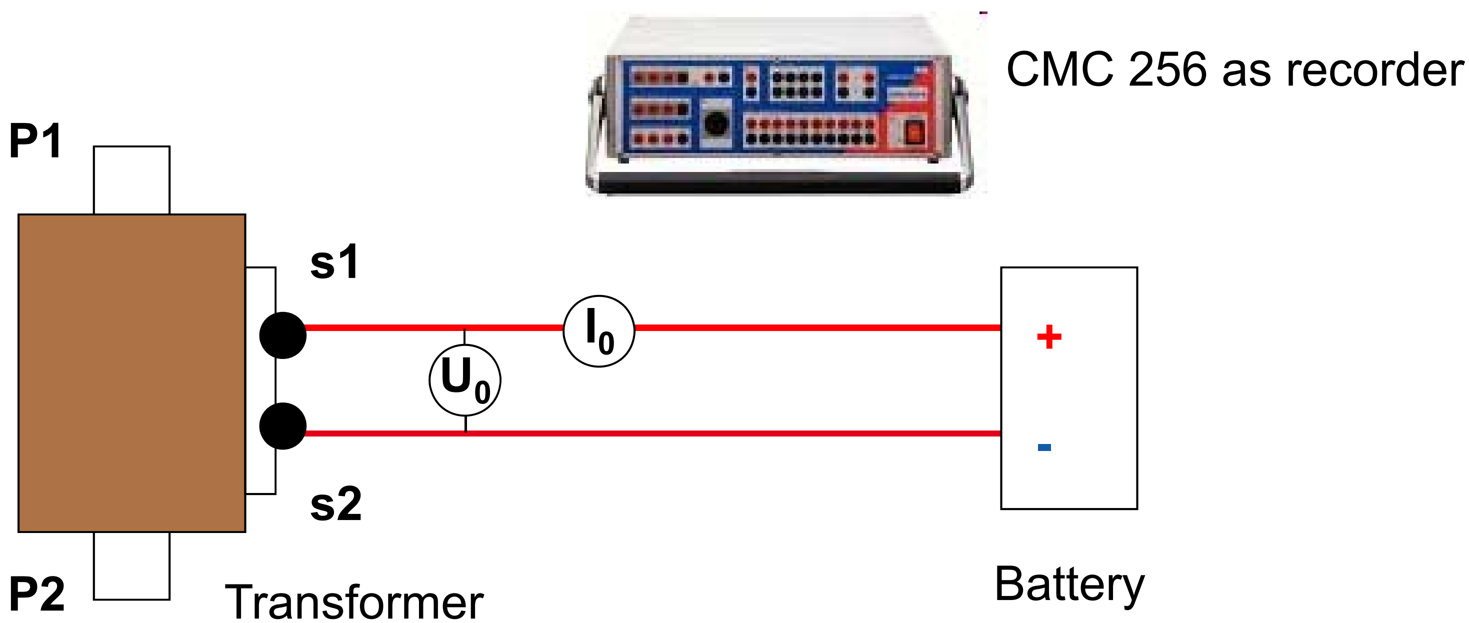
  - recommendation:
  - starting with similar force as the force which drove the core into saturation than reducing step by step to demagnetize the core

Determining the residual magnetism

- Determining the residual magnetism in a field test
- Analysis of the measured values
- Determining the residual magnetism with the CT Analyzer

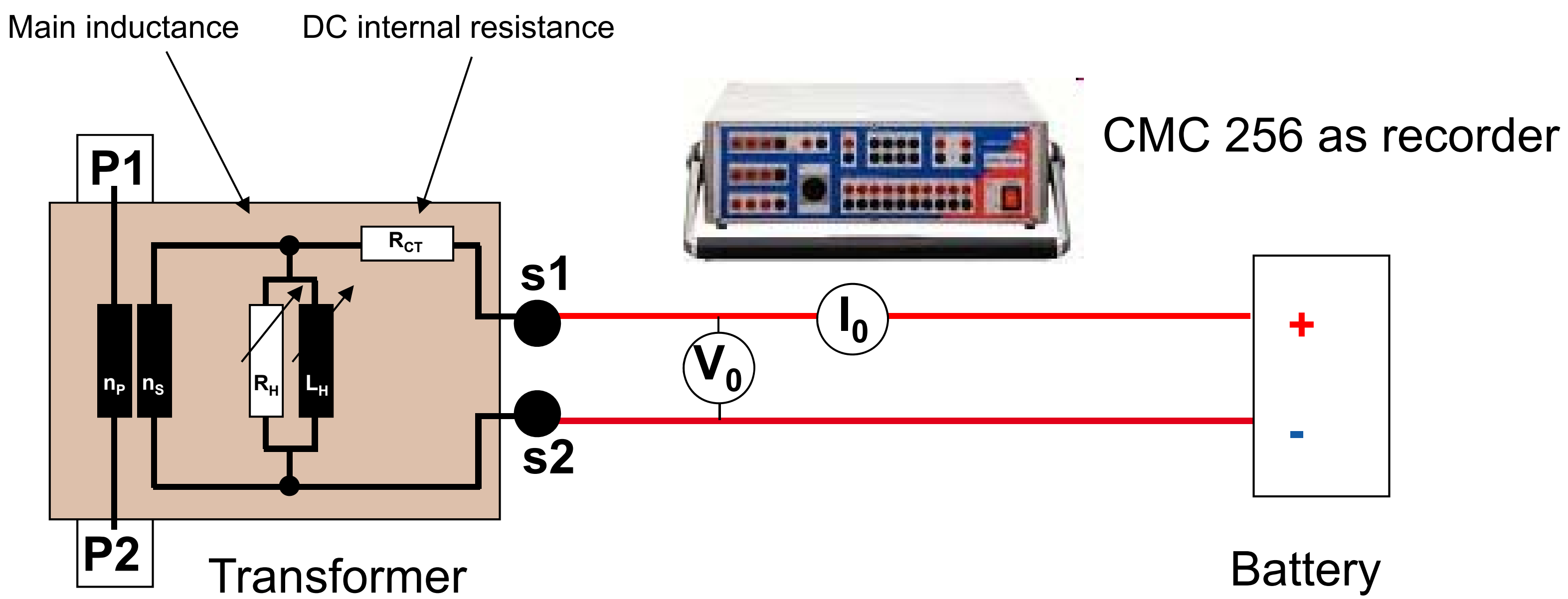
- **Determining the residual magnetism in a field test**

  - The residual magnetism can be determined relatively precisely using simple test apparatus.



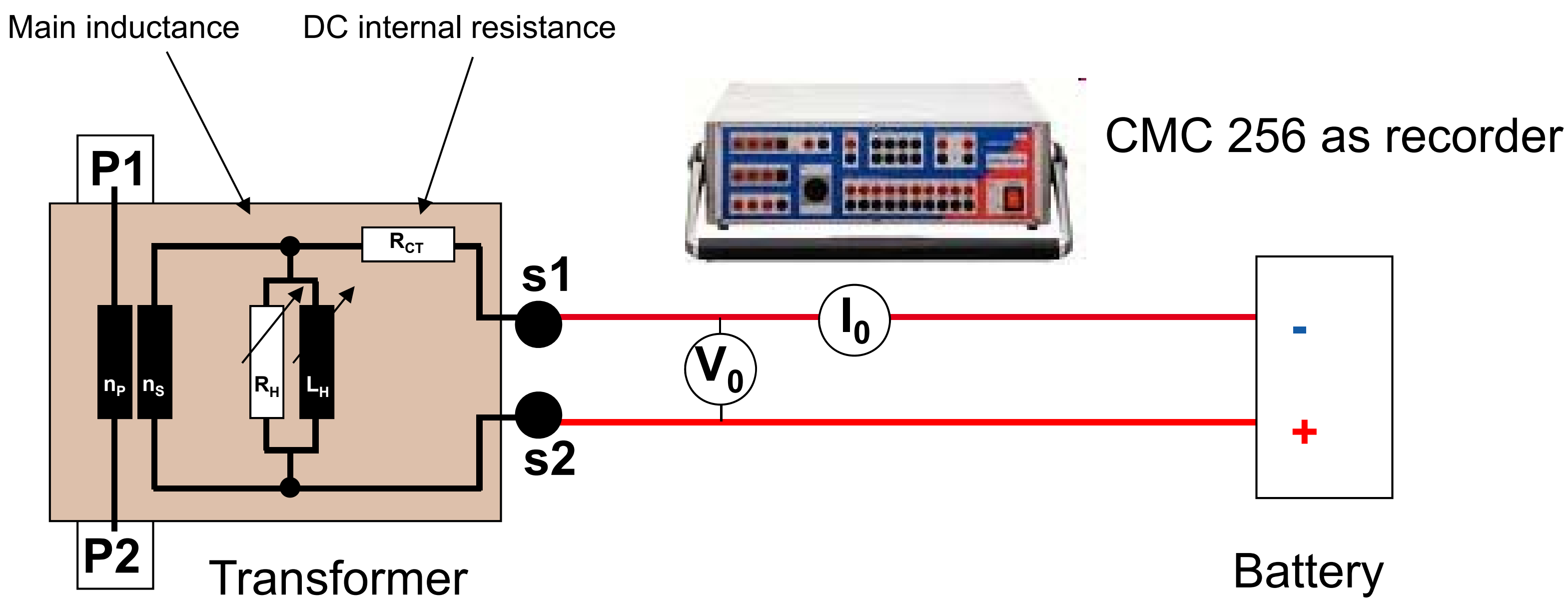
- **Determining the residual magnetism in a field test**

  - The test is performed in three steps
    - Load is applied until I_0 and V_0 are constant.



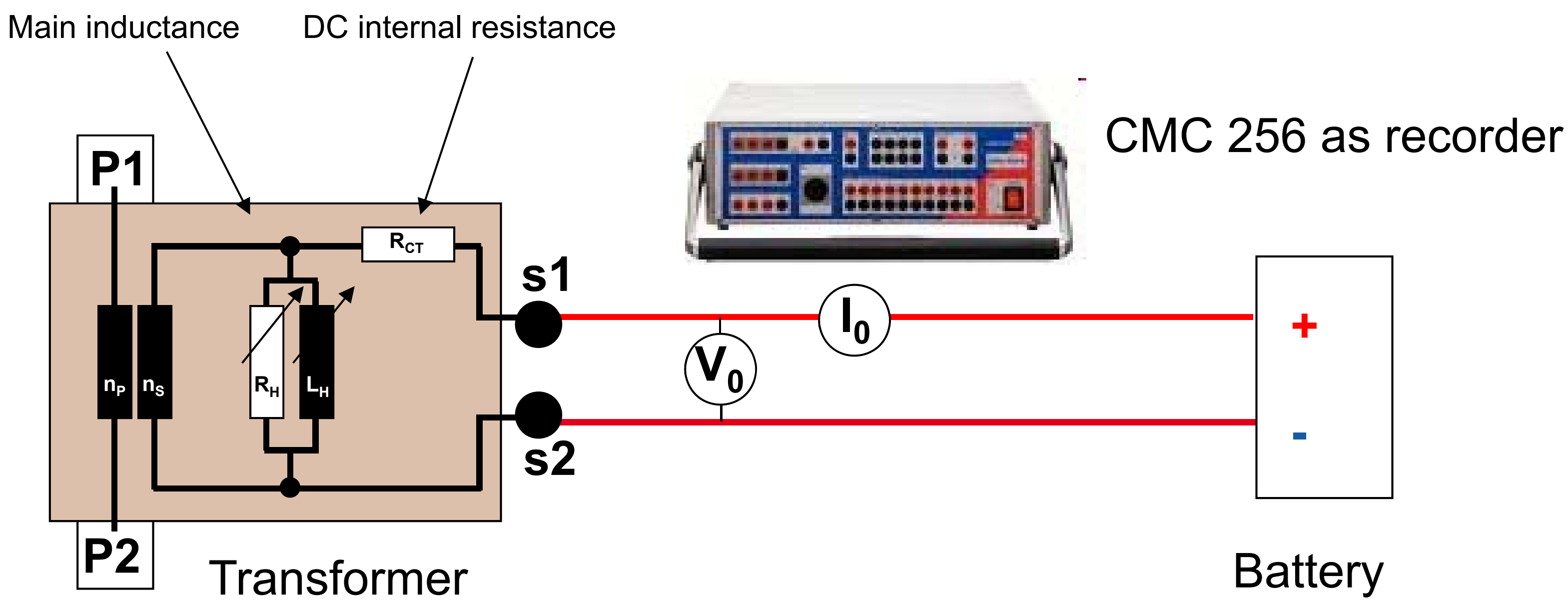
Determining the residual magnetism in a field test

- The test is performed in three steps
  - Load is applied until I_0 and V_0 are constant.
  - This is then repeated with opposite polarity.



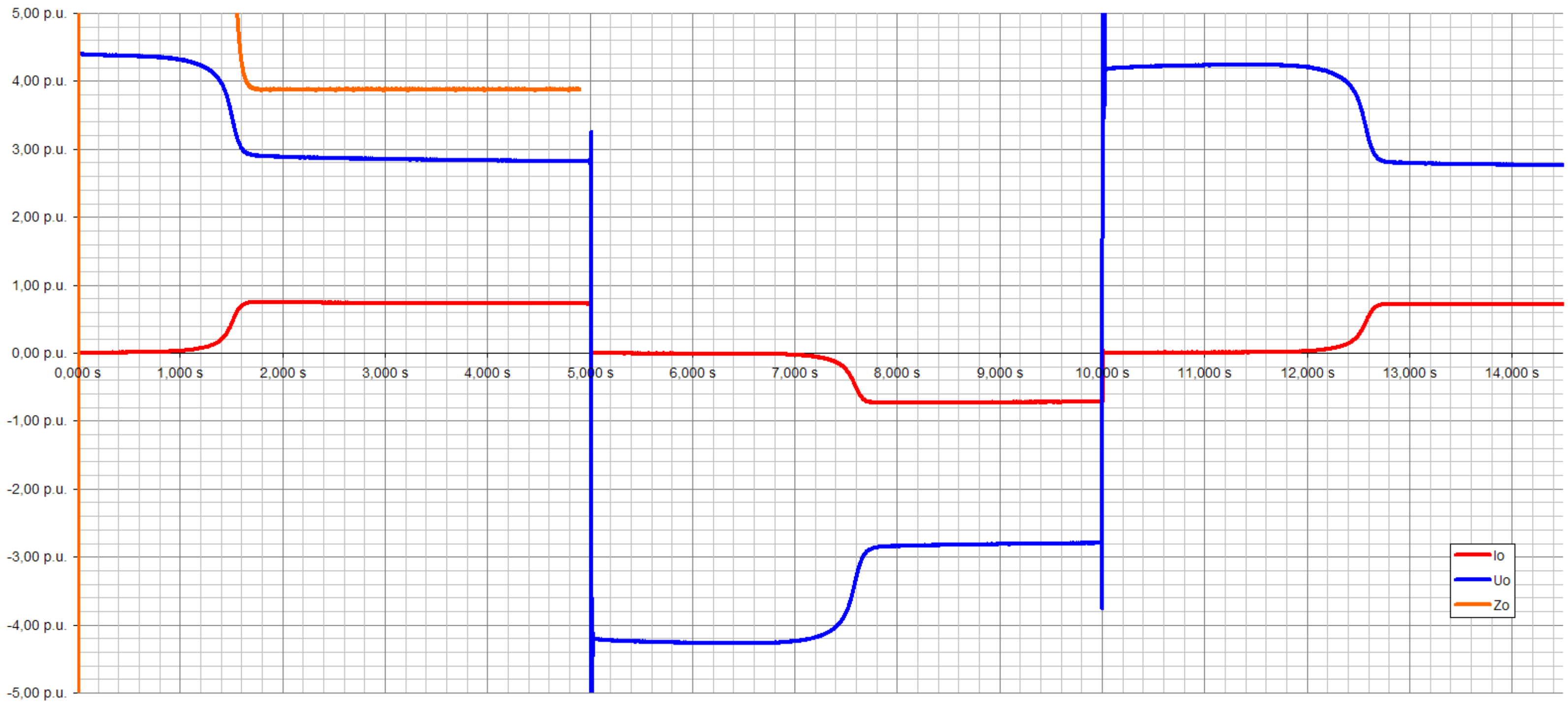
- # Determining the residual magnetism in a field test

– The test is performed in three steps
  - Load is applied until I_0 and V_0 are constant.
  - This is then repeated with opposite polarity.
  - This is then repeated once more with opposite polarity.



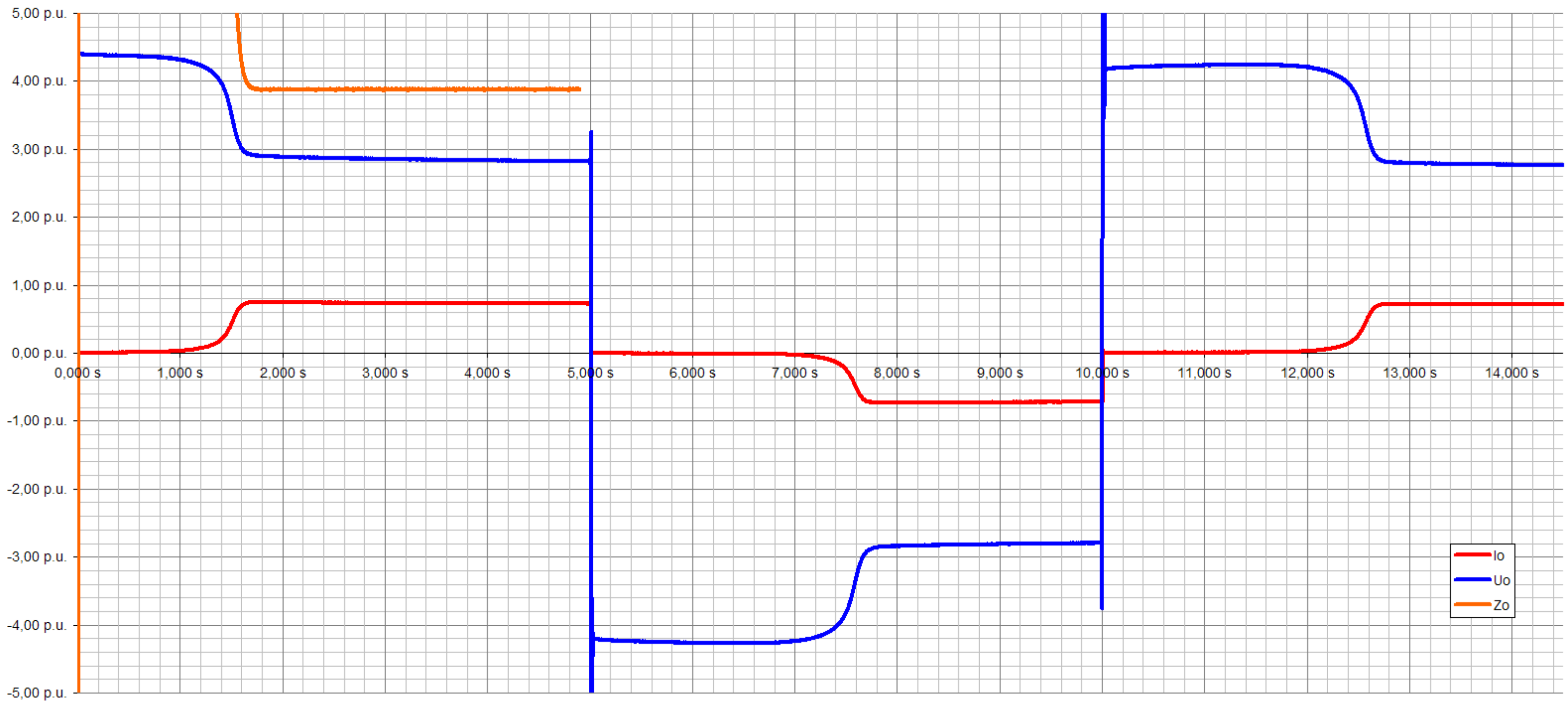
Analysis of the measured values

- With voltage V_0 applied, the current I_0 increases.
  The internal load of the transformer Z_0 drops until V_0, I_0 and Z_0 are constant.



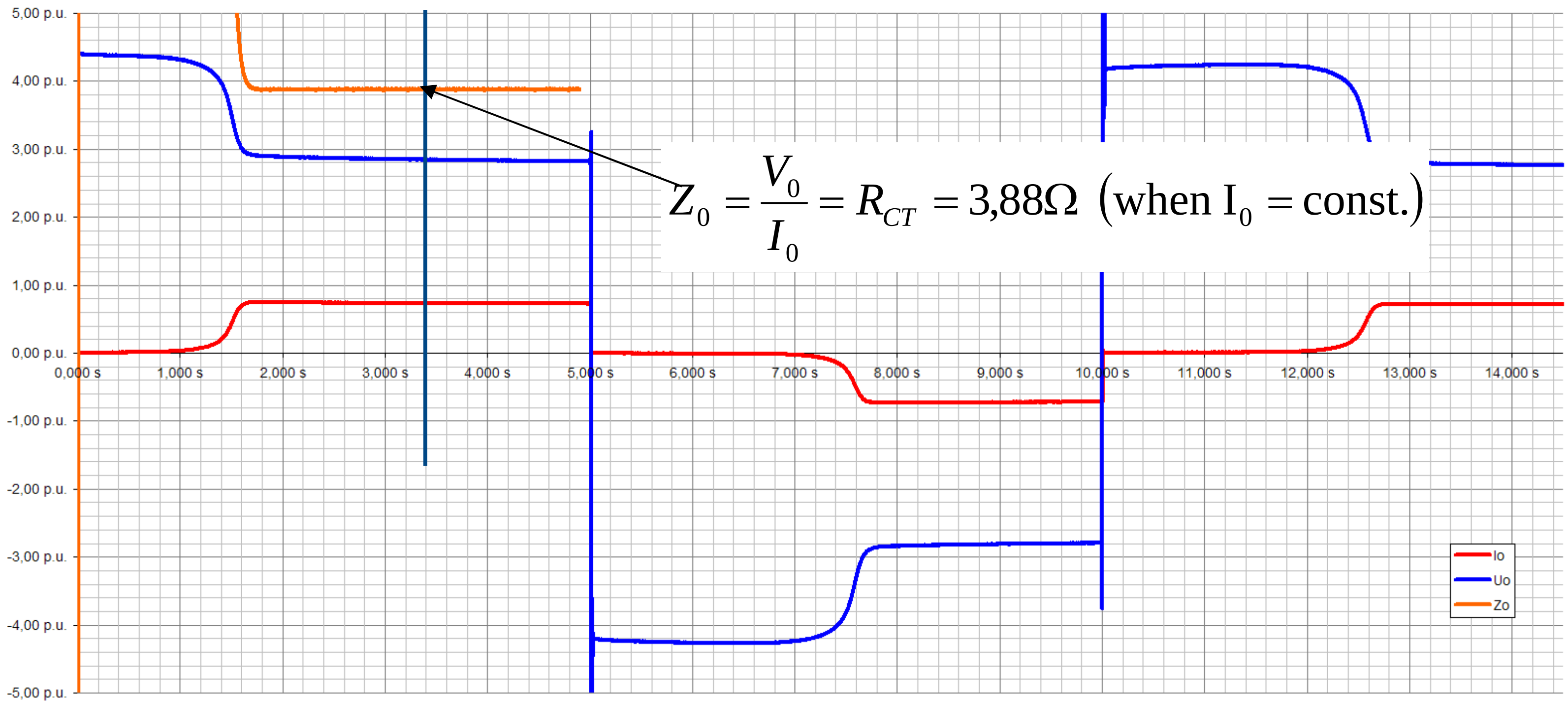
Analysis of the measured values

- As the flux in the core increases, the main inductance L_H of the transformer changes. At maximum flux, the unsaturated inductance L_S becomes the saturated inductance L_S.



- # Analysis of the measured values

  – The reactance X_{LS} of the saturated main inductance L_S is several times lower than the DC internal resistance R_{CT} of the transformer. As such, $Z_0 = R_{CT}$ at constant current flow.

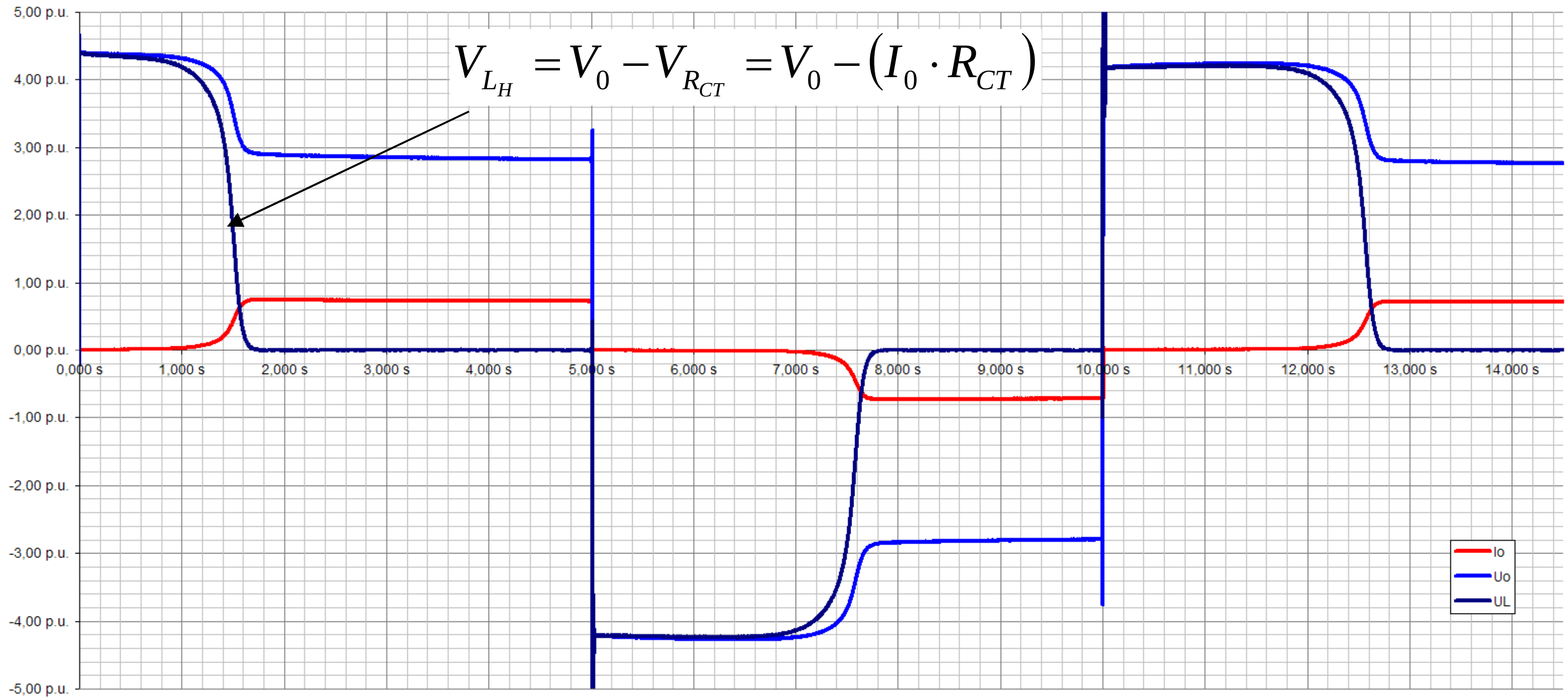


$$Z_0 = \frac{V_0}{I_0} = R_{CT} = 3{,}88\Omega \ \left(\text{when } \mathrm{I}_0 = \text{const.}\right)$$

- # Analysis of the measured values

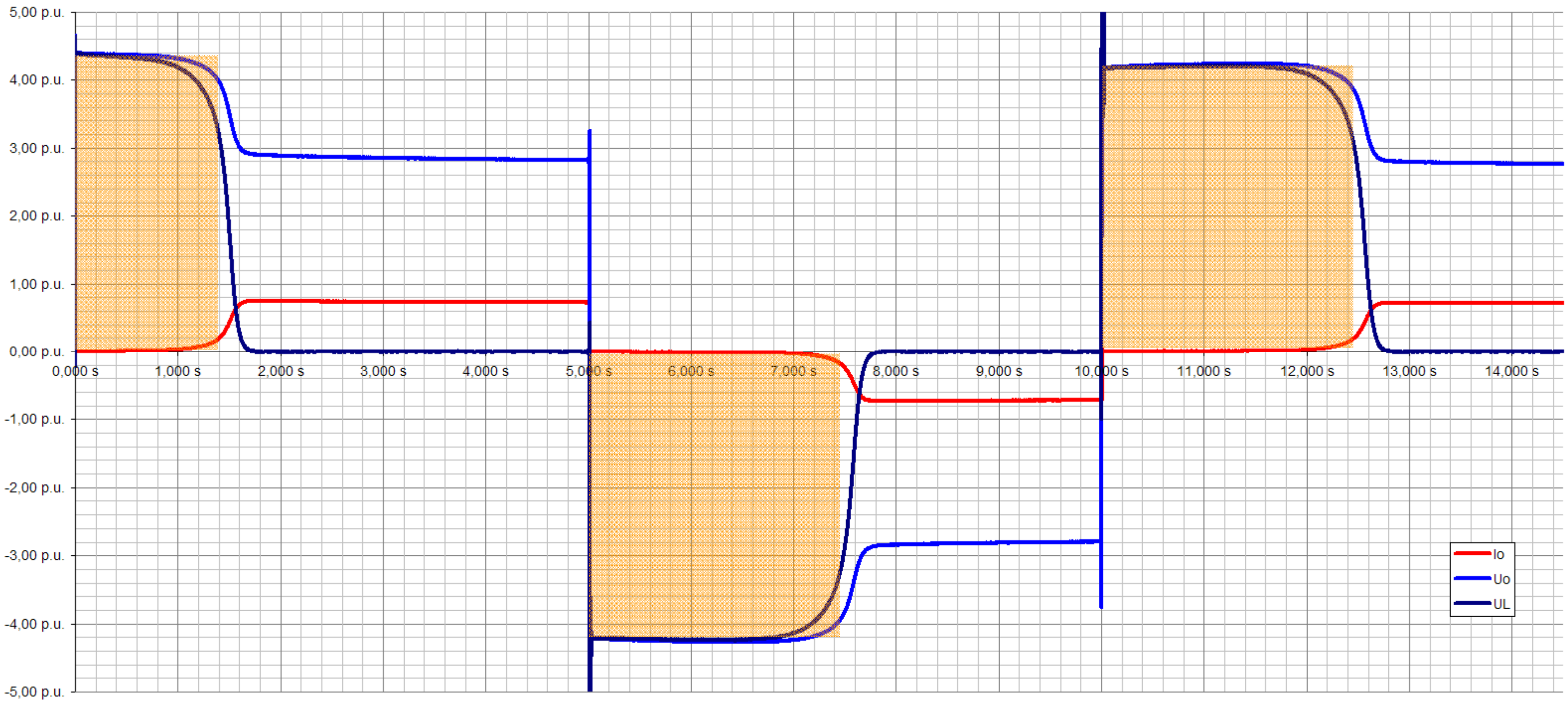
  – If R_{CT} is known, the voltage can be calculated via the main inductance L_H

  .



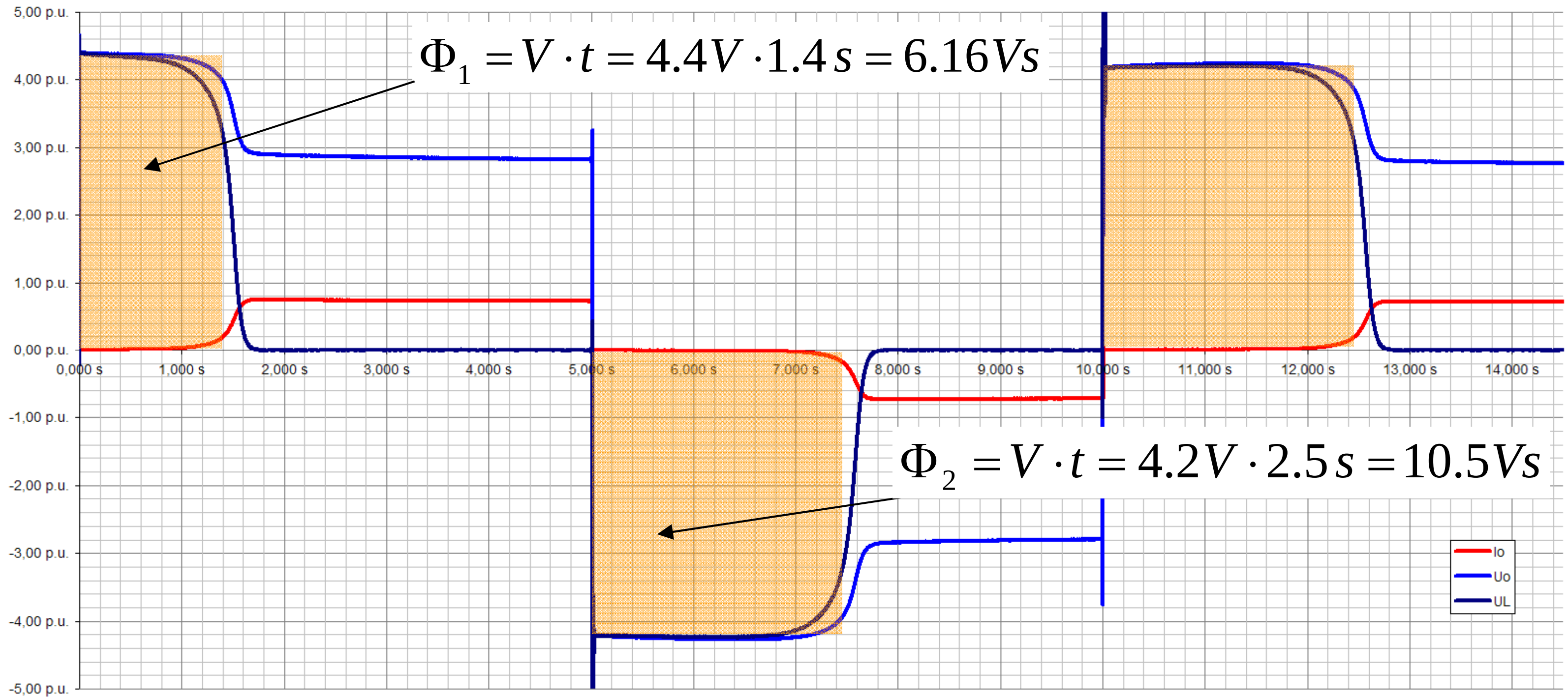
• Analysis of the measured values

– The area below the voltage V_{LH} is the magnetic flux [Φ in Vs] in the current transformer's core.



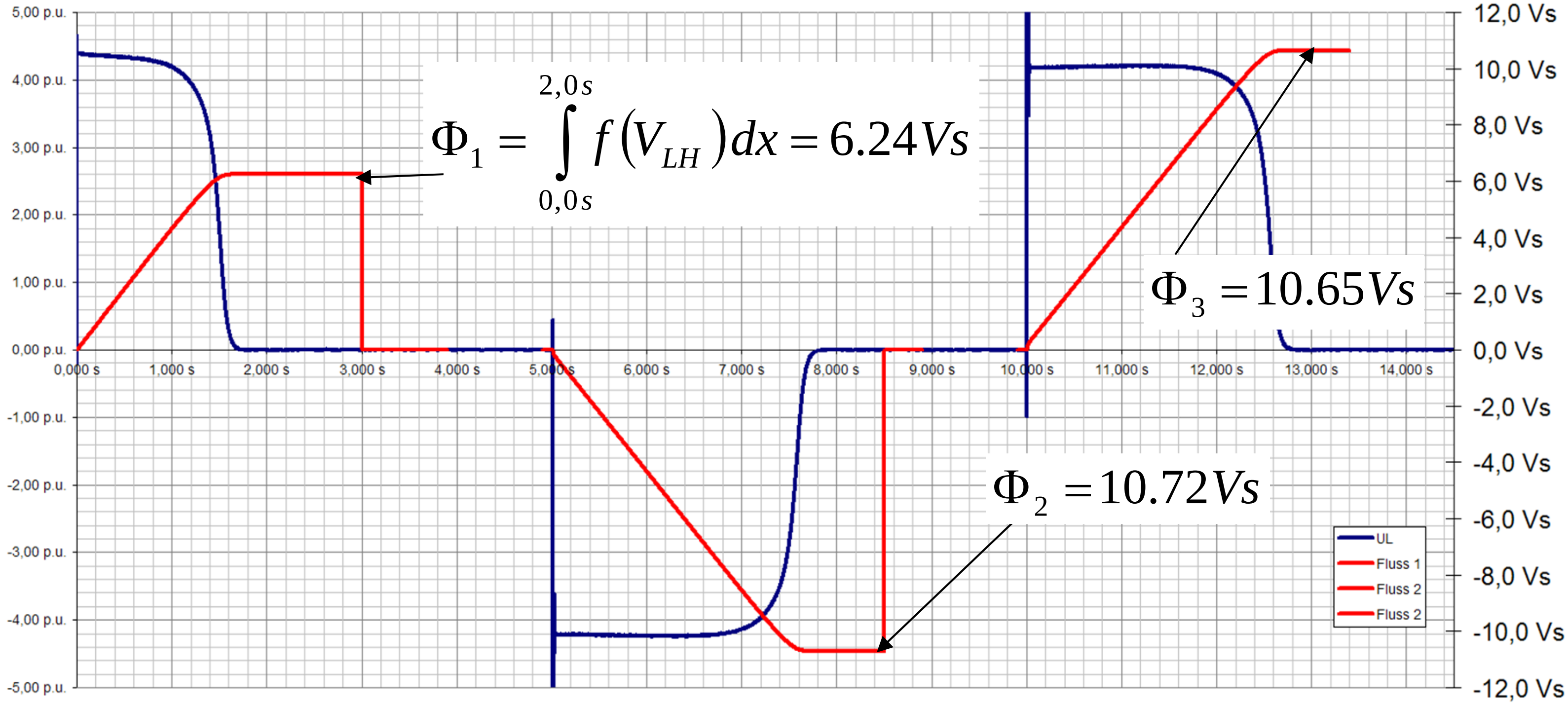
• Analysis of the measured values

– Approximate calculation of the areas (of the flux in the core).



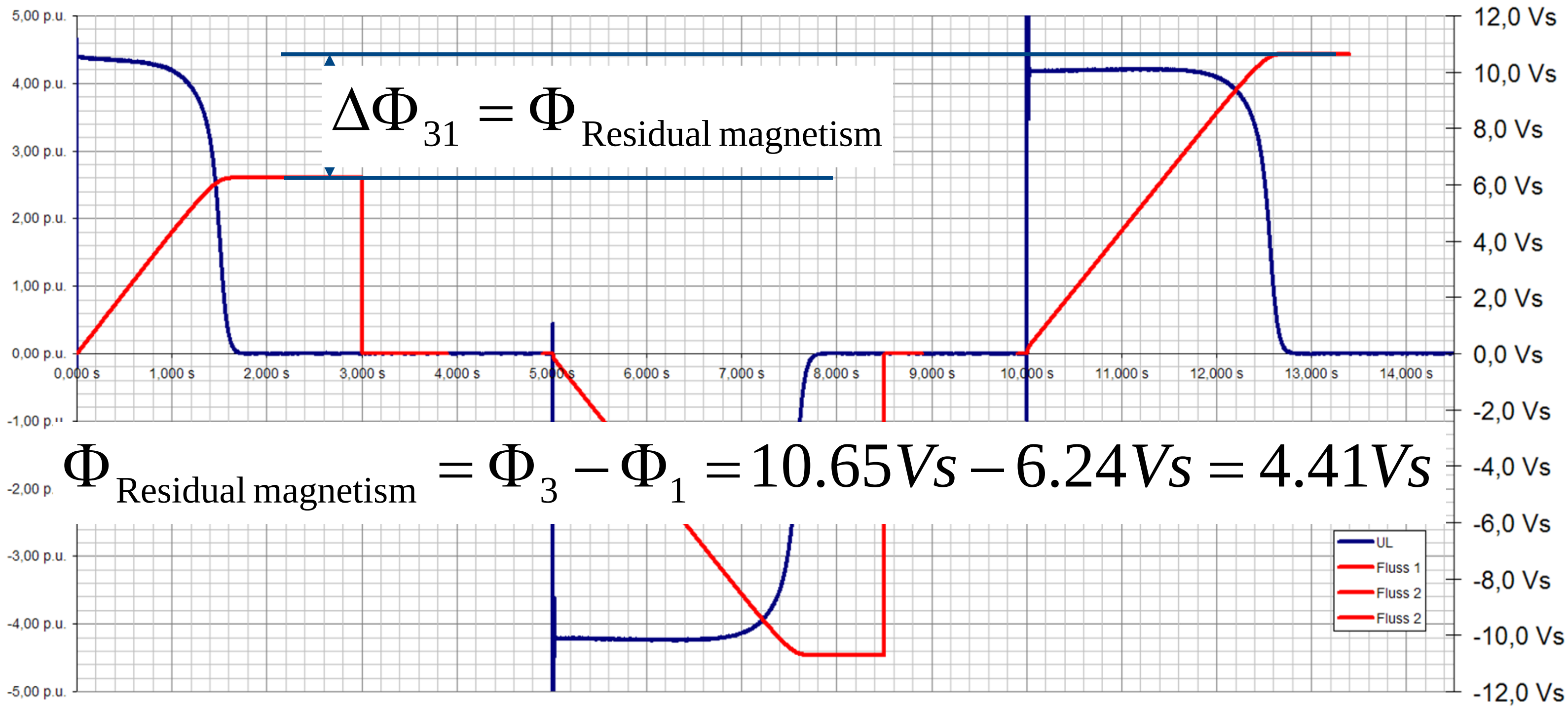
• Analysis of the measured values

– Calculation of the flux via the integral of the voltage V_{LH}.



• Analysis of the measured values

– Conclusions regarding the flux of the transformer at the start of the measurement. The difference between Φ_3 and Φ_1 is the flux level prior to starting the measurement.

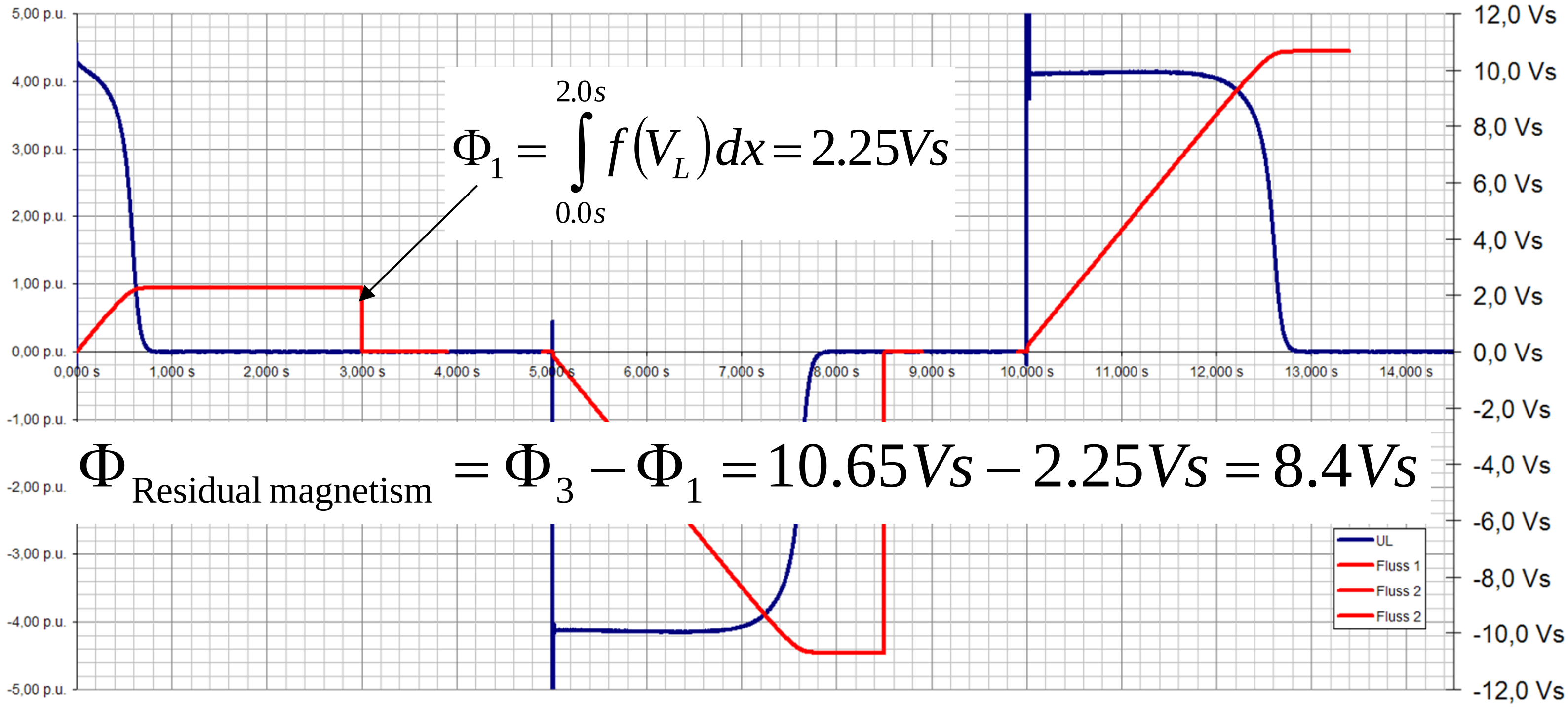


$$\Delta\Phi_{31} = \Phi_{\text{Residual magnetism}}$$

$$\Phi_{\text{Residual magnetism}} = \Phi_3 - \Phi_1 = 10.65Vs - 6.24Vs = 4.41Vs$$

• Analysis of the measured values

– To determine the residual magnetism, the core is <u>fully</u> magnetized in the positive direction right up to saturation (I_0 = constant) prior to starting measurements.

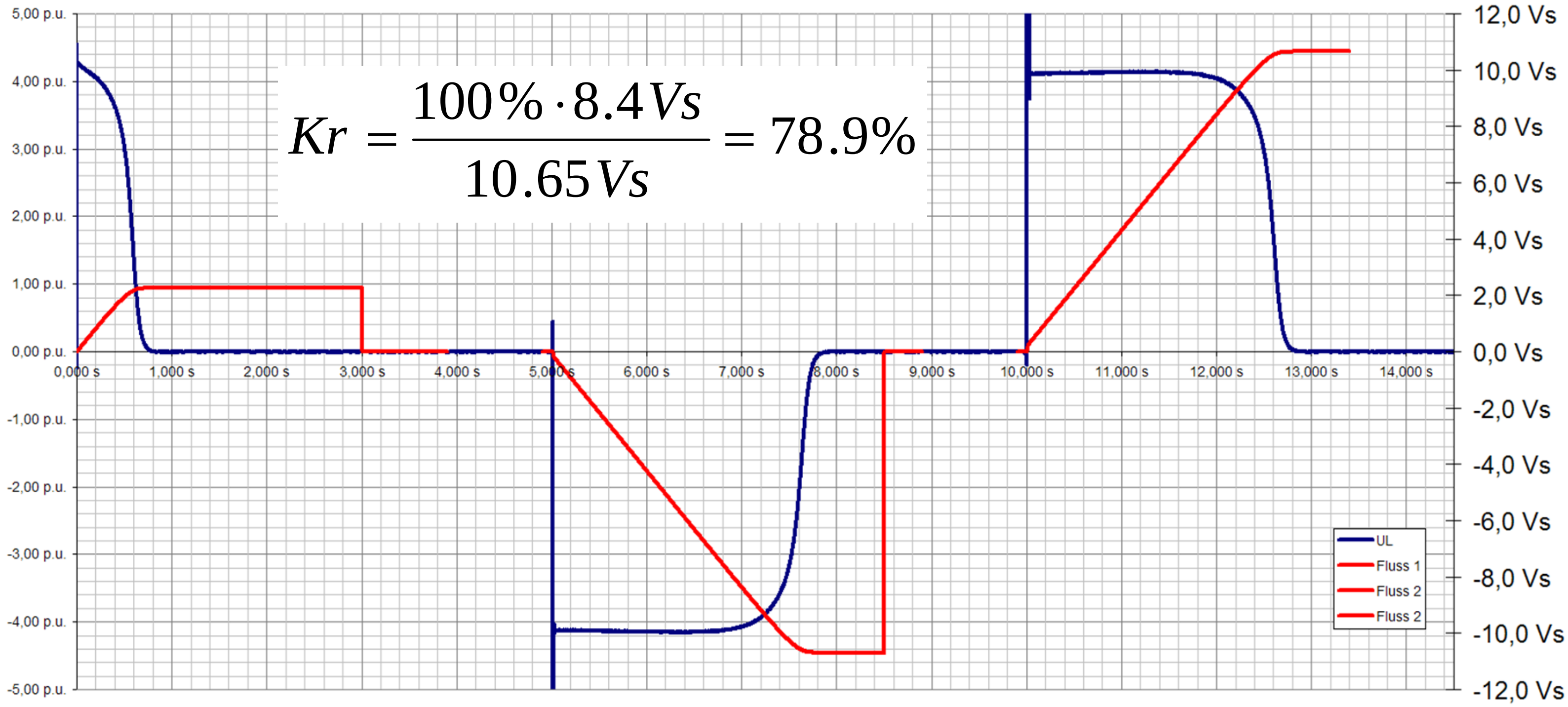


$$\Phi_1 = \int_{0.0s}^{2.0s} f(V_L)\,dx = 2.25Vs$$

$$\Phi_{\text{Residual magnetism}} = \Phi_3 - \Phi_1 = 10.65Vs - 2.25Vs = 8.4Vs$$

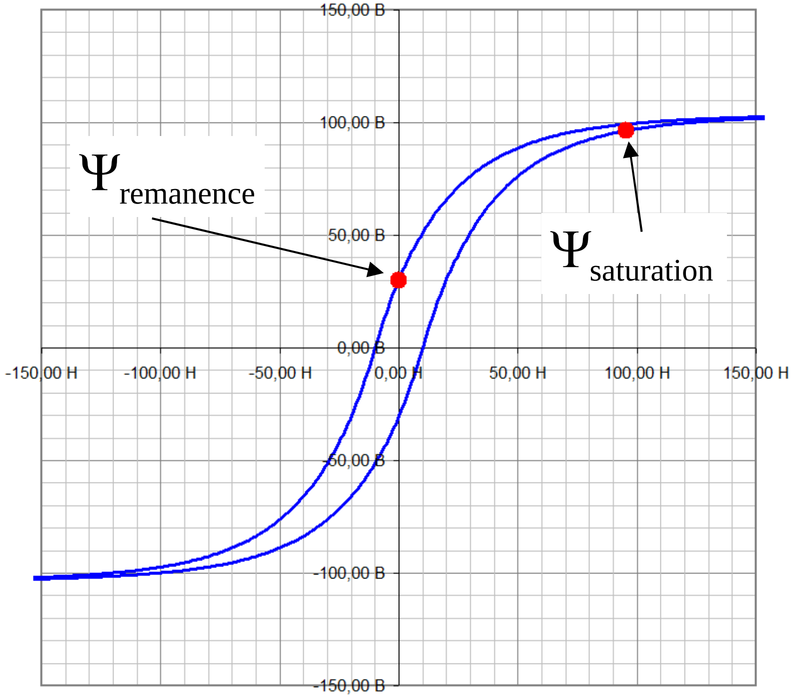
- **Analysis of the measured values**
  - The residual magnetism determined [Kr] for this core is around 78.9%.

$$Kr = \frac{100\% \cdot 8.4Vs}{10.65Vs} = 78.9\%$$



• Analysis of the measurement results

– For the sake of completeness it should be mentioned, that the saturation flux acc. IEC is reached when a 10% increase of B causes a 50% increase of H.



$$K_{\text{remanence}} = 100 \cdot \frac{\Psi_{\text{remanence}}}{\Psi_{\text{saturation}}}$$

Summary

> Residual Magnetism will effect how a CT performs during a fault.

> Demag after all tests.

> May want to consider Demag after faults on critical circuits.

> Questions??

Thanks for your attention.

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