Inrush Currents and Their Effect on Protective Relays

Roberto Cimadevilla

Overview

- Inrush currents theory:
  - Transformer energization
  - Voltage recovery after an external fault
  - Sympathetic inrush
- Influence of inrush currents on transformer differential:
  - Harmonic restraint / blocking
  - Crossed logics
  - Dynamic application of restraint / blocking
- Influence of inrush currents on the rest of protective functions

Inrush Currents Theory

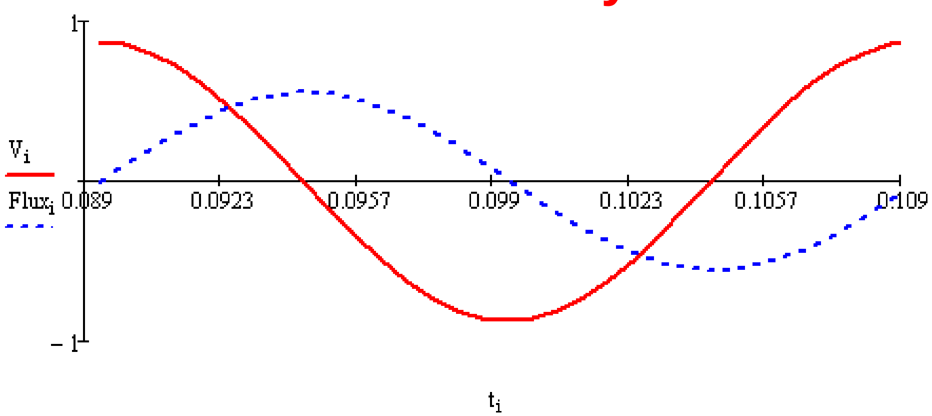
Magnetic Flux

- Inrush currents occur because of a saturation of the power transformer due to a DC offset in the flux

$$v = N1 \cdot \frac{d\phi}{dt} \qquad v = Vm \cdot \sin(wt + \theta)$$

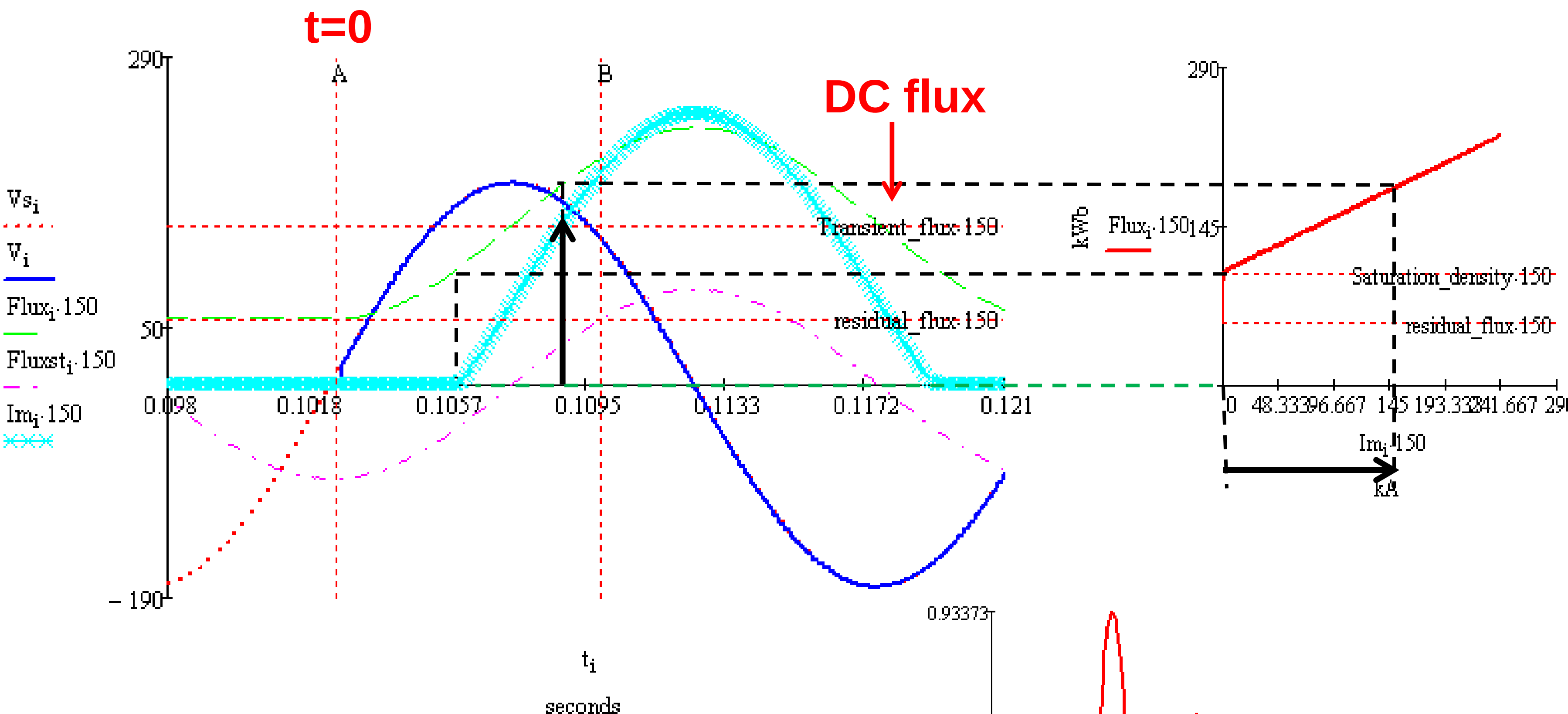
$$\phi = \frac{1}{N1}\int_0^t v(t)dt = \underbrace{-\frac{Vm}{N1 \cdot w} \cdot \cos(wt + \theta)}_{\text{Steady state flux}} + \underbrace{k}_{\text{DC flux} \rightarrow t=0}$$

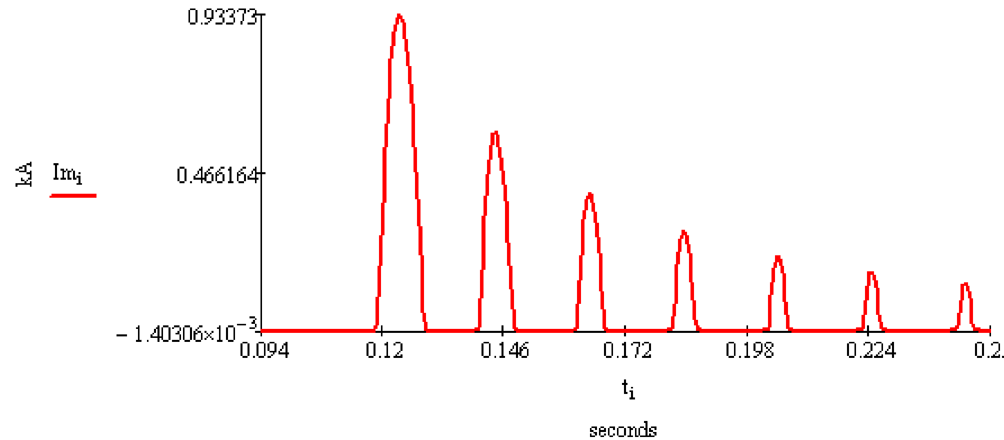
Steady state flux **DC flux → t=0**



$$k = \phi_0 - \left(-\frac{Vm}{N1 \cdot w} \cdot \cos(\theta)\right)$$

Transformer Energization





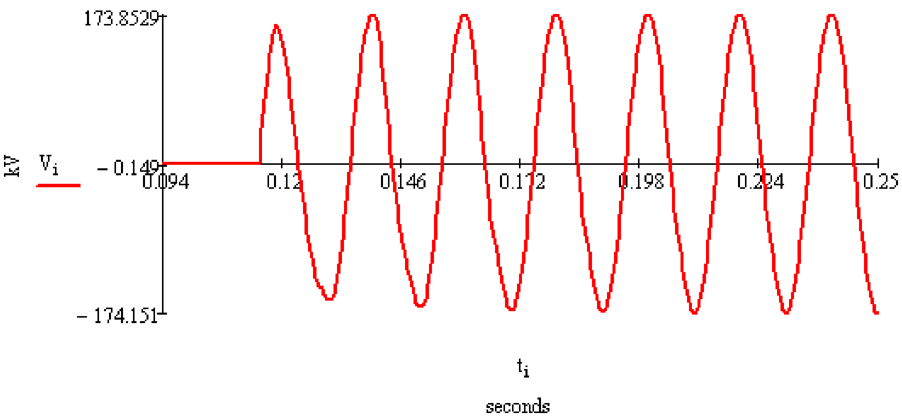
Damping of Flux and Imag

$$v' = N1 \cdot \frac{d\phi}{dt} \qquad v' = v - R \cdot i - L \cdot \frac{di}{dt} \qquad \phi = \int_0^t v(t)\cdot dt - \int_0^t R\cdot i(t)\cdot dt - \int_0^t L\cdot \frac{di(t)}{dt}\cdot dt$$

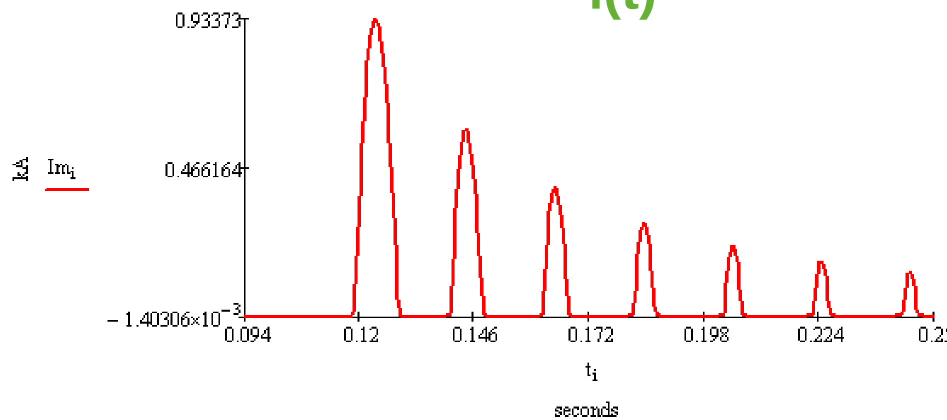
$$\phi_t - \phi_{t-T} \square \int_{t-T}^{t} v(t)\cdot dt - \int_{t-T}^{t} R\cdot i(t)\cdot dt - \int_{t-T}^{t} L\cdot \frac{di(t)}{dt}\cdot dt$$

0 0

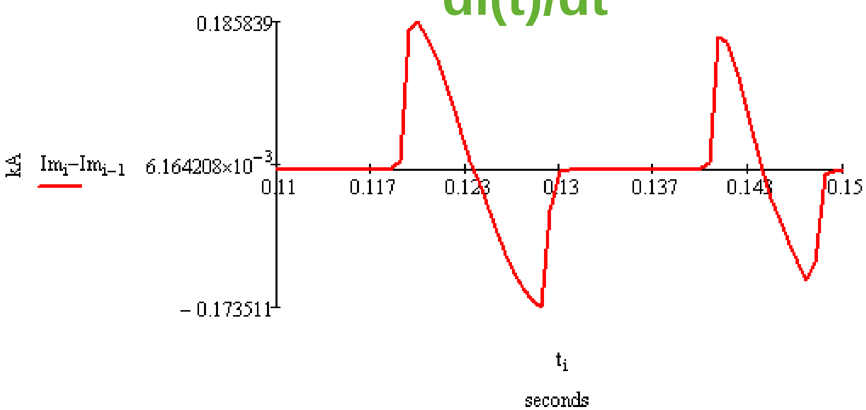
v(t)



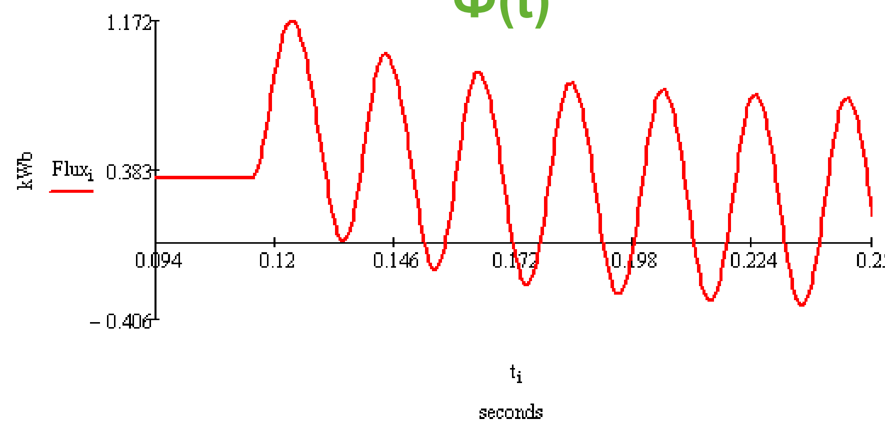
i(t)



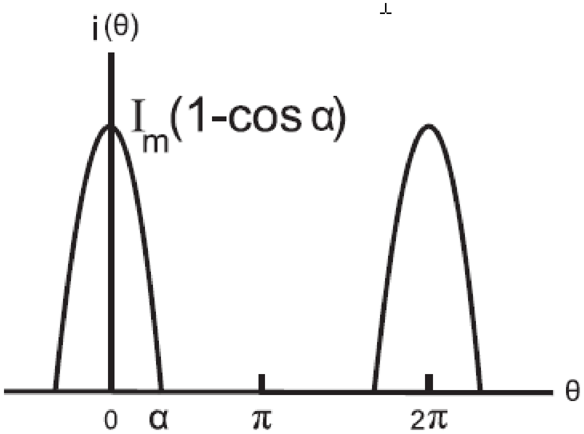
di(t)/dt



Φ(t)



Harmonic Content of the Inrush Current

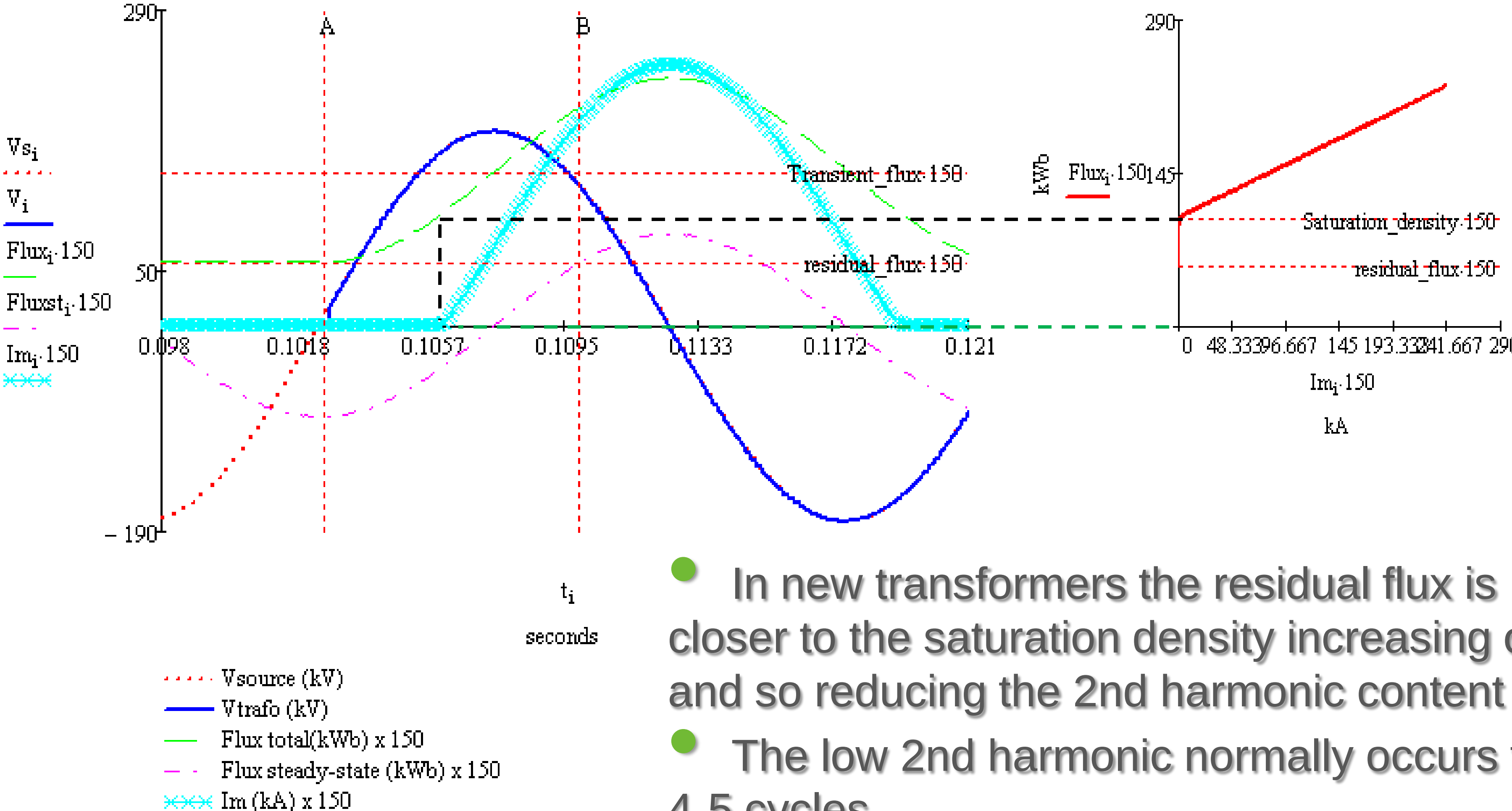


$$i(\theta) = \mathrm{Im} \cdot (\cos\theta - \cos\alpha),\ 0 \le \theta \le \alpha,\ (2\pi\text{-}\alpha) \le \theta \le 2\pi$$
$$0,\ \alpha \le \theta \le (2\pi - \alpha)$$

$$a_n = \frac{\mathrm{Im}}{\pi} \cdot [\frac{1}{n+1} \cdot \sin((n+1)\cdot\alpha) + \frac{1}{n+1} \cdot \sin((n-1)\cdot\alpha) - \frac{2}{n} \cdot \sin(n\alpha) cons\alpha]$$

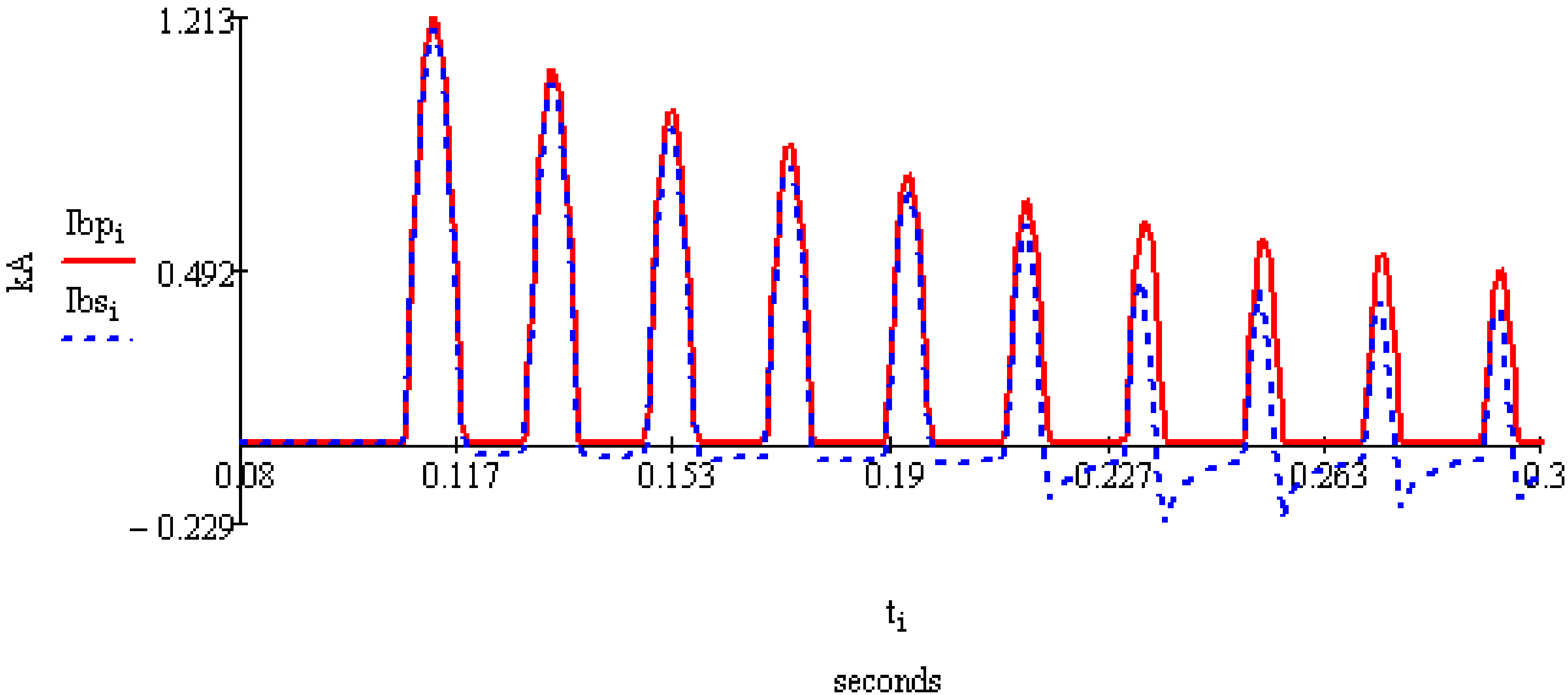
Harmonic	an/a1		
	α=60°	α=90°	α=120°
2	0.705	0.424	0.171
3	0.352	0.000	0.086
4	0.070	0.085	0.017
5	0.070	0.000	0.017
6	0.080	0.036	0.019
7	0.025	0.000	0.006
8	0.025	0.029	0.006
9	0.035	0.000	0.008
10	0.013	0.013	0.003
11	0.013	0.000	0.003
12	0.020	0.009	0.005
13	0.008	0.000	0.002

Harmonic Content of the Inrush Current

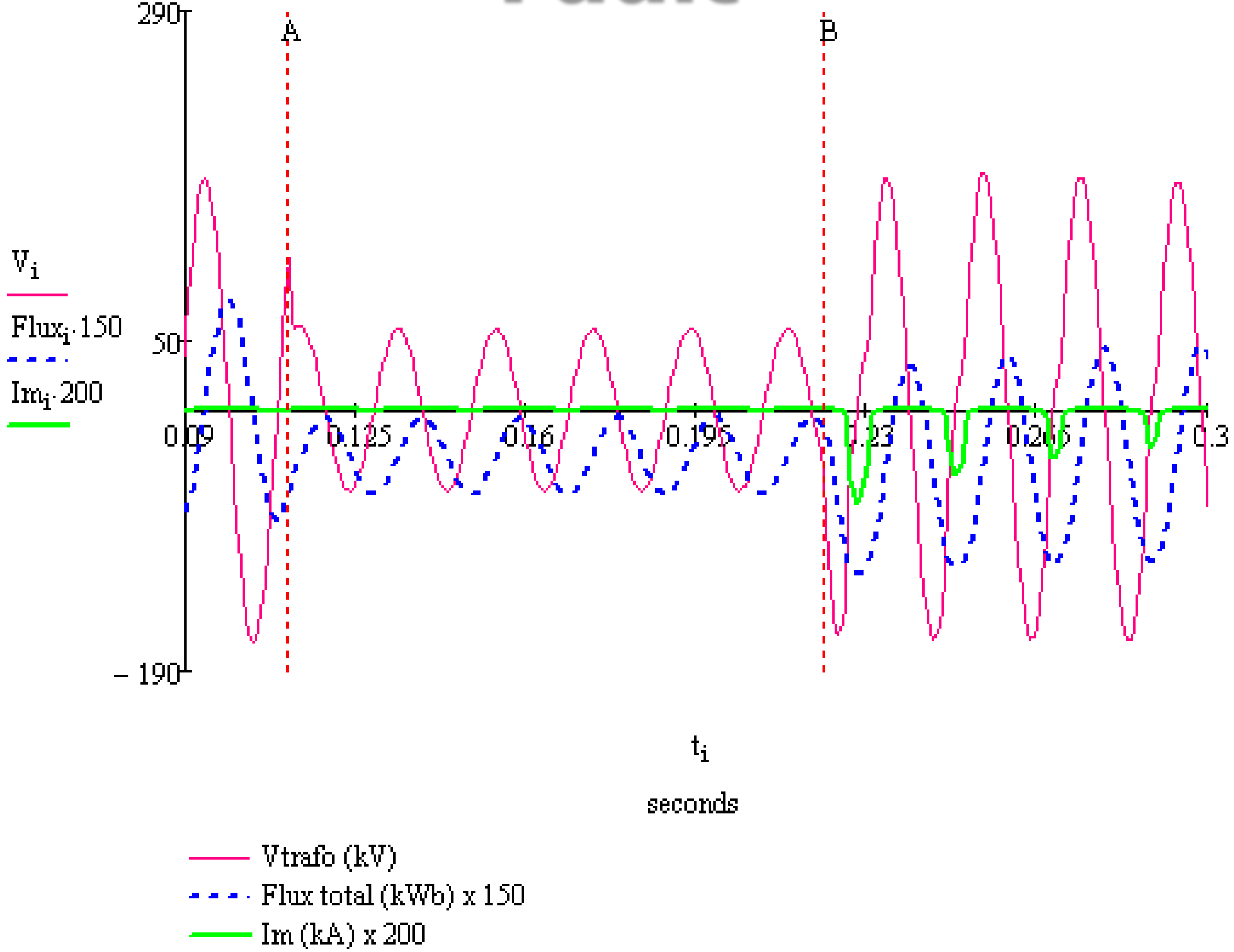


- In new transformers the residual flux is closer to the saturation density increasing α and so reducing the 2nd harmonic content
- The low 2nd harmonic normally occurs for 4-5 cycles

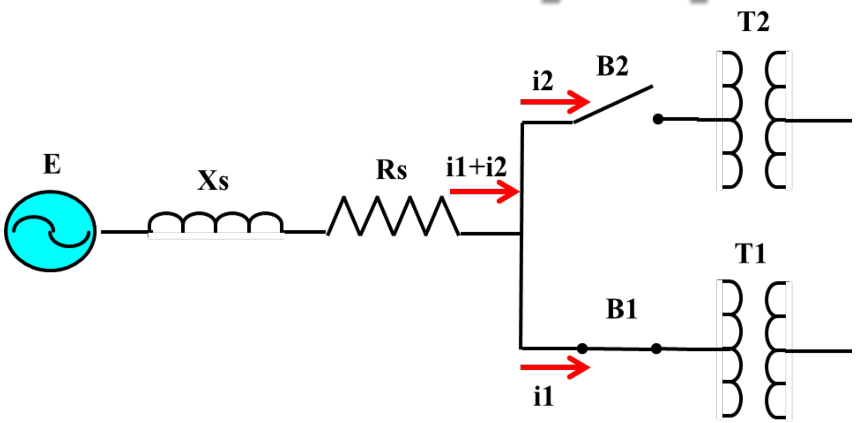
CT Saturation



Voltage Recovery after External Fault

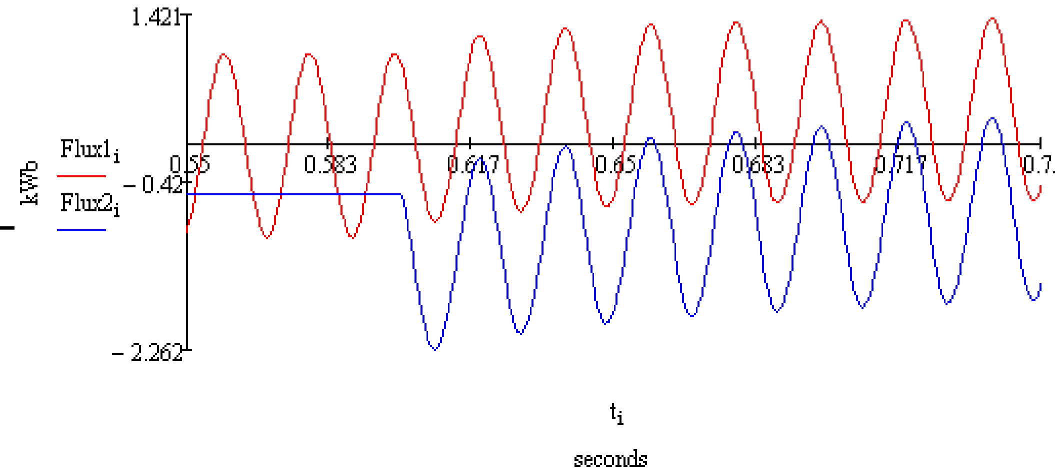


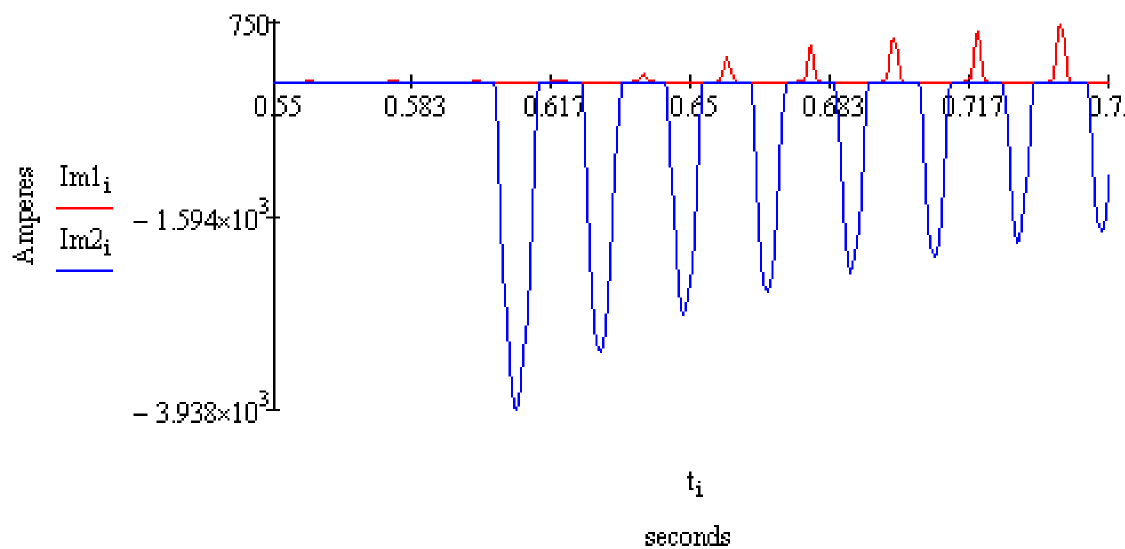
Sympathetic Inrush



$$\phi2_t - \phi2_{t-T} \square -\int_{t-T}^{t} [Rs \cdot (i1 + i2) + R2 \cdot i2] \cdot dt$$

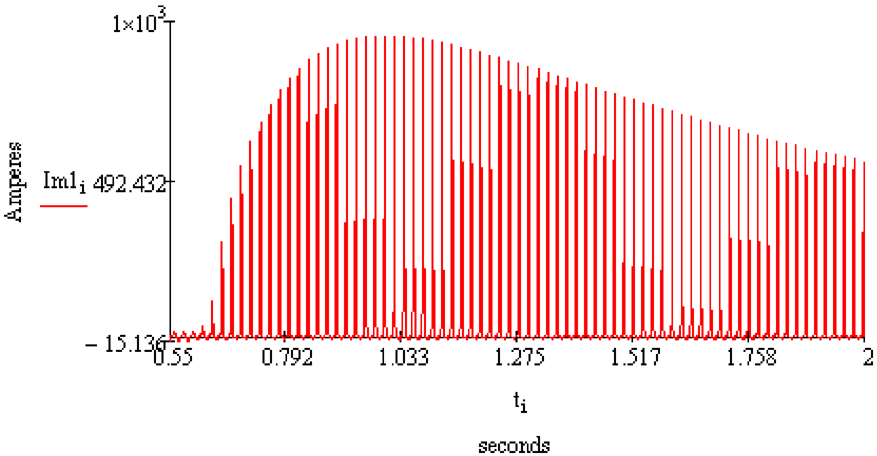
$$\phi1_t - \phi1_{t-T} \square -\int_{t-T}^{t} [Rs \cdot (i1 + i2) + R1 \cdot i1] \cdot dt$$



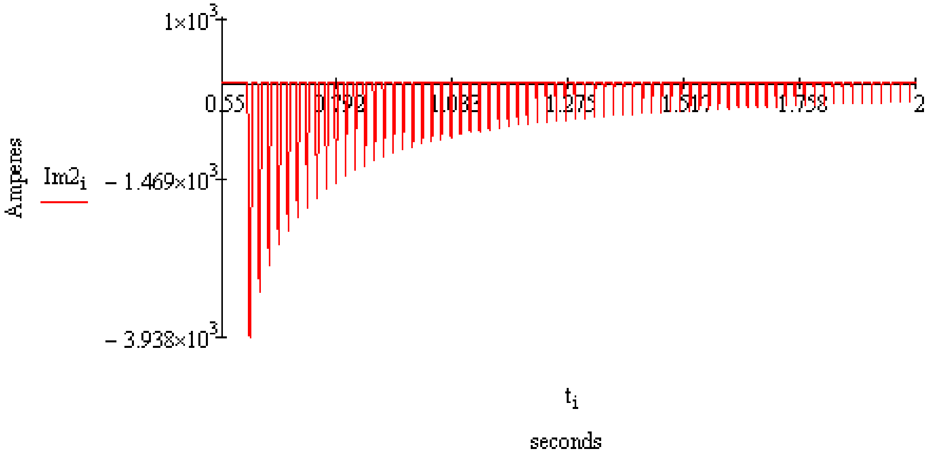


Sympathetic Inrush

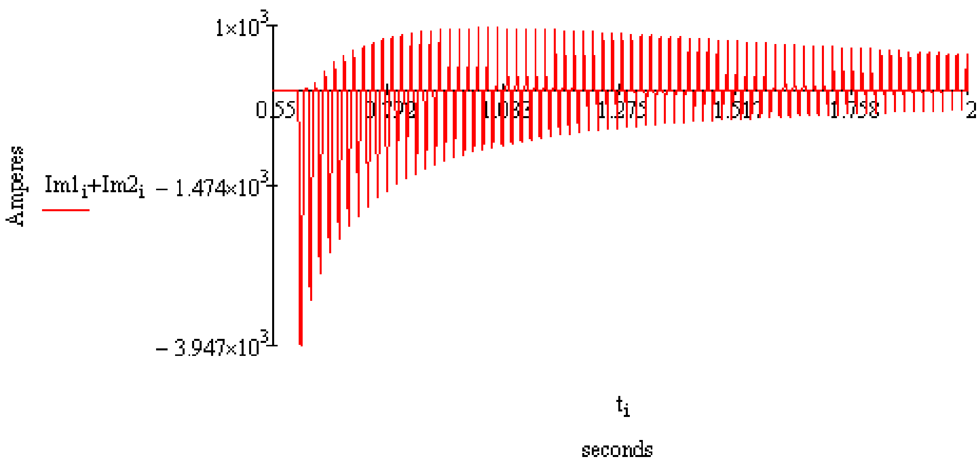
IM1



IM2



IM1+IM2

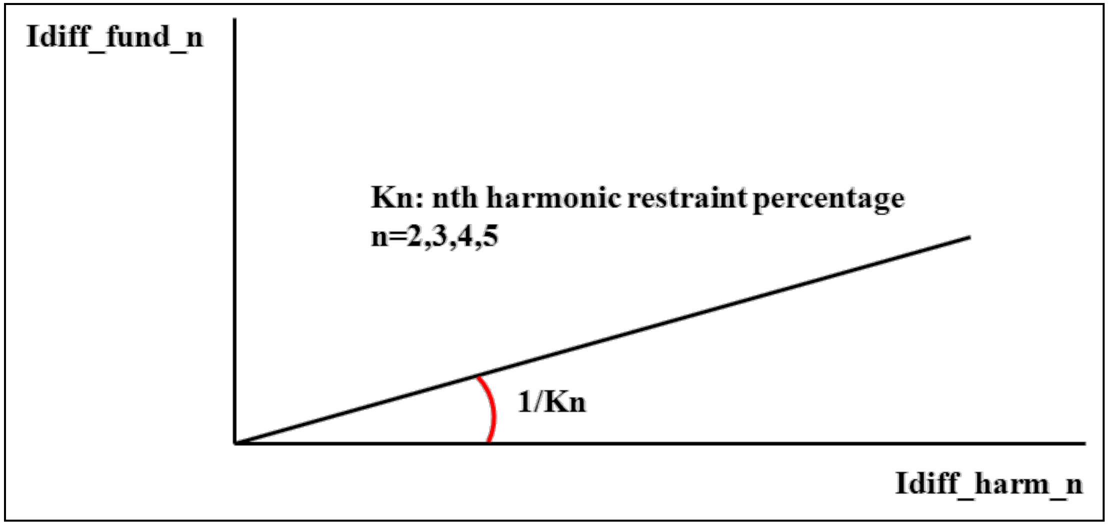


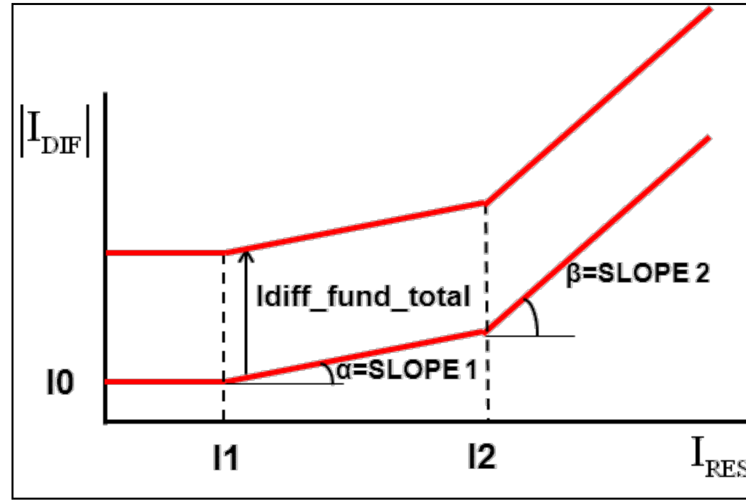
Inrush Currents Effect on Transformer Differential

Inrush Effect on 87T

- Magnetizing reactance is a shunt branch so inrush current is a differential current
- Methods commonly used to avoid operation of 87T:
  - Harmonic restraint
  - Harmonic blocking
  - Wave-shape recognition

Harmonic Restraint





Operating condition:

$$I_{diff\_fund} > I_{\substack{diff \\ through \\ current \\ restraint}} + I_{\substack{diff \\ harmonic \\ restraint}} = I_{rest} \cdot f(\alpha, \beta) + \sum_{n=2}^{5} \frac{I_{diff\_harm\_n}}{Kn}$$

Harmonic Blocking

$$\frac{I_{diff\_harm\_n}}{I_{diff\_fund}} > Kn$$

Operating condition:

$$\left(I_{diff\_fund} > I_{\substack{diff\\through\\current\\restraint}} = I_{rest} \cdot f(\alpha, \beta) \right) \otimes \left(\frac{I_{diff\_harm\_n}}{I_{diff\_fund}} < Kn \right)$$

$$\left(I_{diff\_fund} > I_{rest} \cdot f(\alpha, \beta) \right) \otimes \left(I_{diff\_fund} > \frac{I_{diff\_harm\_n}}{Kn} \right)$$

Harmonic Restraint vs Blocking

Harmonic Restraint

$$I_{diff\_fund} > I_{\substack{diff \\ through \\ current \\ restraint}} + I_{\substack{diff \\ harmonic \\ restraint}} = I_{rest} \cdot f(\alpha, \beta) + \sum_{n=2}^{5} \frac{I_{diff\_harm\_n}}{Kn}$$

Harmonic Blocking

$$\left(I_{diff\_fund} > I_{rest} \cdot f(\alpha, \beta) \right) \otimes \left(I_{diff\_fund} > \frac{I_{diff\_harm\_n}}{Kn} \right)$$

- Harmonic restraint is more secure than harmonic blocking

Crossed Logics for Harmonic Blocking

- 1 out of 3: dependability problems with close onto single-phase and two-phase faults
- 2 out of 3: can have dependability problems for close onto single-phase faults. If the transformer is YD (or 3-legged YY) and it is energized from the Y side it operates correctly
- Average:

$$average\_2nd\_harm\_ratio = \frac{1}{3} \cdot \left(\frac{I_{diff\_harm\_2nd\_A}}{I_{diff\_fund\_A}} + \frac{I_{diff\_harm\_2nd\_B}}{I_{diff\_fund\_B}} + \frac{I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_C}} \right)$$

Crossed Logics for Harmonic Blocking

- Sharing:

$$PhaseA\_2nd\_harm\_ratio = \left(\frac{I_{diff\_harm\_2nd\_A} + I_{diff\_harm\_2nd\_B} + I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_A}} \right)$$

$$PhaseB\_2nd\_harm\_ratio = \left(\frac{I_{diff\_harm\_2nd\_A} + I_{diff\_harm\_2nd\_B} + I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_B}} \right)$$

$$PhaseC\_2nd\_harm\_ratio = \left(\frac{I_{diff\_harm\_2nd\_A} + I_{diff\_harm\_2nd\_B} + I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_C}} \right)$$

$$3phase\_2nd\_harm\_ratio = \left(\frac{I_{diff\_harm\_2nd\_A} + I_{diff\_harm\_2nd\_B} + I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_A} + I_{diff\_fund\_B} + I_{diff\_fund\_C}} \right)$$

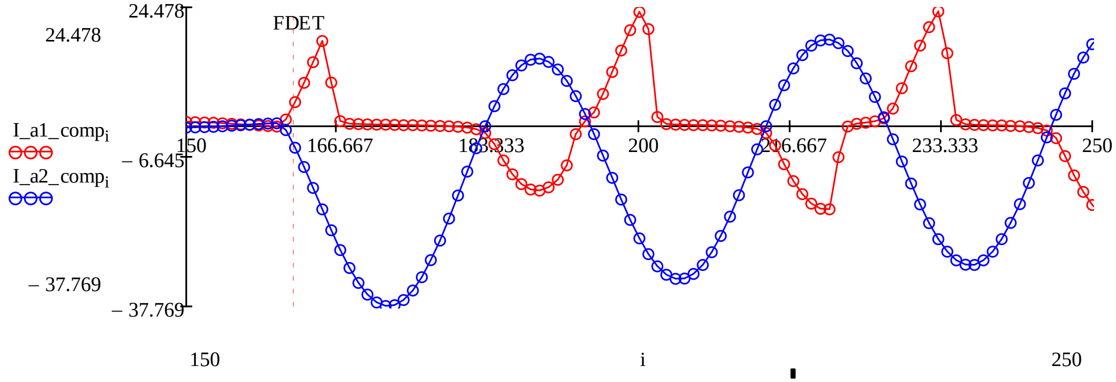
  - The harmonic blocking percentage should be increased (25%)

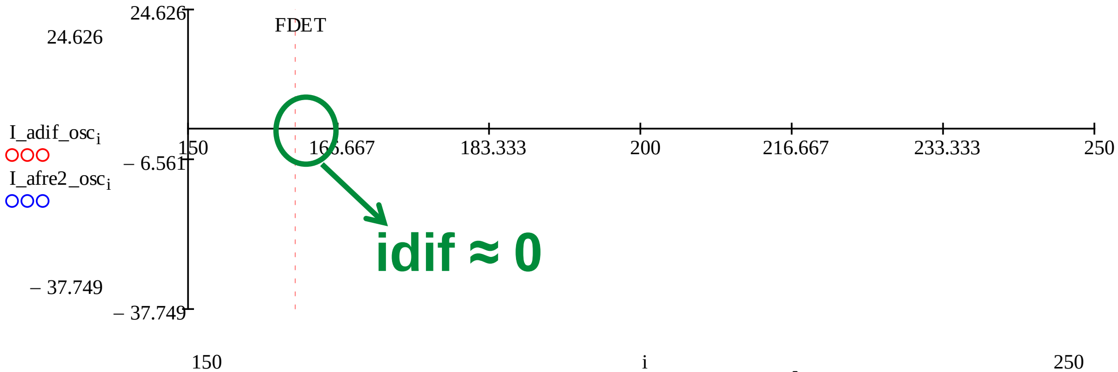
- Time for cross-blocking: 4-5 cycles

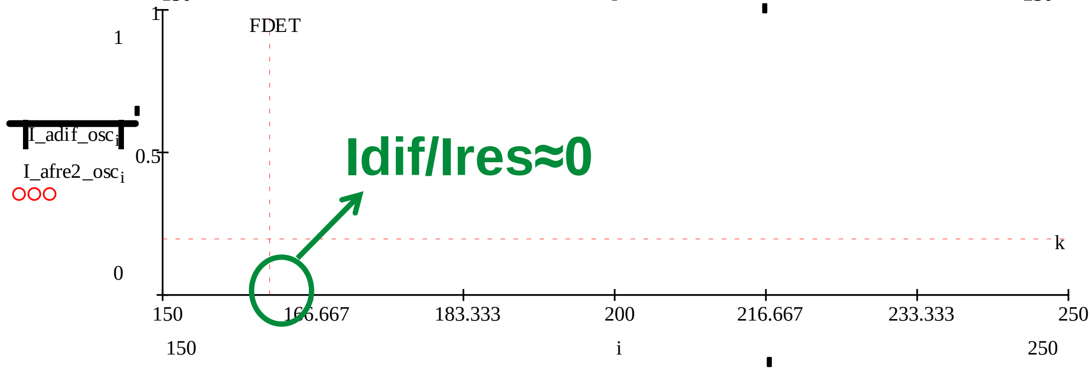
Dynamic Harmonic Restraint / Blocking

- Harmonic restraint / blocking can reduce the dependability for internal faults with CT saturation
- Use of unrestrained differential unit
- Use of dynamic harmonic restraint / blocking: based on an external fault detector:
  - One detector based on idif/irest ratio
  - Two directional comparison units: phase and positive-sequence

Detector based on idif / ires







Directional Comparison

INTERNAL FAULT

Currents "in phase"

$$|\arg(I2)-\arg(I1)| < 90^{o}$$

EXTERNAL FAULT

Currents "out of phase"

$$|\arg(I2)-\arg(I1)| > 90^{o}$$

- First unit is based on phase currents
- Second unit is based on positive-sequence pure fault values

Dynamic Application of 2nd Harmonic Restraint / Blocking

- Harmonic blocking / restraint is always applied during a settable time when the transformer energization is detected
- Once the transformer has been energized the harmonic restraint / blocking can be inhibited during 3 cycles if:
  - A fault detector has activated
  - The units comprising the external fault detector do not indicate an external fault condition (2 out of 3 logic is used)
- After the 3 cycles the harmonic restraint / blocking cannot be inhibited again during a settable time
- Both for an external fault and for the energization of a parallel transformer an external fault condition will be detected prior to the inrush of the protected transformer, therefore the harmonic restraint / blocking will be applied

Dynamic Application of 2nd Harmonic Restraint / Blocking

- Undervoltage units can also be used to complement the logic, inhibiting the 2nd harmonic restraint / blocking if they pick-up (75% of Vrated can be used)
- An undervoltage unit per phase will be used

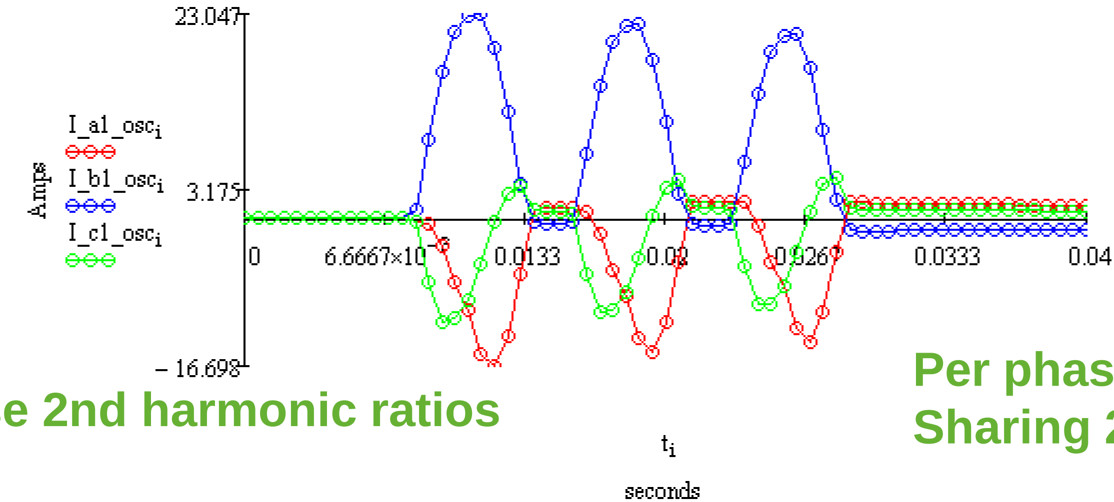
Dynamic Application of 5th Harmonic Restraint / Blocking

- Underexcitation units based on V/f ratio will be used to inhibit 5th harmonic restraint / blocking: they will pick-up if V/f<k*Vrated/frated
- An underexcitation unit per phase will be used

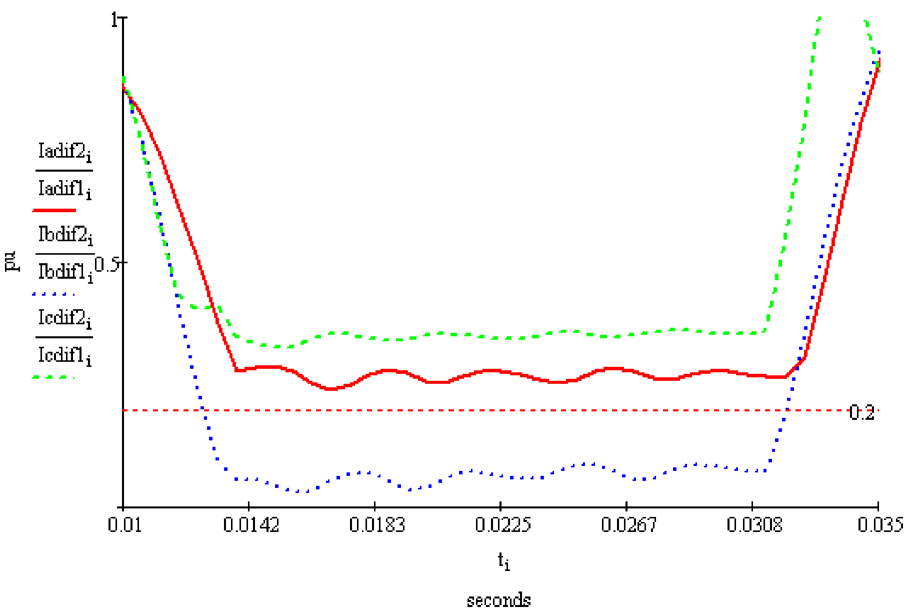
Simulated and Real cases

Energization with low 2nd harmonic (real case)

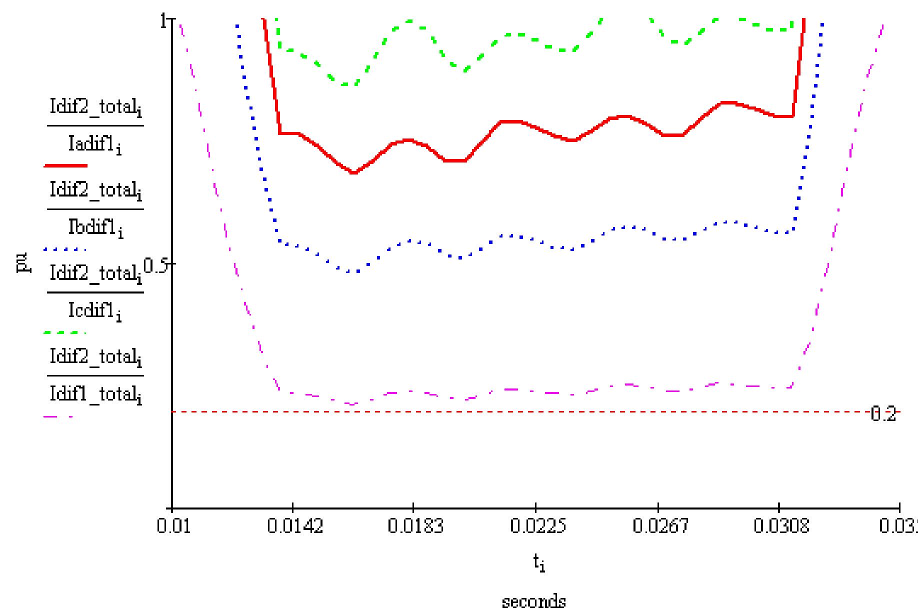
YND 132 kV / 15 kV



Per phase 2nd harmonic ratios

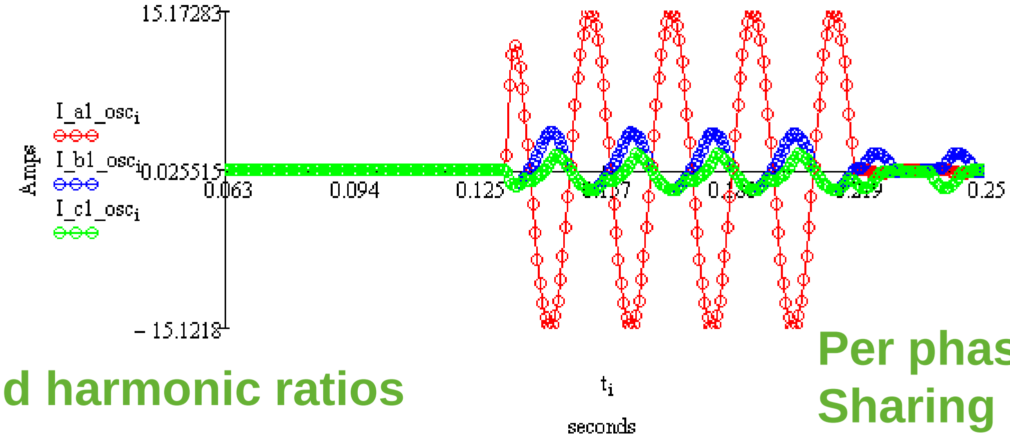


Per phase and three phase Sharing 2nd harmonic ratios

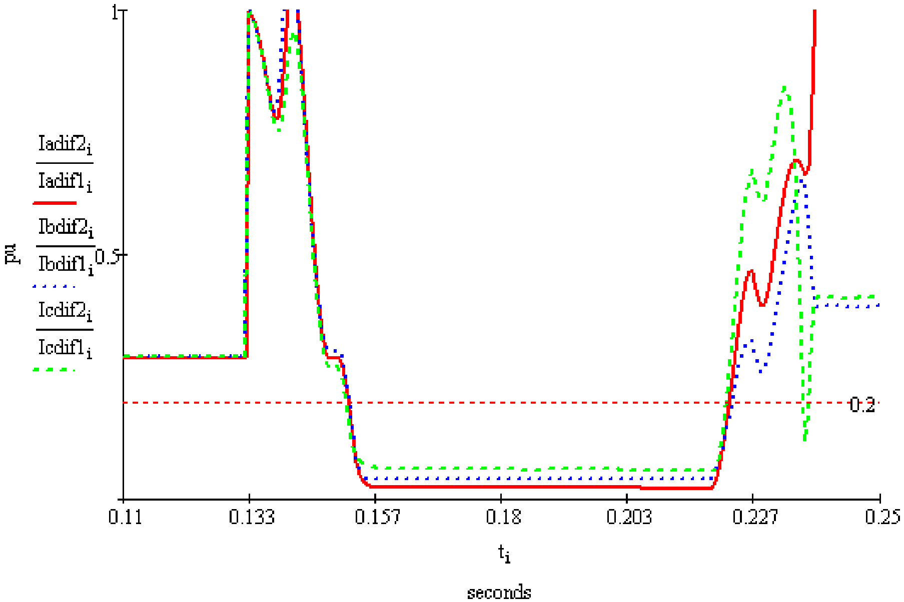


Close onto AG Fault (simulated case)

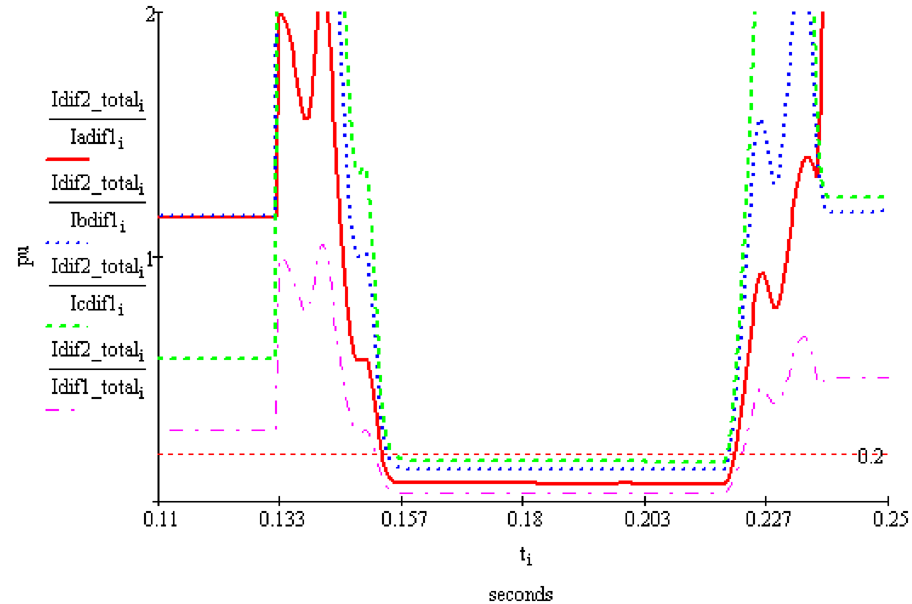
YNynd 400 kV / 220 kV / 33 kV



Per phase 2nd harmonic ratios

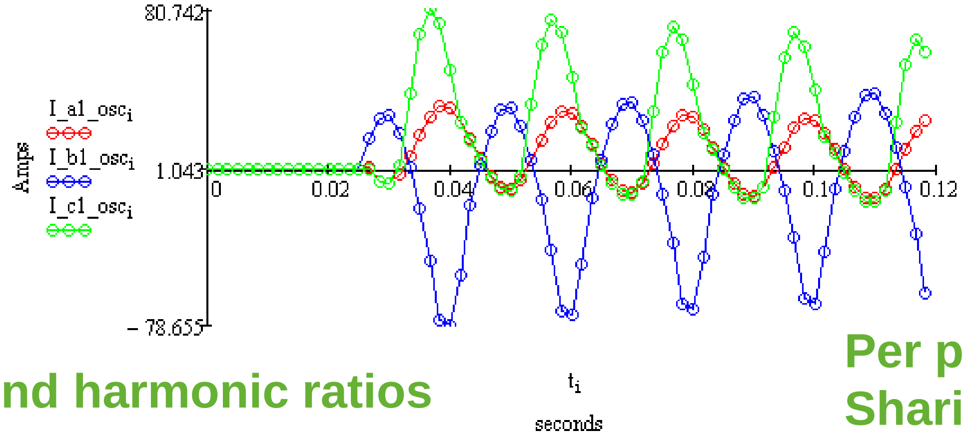


Per phase and three phase Sharing 2nd harmonic ratios

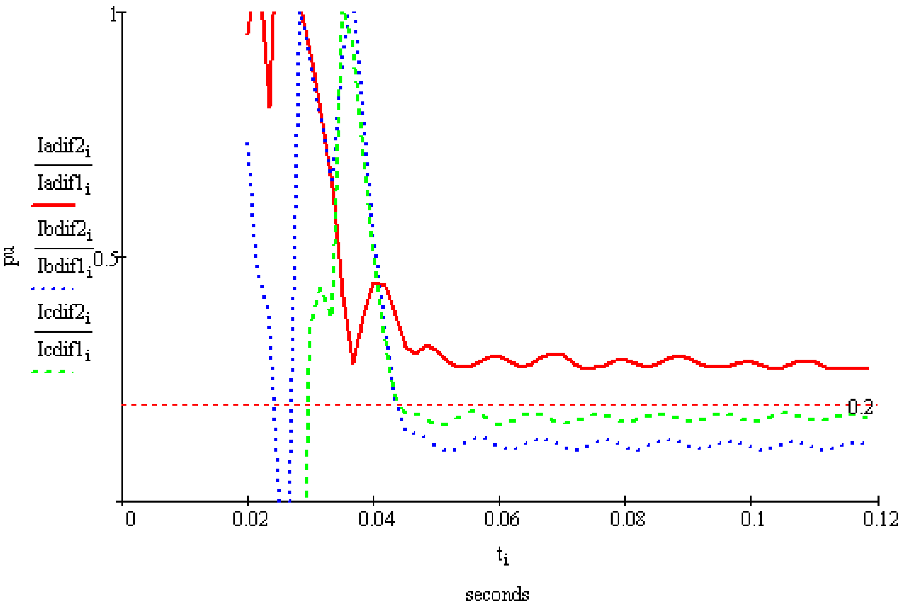


Close onto BC Fault (real case)

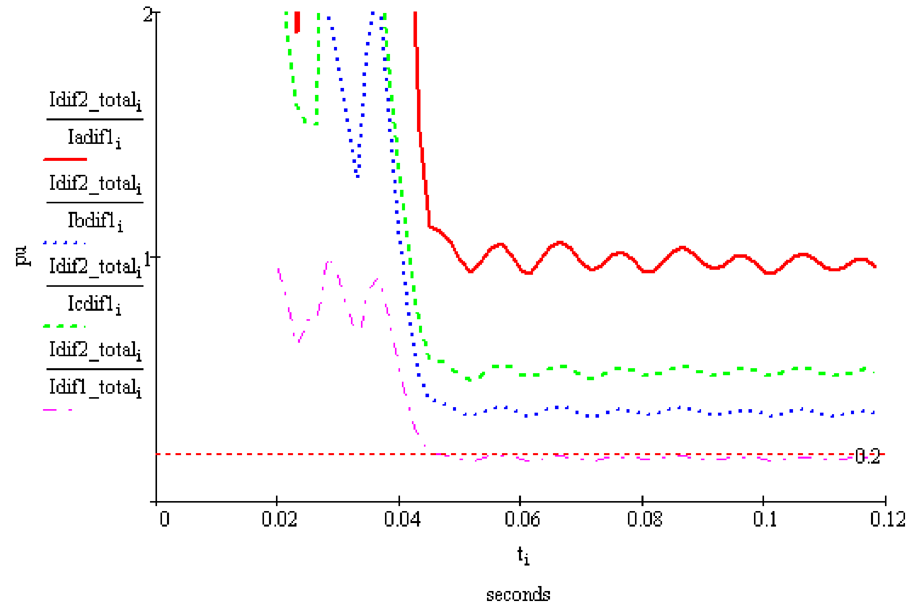
YNynd 220 kV / 132 kV / 30 kV



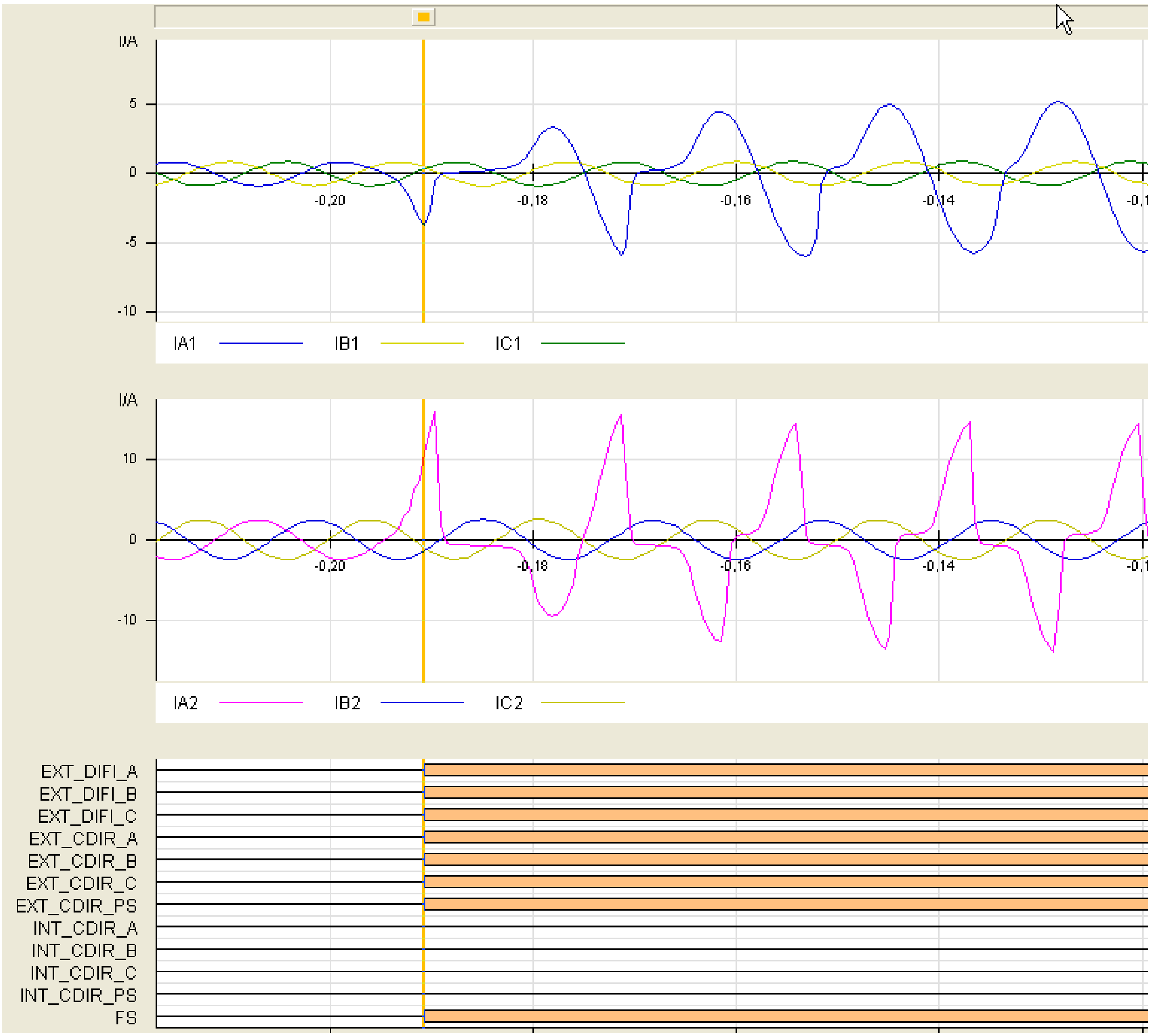
Per phase 2nd harmonic ratios



Per phase and three phase Sharing 2nd harmonic ratios

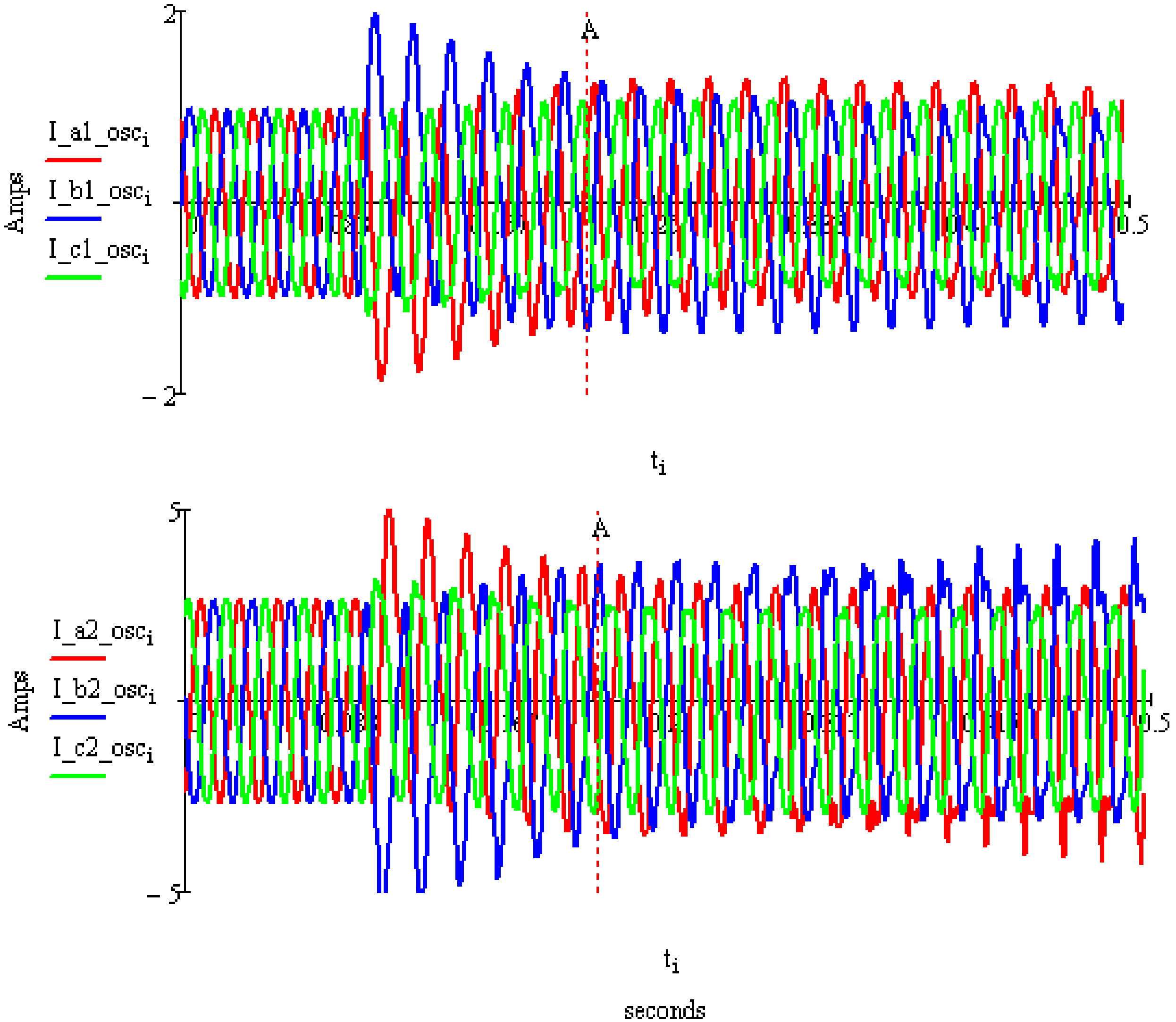


External Fault with CT Saturation

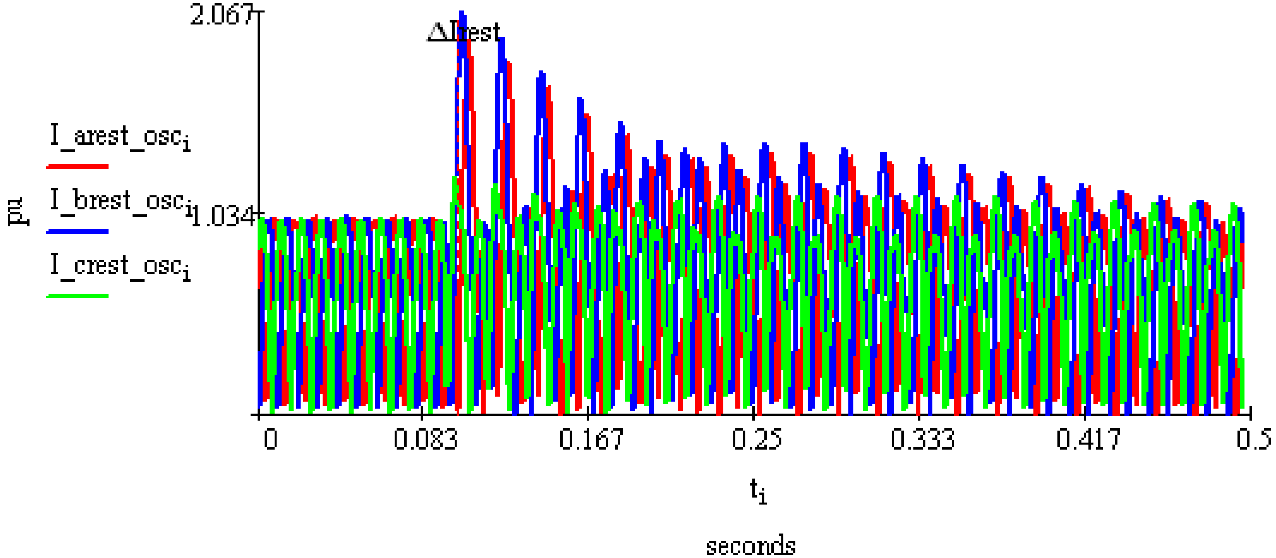


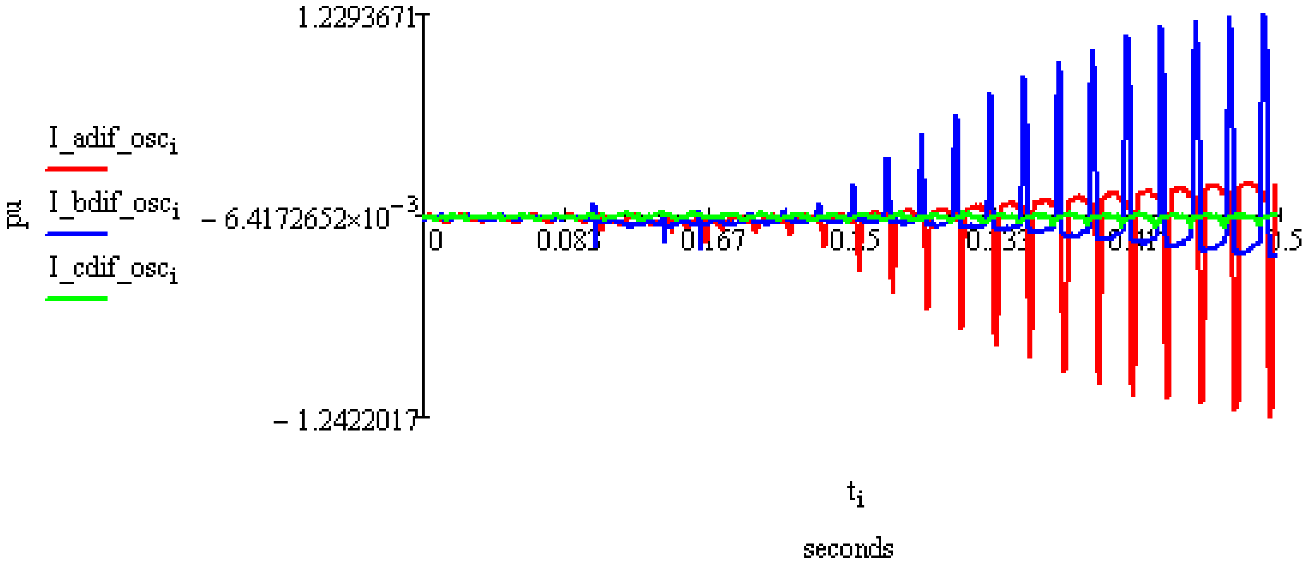
Sympathetic Inrush

YNynd 400 kV / 220 kV / 33 kV



Sympathetic Inrush





Inrush Currents Effect on Other Protection Functions

Influence of Inrush Currents on 50/51

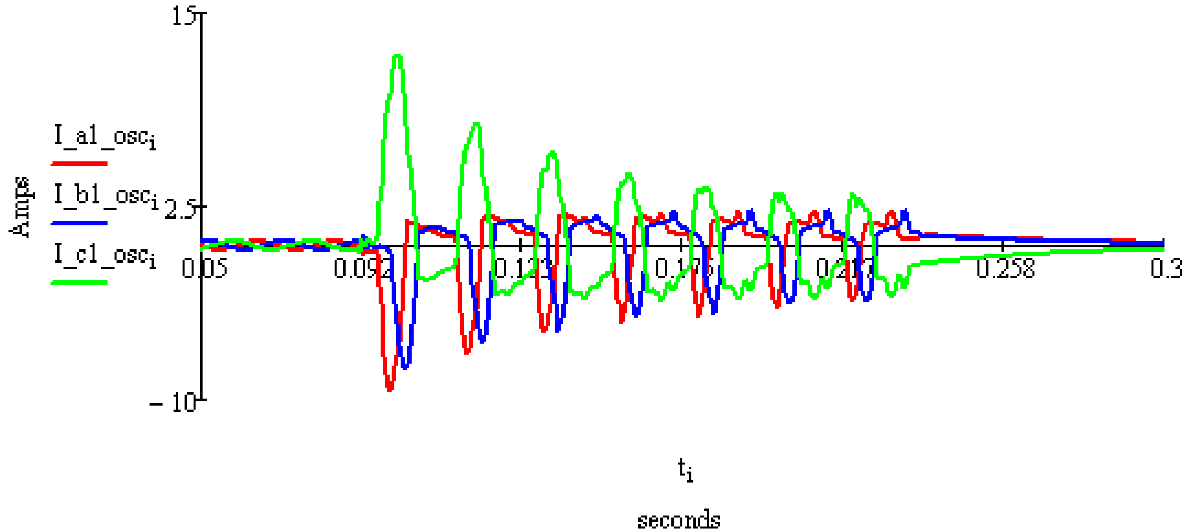
- The most affected units are the ground ones as they are set more sensible than the phase ones
- The following connection groups allow the flow of inrush ground current (energization done from the primary: YNyn, YNy, YD, 3 legged YY
- The following groups do not allow the flow of inrush ground current: Yyn, Yy, Dyn, Dy

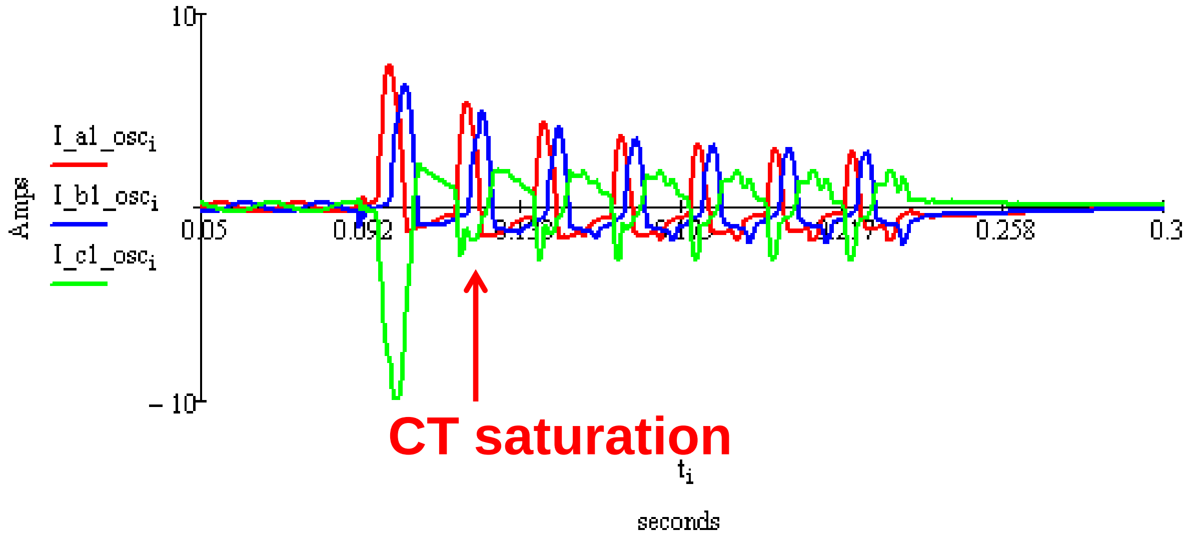
Influence of Inrush Currents on 50/51

- 2nd Harmonic blocking / restraint is normally used
- Cross-blocking is recommended for instantaneous units
- Unrestrained units are also recommended to increase the dependability
- When the inrush current is mixed with the load current the 2nd harmonic content will be lower
- The sum current in a sympathetic inrush will have low 2nd harmonic content. If overcurrent units operate with this current their restraint will be very low. Third or fifth harmonic restraint can help
- If pilot schemes are used care has to be taken with DCB and POTT+weak infeed logic because of CT saturation

Inrush Currents for a POTT+Weak Infeed

Downstream transformer energization (real case)





Influence of Inrush Currents on 87B / 87L

- CT saturation can affect the security of 87B and 87L units
- The restraint current is normally low so the tendency to operate is high
- The use of the described external fault detector will increase the security

Influence of Inrush Currents on 21

- Affected when:
  - A distance zone is used as a back-up of the transformer differential protection
  - A distance zone is used to protect line + transformer
  - A distance protection is used to protect a line with tapped transformers
- Use of 2nd harmonic blocking / restraint
- Harmonic blocking / restraint can be inhibited with undervoltage units or with overcurrent units

Conclusions

- Harmonic restraint is more secure than harmonic blocking
- The low second harmonic content of modern transformers requires the use of harmonic restraint / blocking crossed logics
- For transformers with a delta winding (either real or phantom) energized from the wye winding/s the “two out of three” crossed logic provides good balance between security and dependability
- For other type of transformer connection group or in a wye-delta transformer if the energization is done from the delta side the harmonic sharing logic is considered the best one. In order to increase the dependability a three-phase sharing second harmonic ratio is recommended.

Conclusions

- The logic that inhibits the harmonic restraint / blocking allows accelerating the trip for an internal fault that occurs once the transformer is energized. It is based on an external fault detector consisting of three units:
    - Detector based on idif / ires ratio
    - Phase directional comparison unit
    - Pure fault positive-sequence directional comparison unit
- CT saturation during inrush can affect any type of differential relay and also overcurrent units working with a DCB or POTT with a weak infeed logic. The use of an external fault detector as the one described in this paper will increase the security of the differential units.

Thank you

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