Low Second-Harmonic Content in Transformer Inrush Currents – Analysis and Practical Solutions for Protection Security

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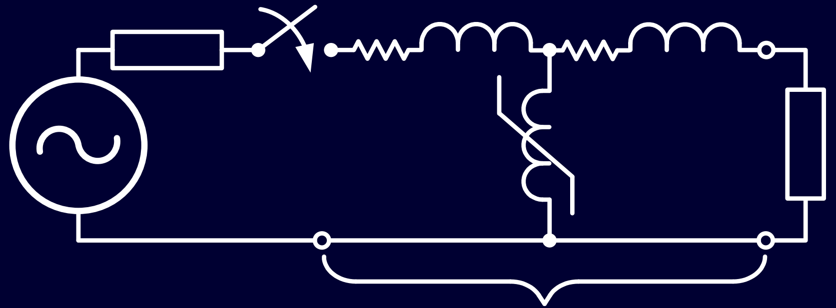
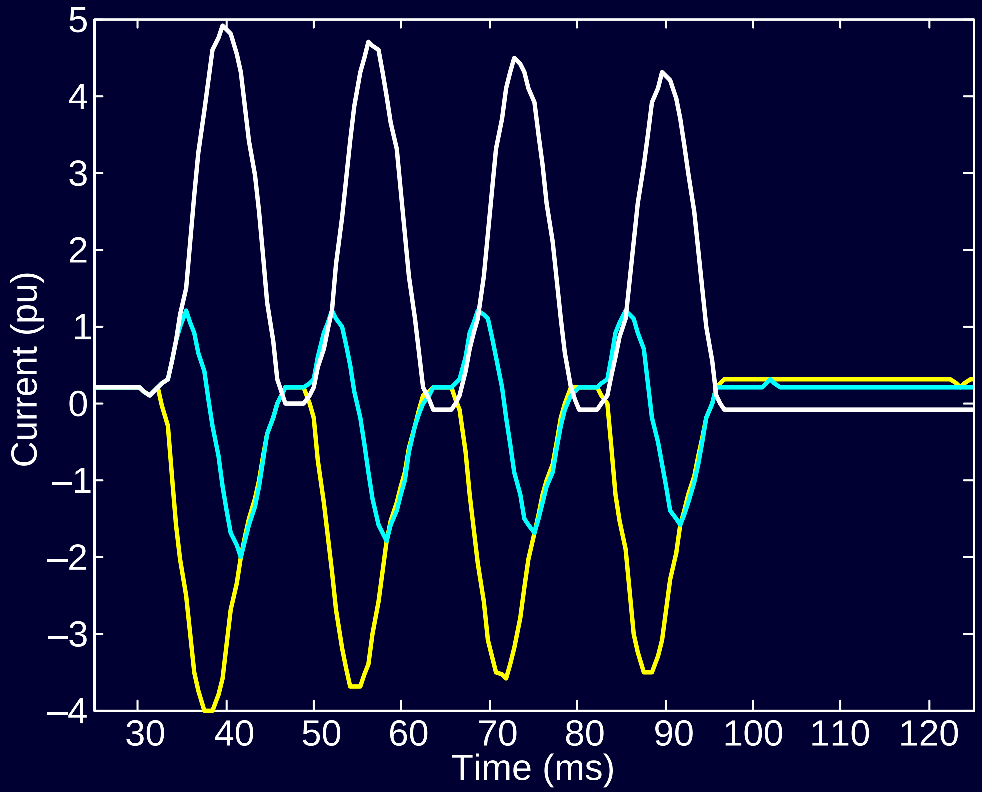
Transformer Energization





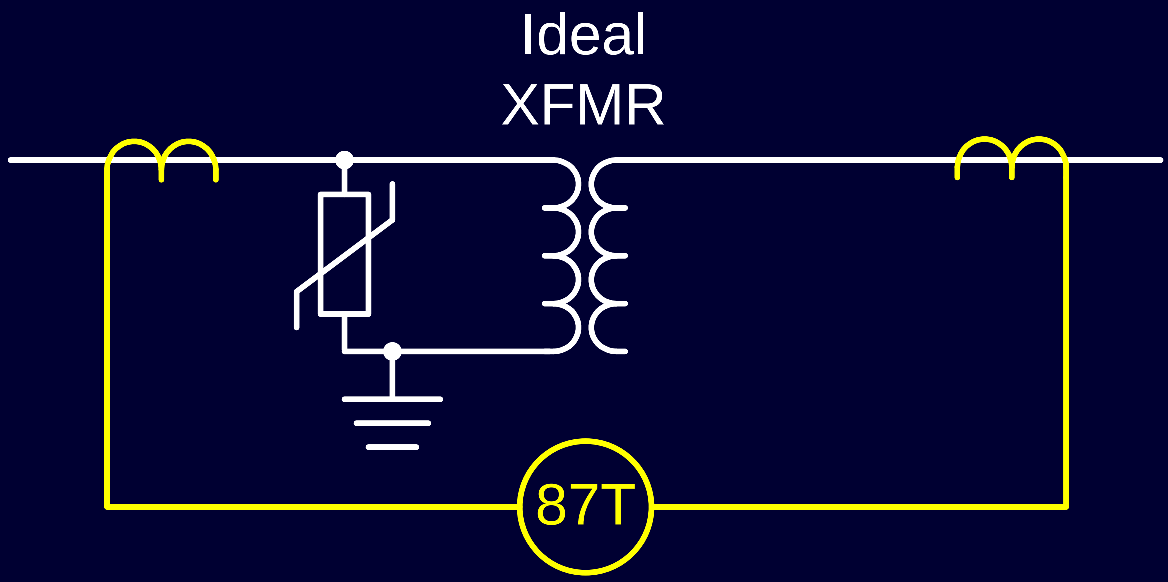
Relay Misoperation During Inrush

- Sporadically, 87T relays trip undesirably
- Low second harmonic is root cause
- Problem is more common in new transformers
- Undesired trips are troublesome
  - CB interrupts an inductive current
  - Analysis is required before energizing again

Outline

- Magnetizing inrush and 87T elements
- Ultrasaturation
- Mitigation
- New inrush detection algorithm
- Conclusions

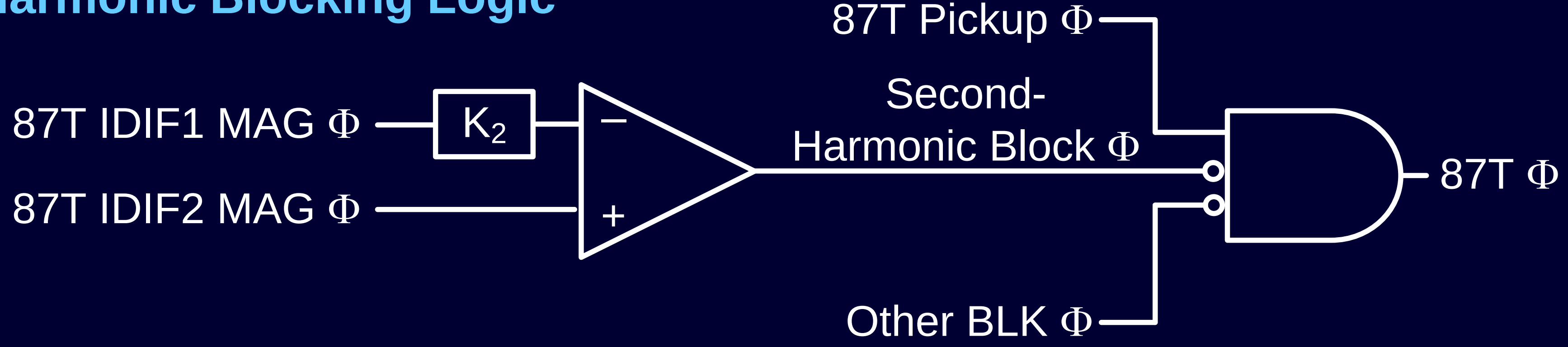
Inrush Current and 87T Element



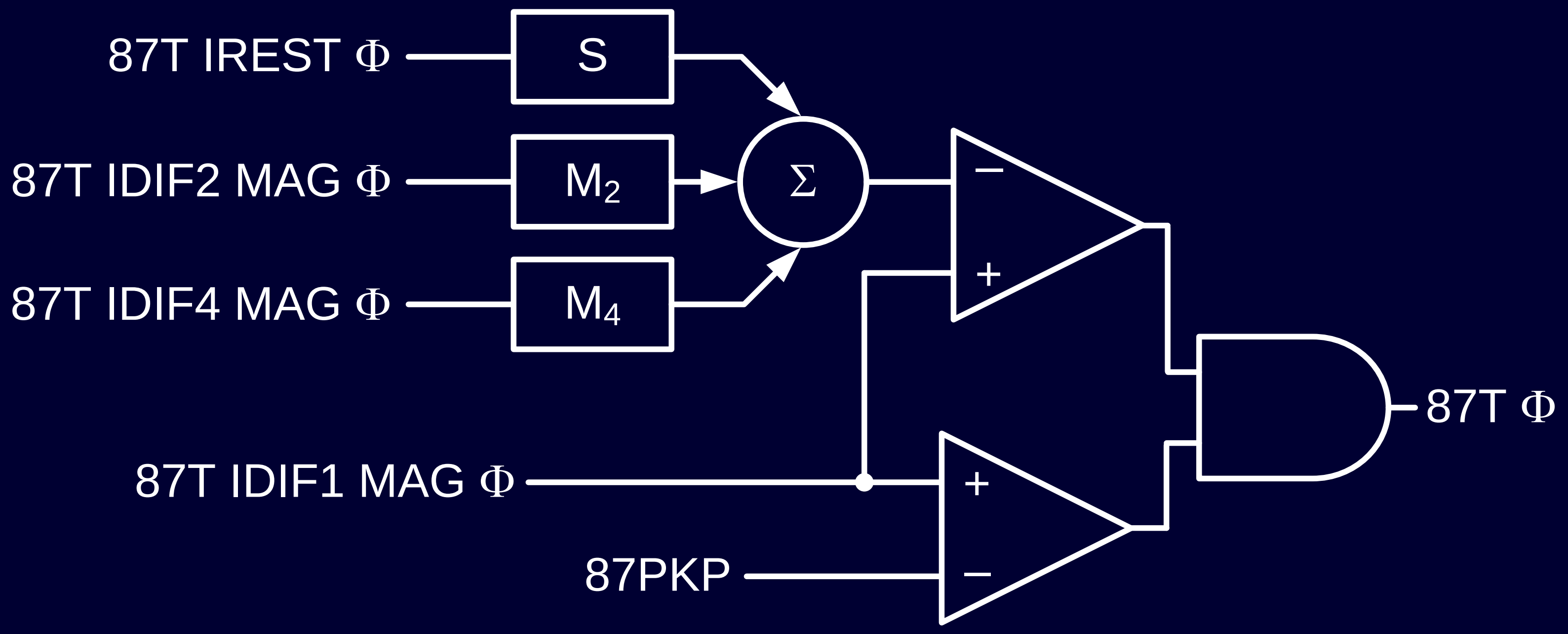
- Magnetizing branch is in zone
- Inrush current measured as differential
- Second harmonic used to block / restrain

Harmonic Blocking and Restraining

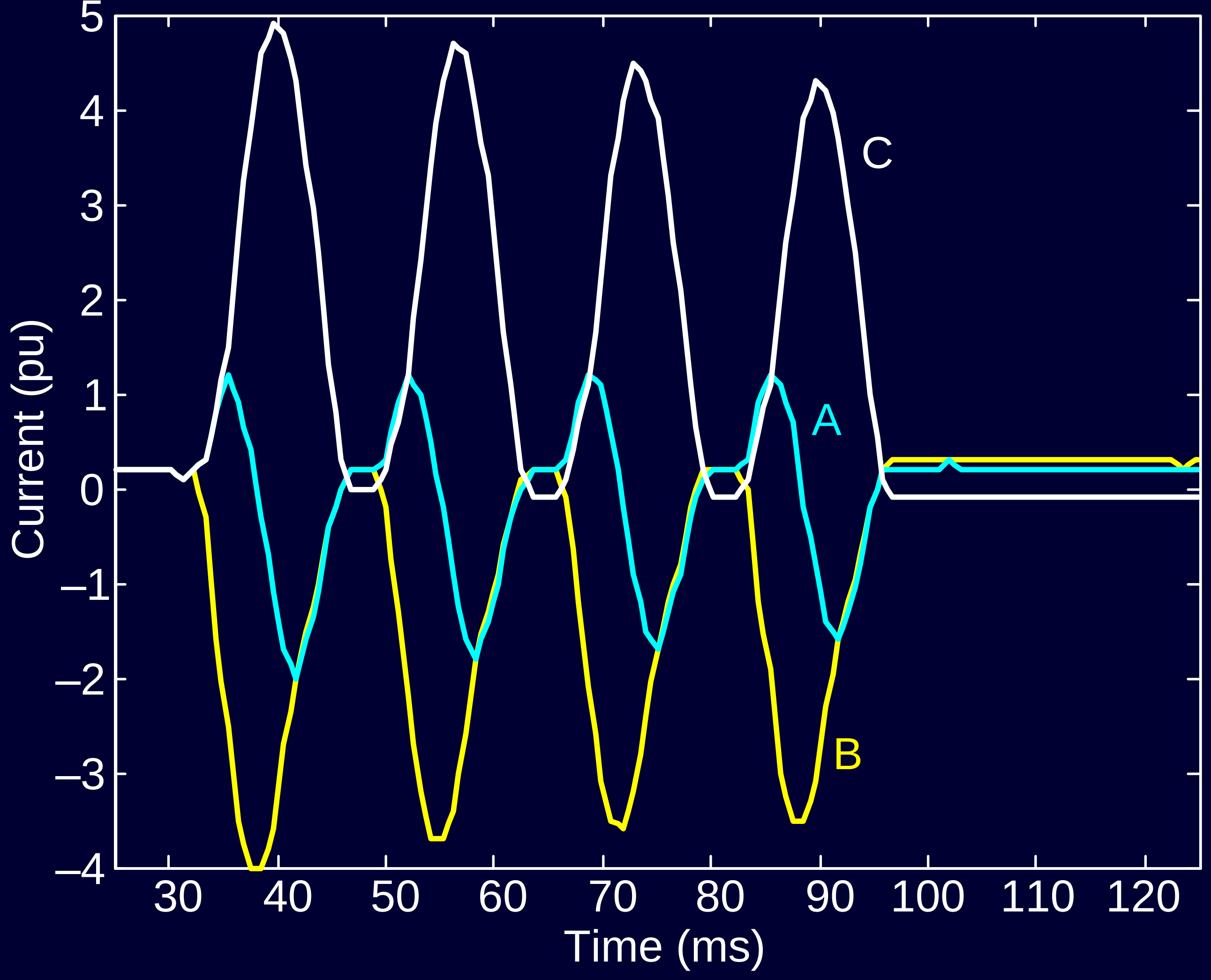
Harmonic Blocking Logic



Harmonic Restraining Logic



Typical Inrush Current



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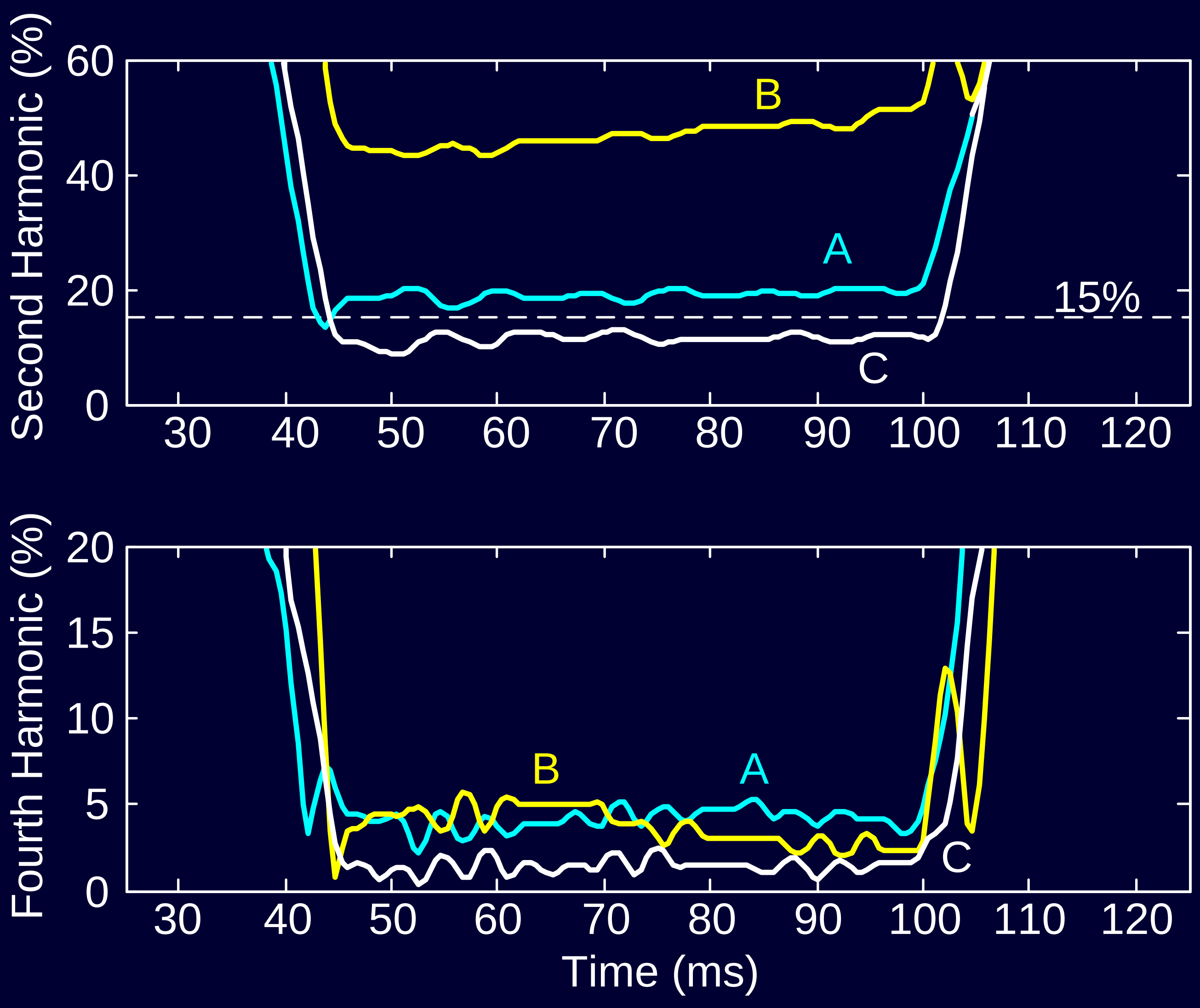
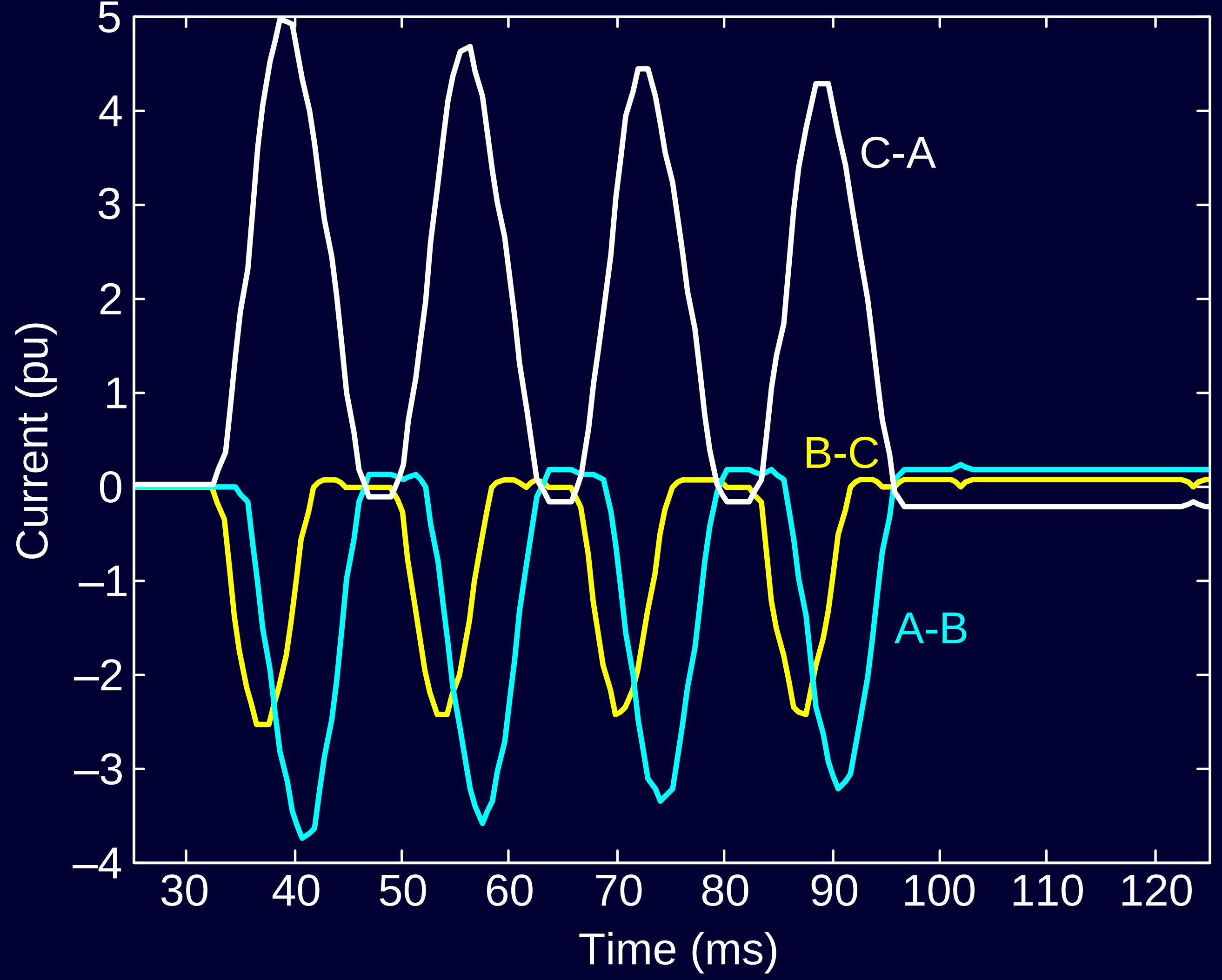


Impact of Winding Compensation



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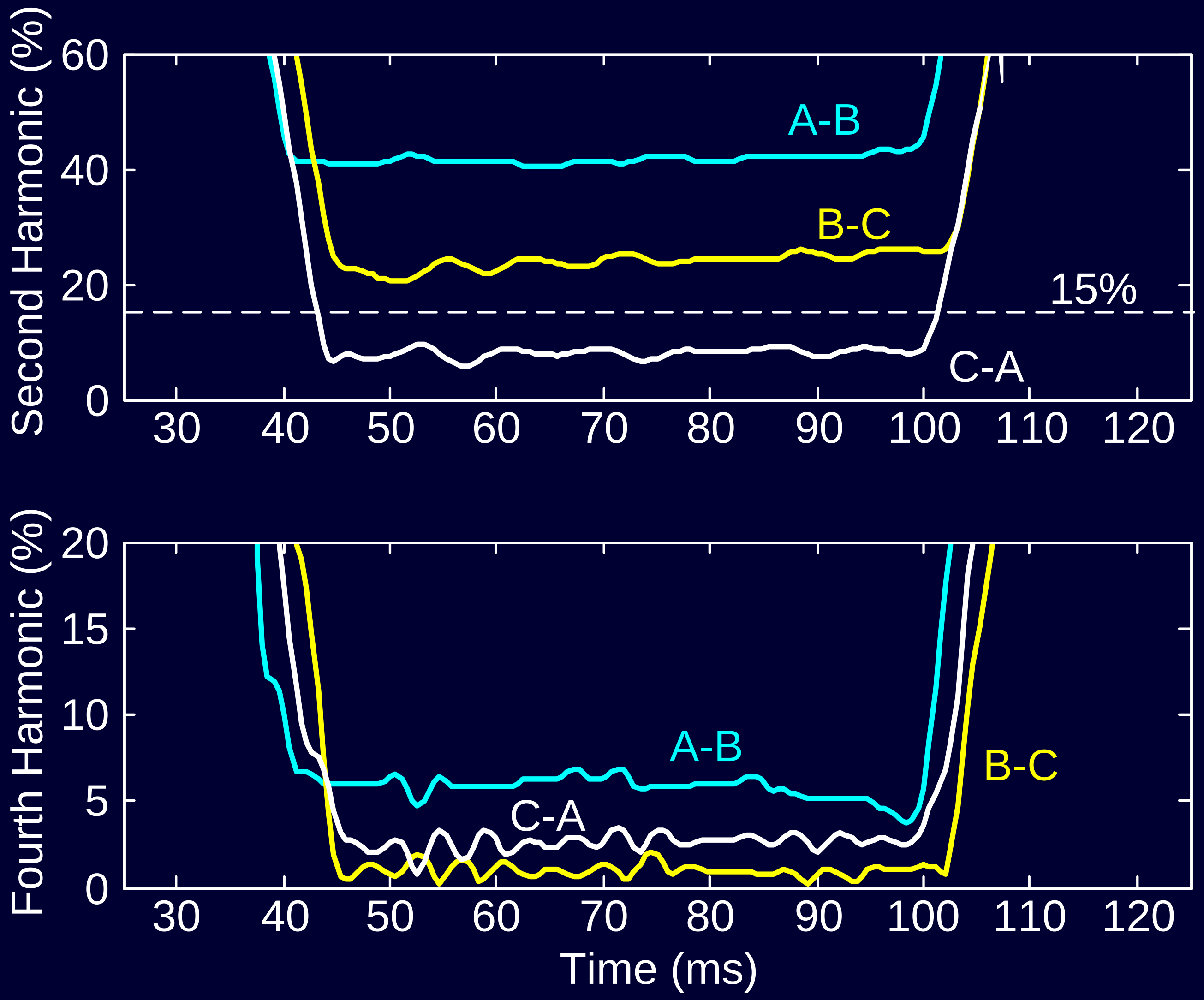
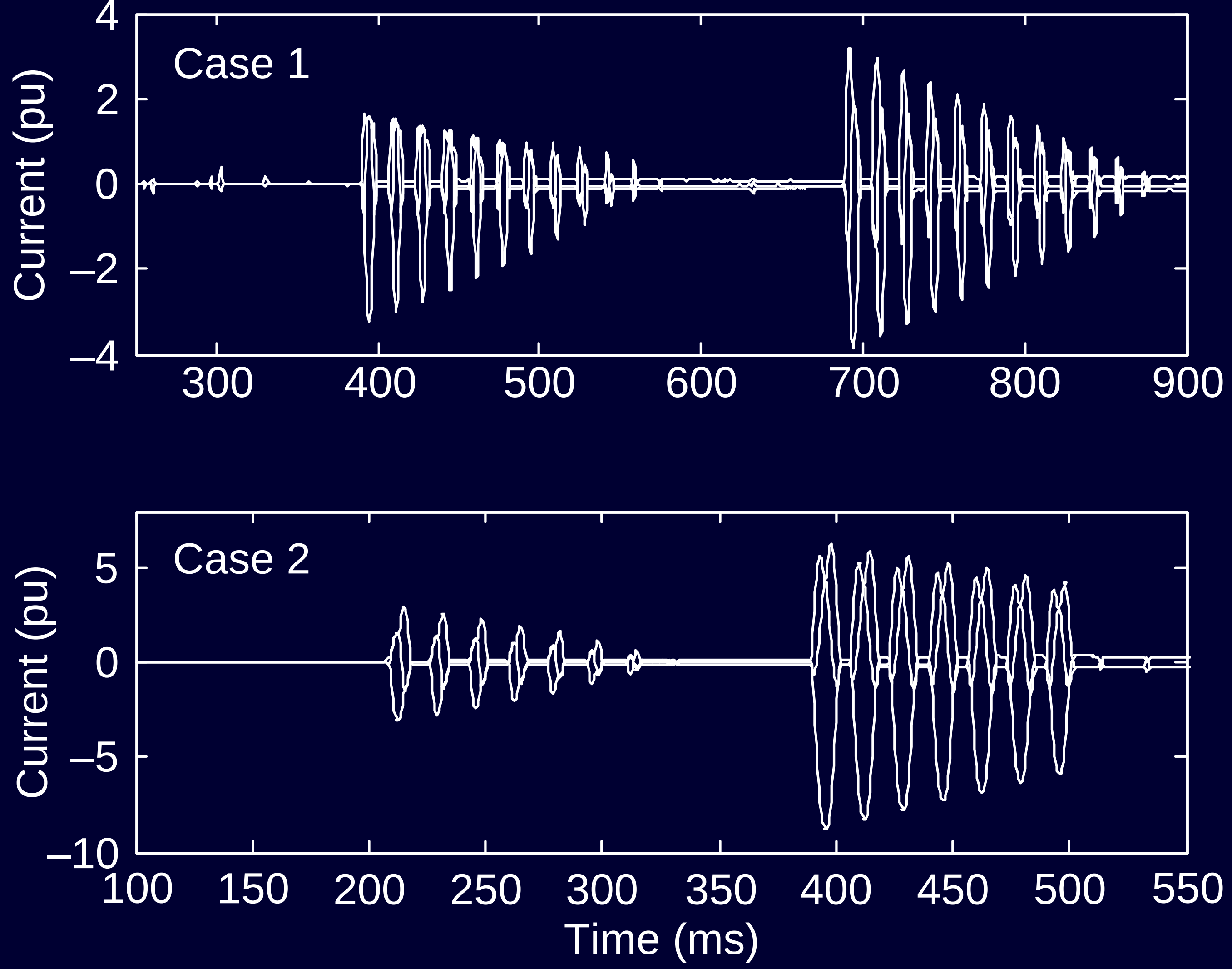


Disconnect Restrike



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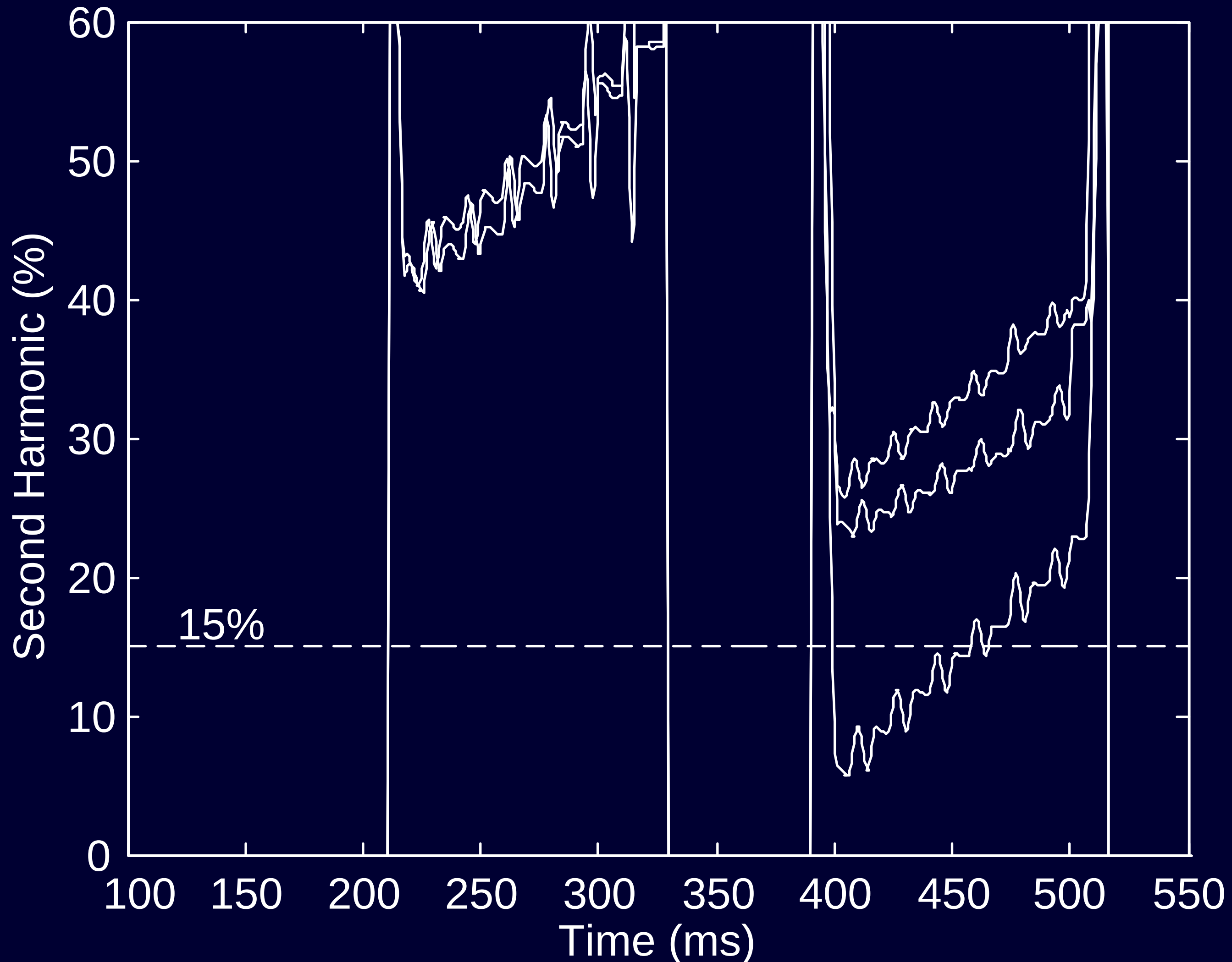
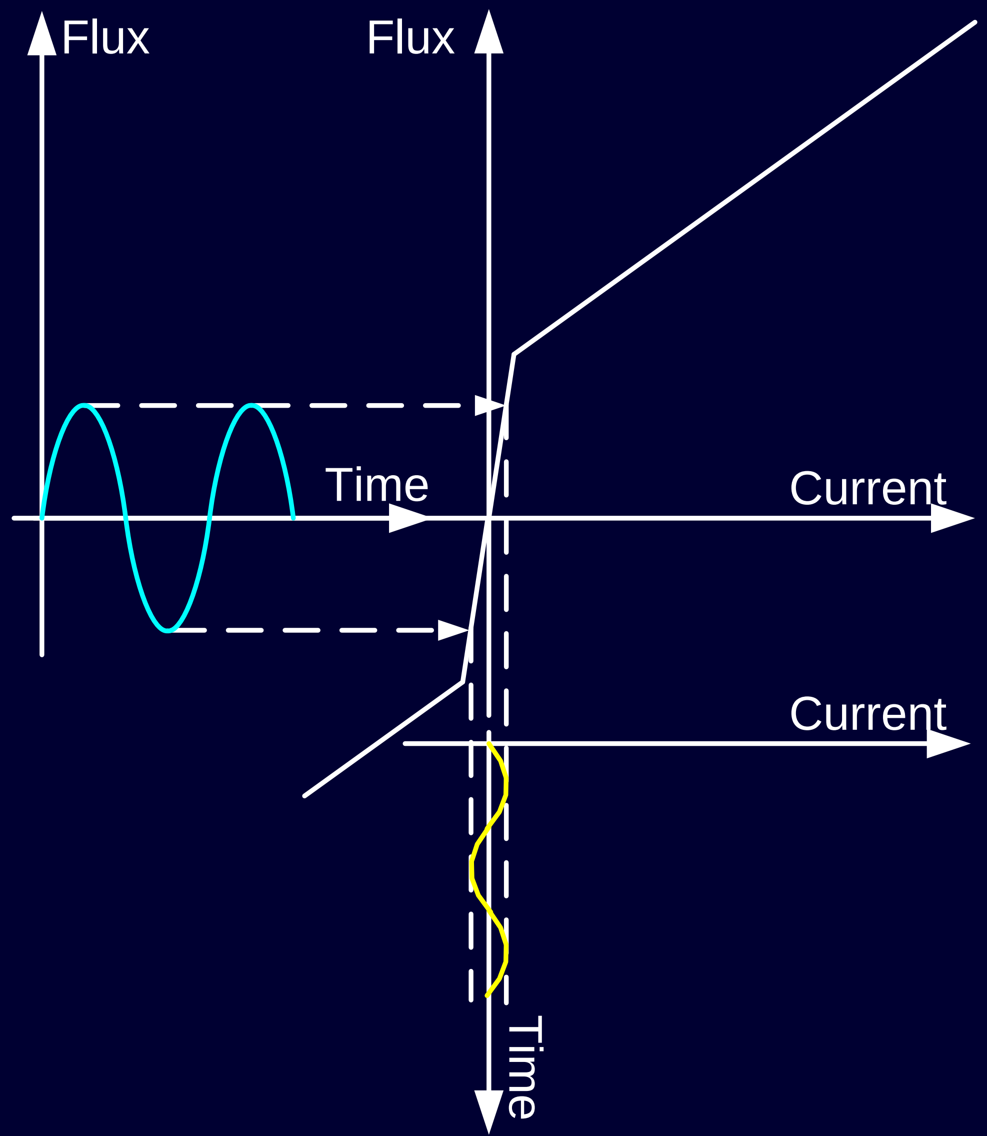


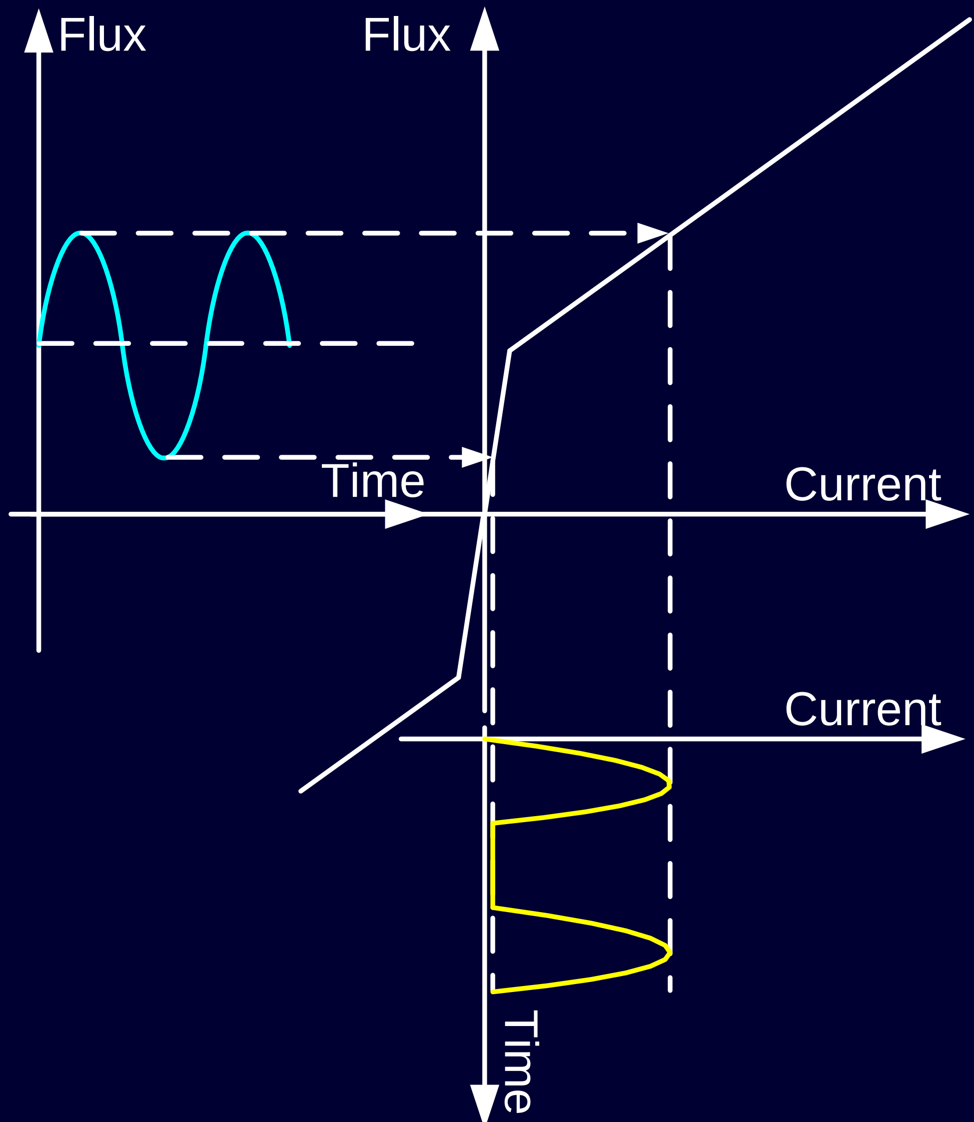
87T Operating Conditions

- Second-harmonic ratio can be well below typical 20% threshold
- Typically, only one phase measures low second harmonic
- Usually, second-harmonic ratio recovers after short time
- Deep saturation (ultrasaturation) of core is root cause

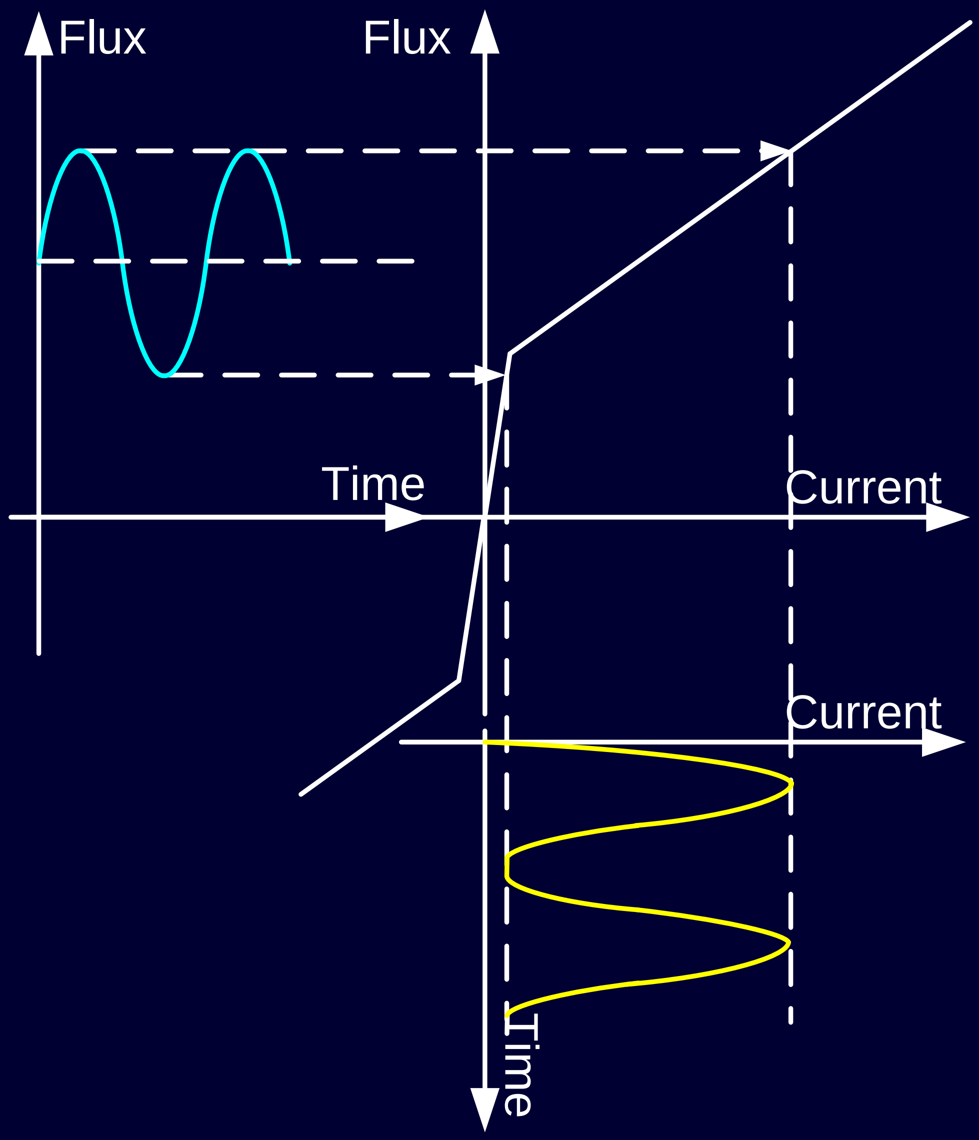
Flux Below Saturation



Maximum Flux Above Saturation



Minimum Flux Below Saturation



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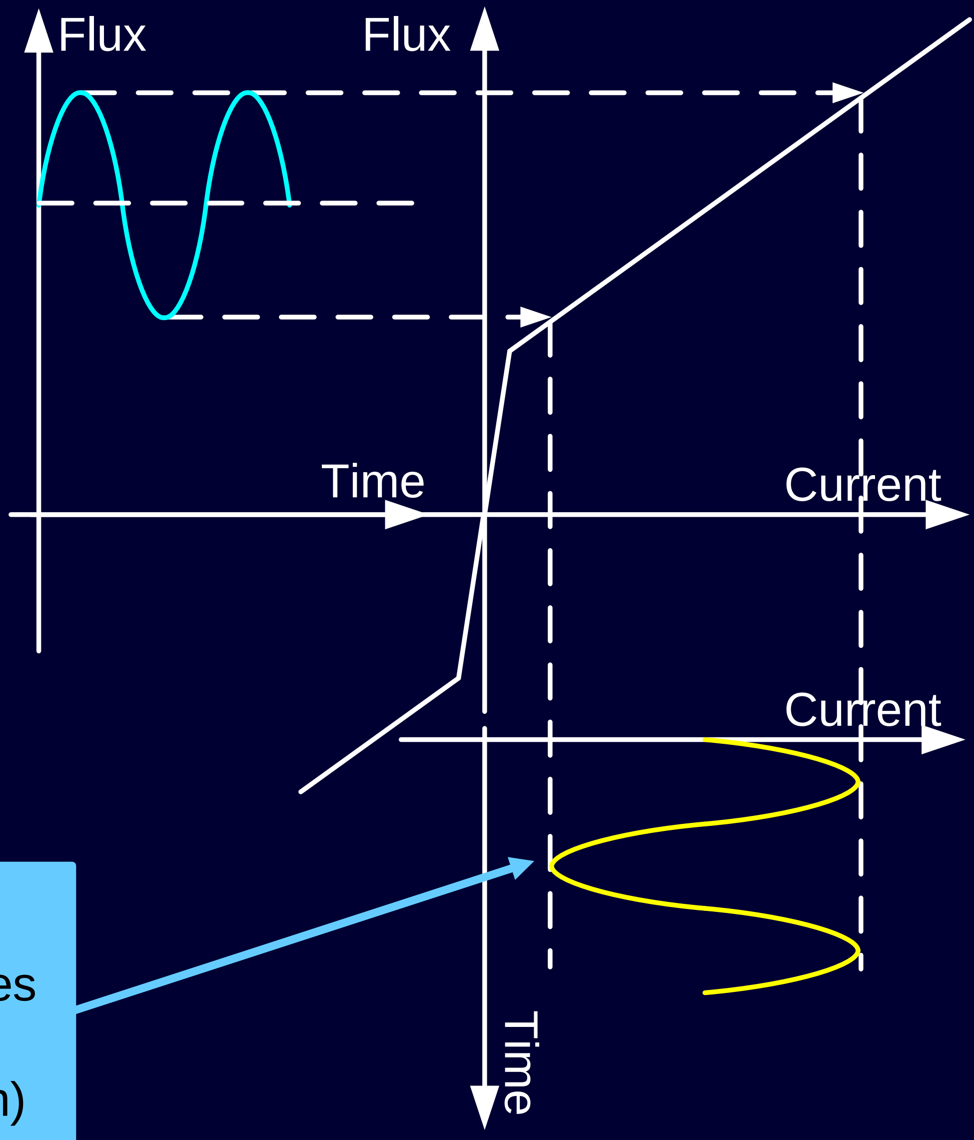
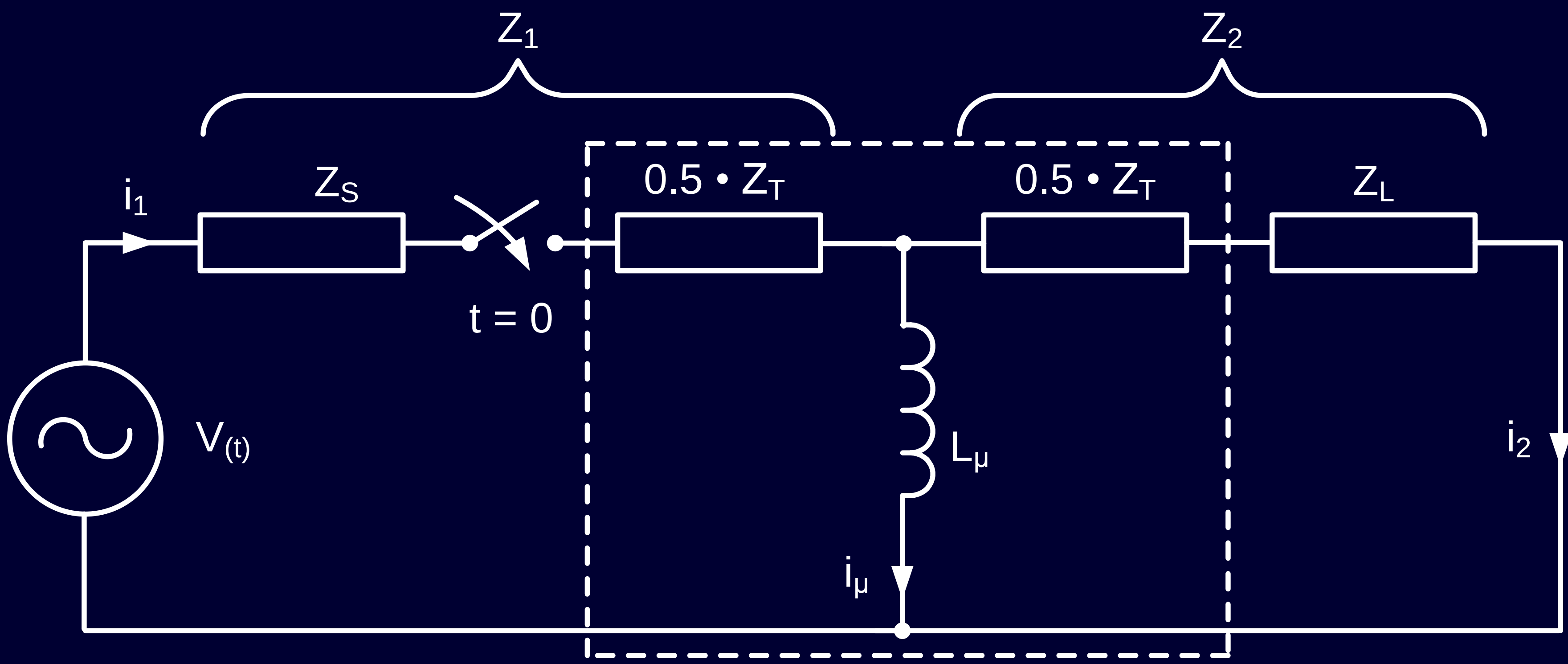


Magnetizing current becomes sinusoidal (ultrasaturation)

Transient Flux During Energization

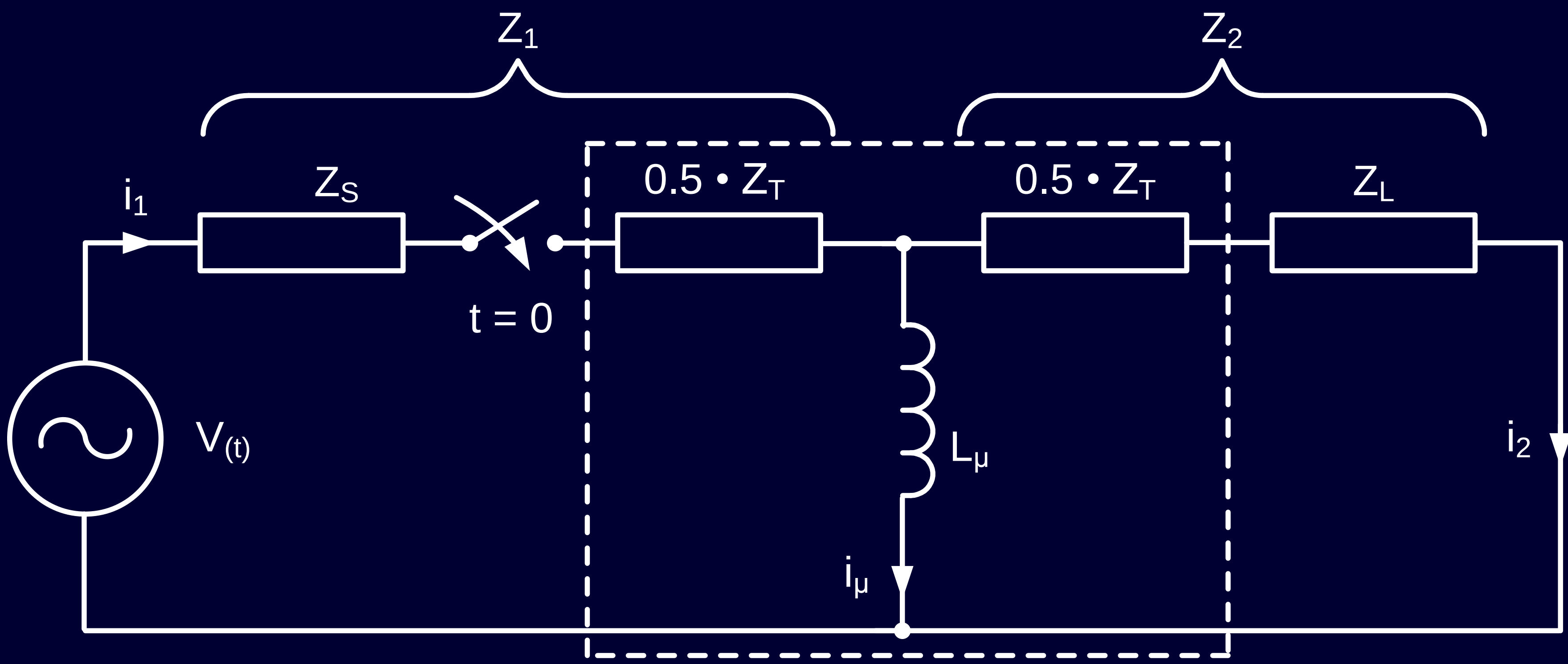


$$v = R_1 i_1 + L_1 \frac{d}{dt} i_1 + \frac{d}{dt}\psi$$

$$i_1 = i_\mu + i_2$$

$$R_2 i_2 + L_2 \frac{d}{dt} i_2 = \frac{d}{dt}\psi$$

Transient Flux During Energization

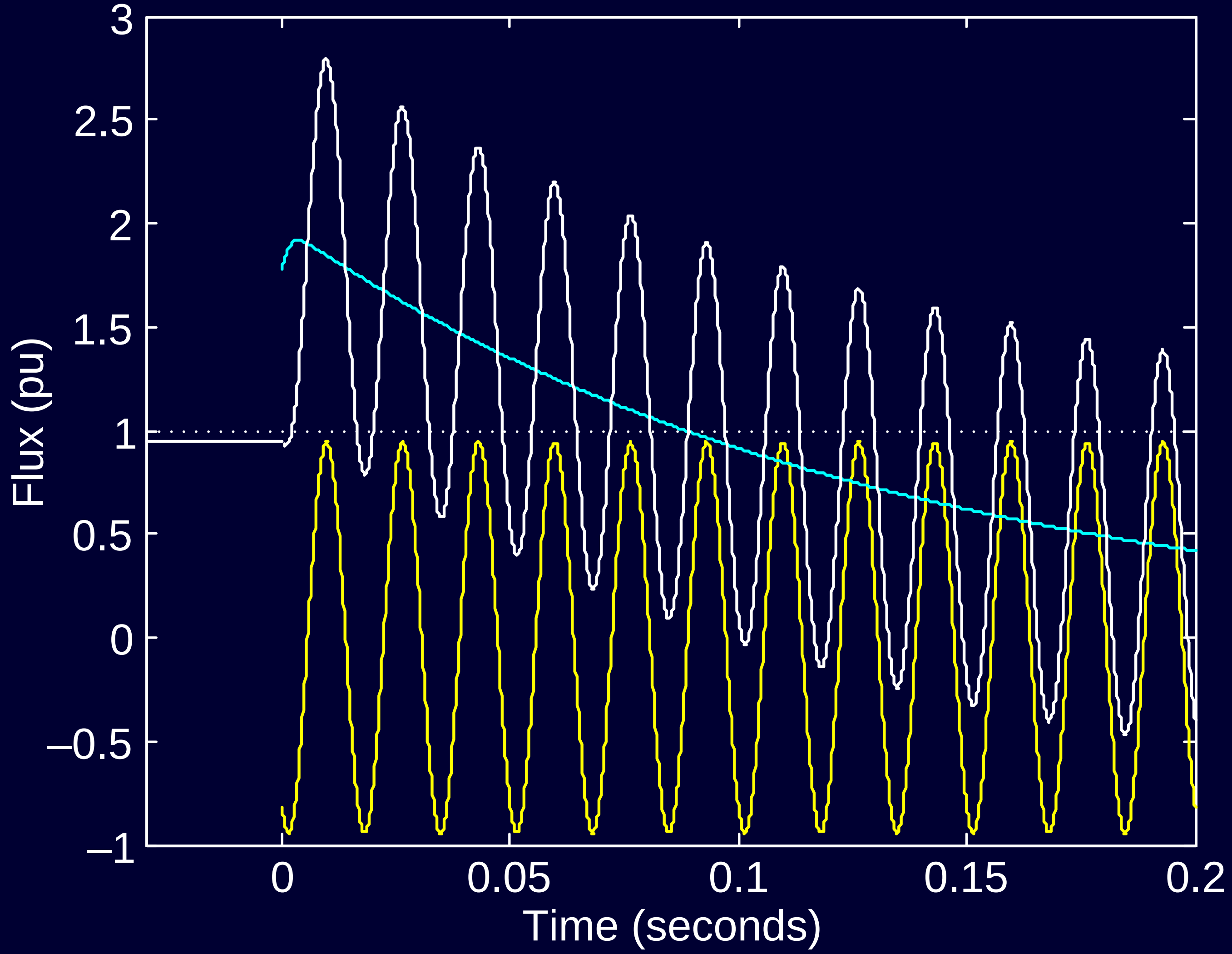


$$v_{(t)} = v_m \sin(\omega t + \alpha)$$

$$\psi = \psi_{AC} \sin(\omega t + \alpha - \Theta_0) + \psi_1 e^{-t/T_1} + \psi_2 e^{-t/T_2}$$

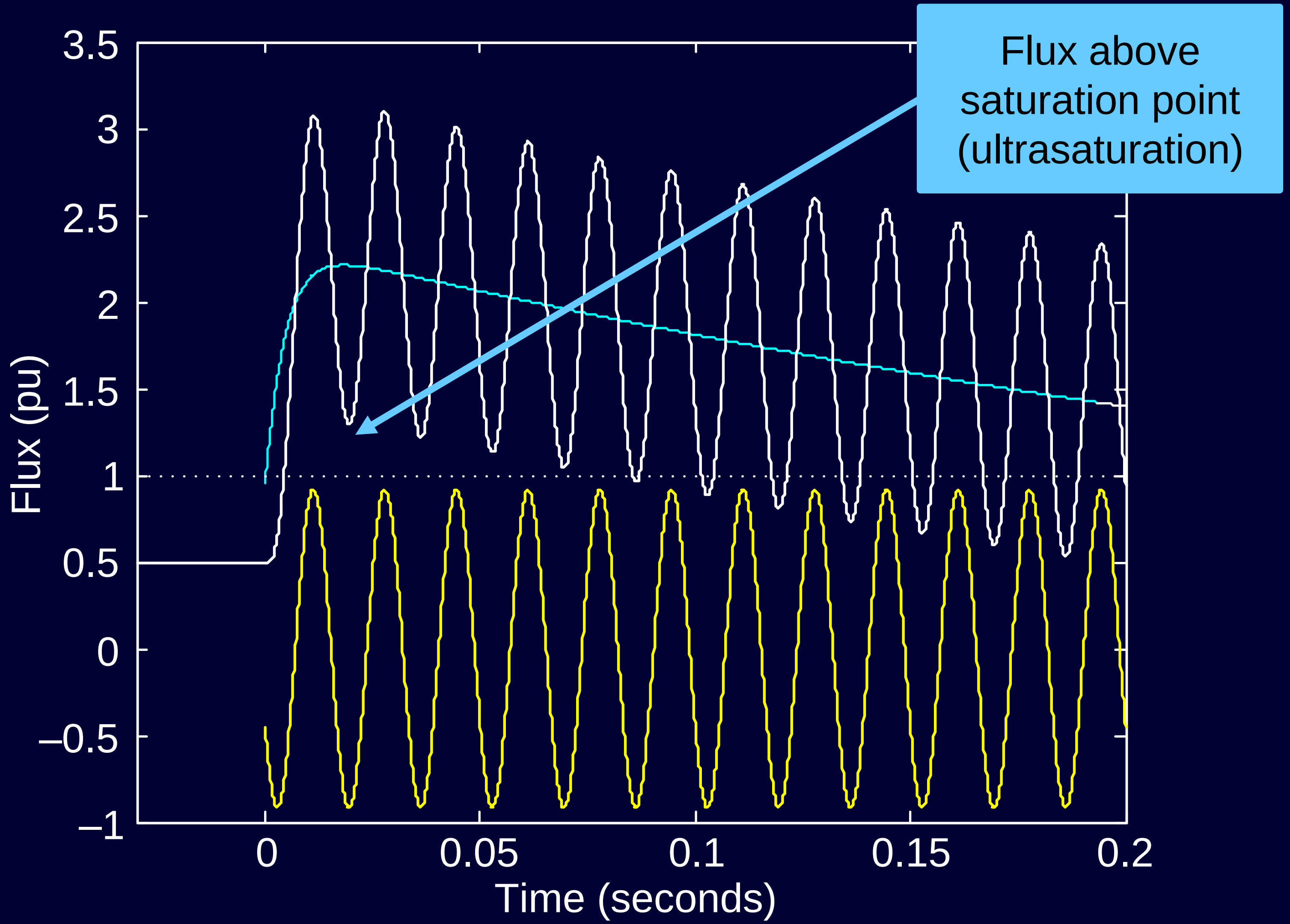
Transient Flux During Energization

Aperiodic Component Decays



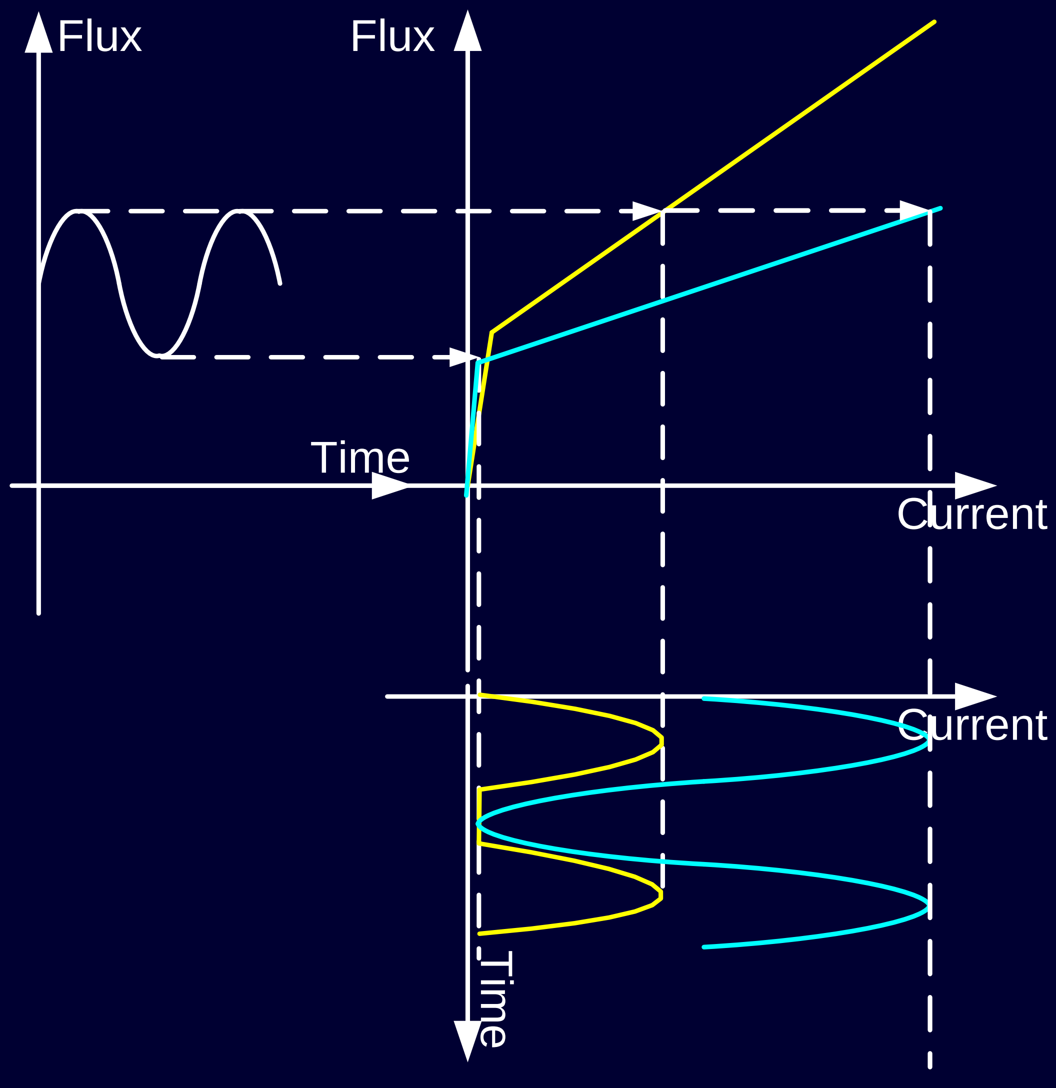
Transient Flux During Energization

Aperiodic Component Increases



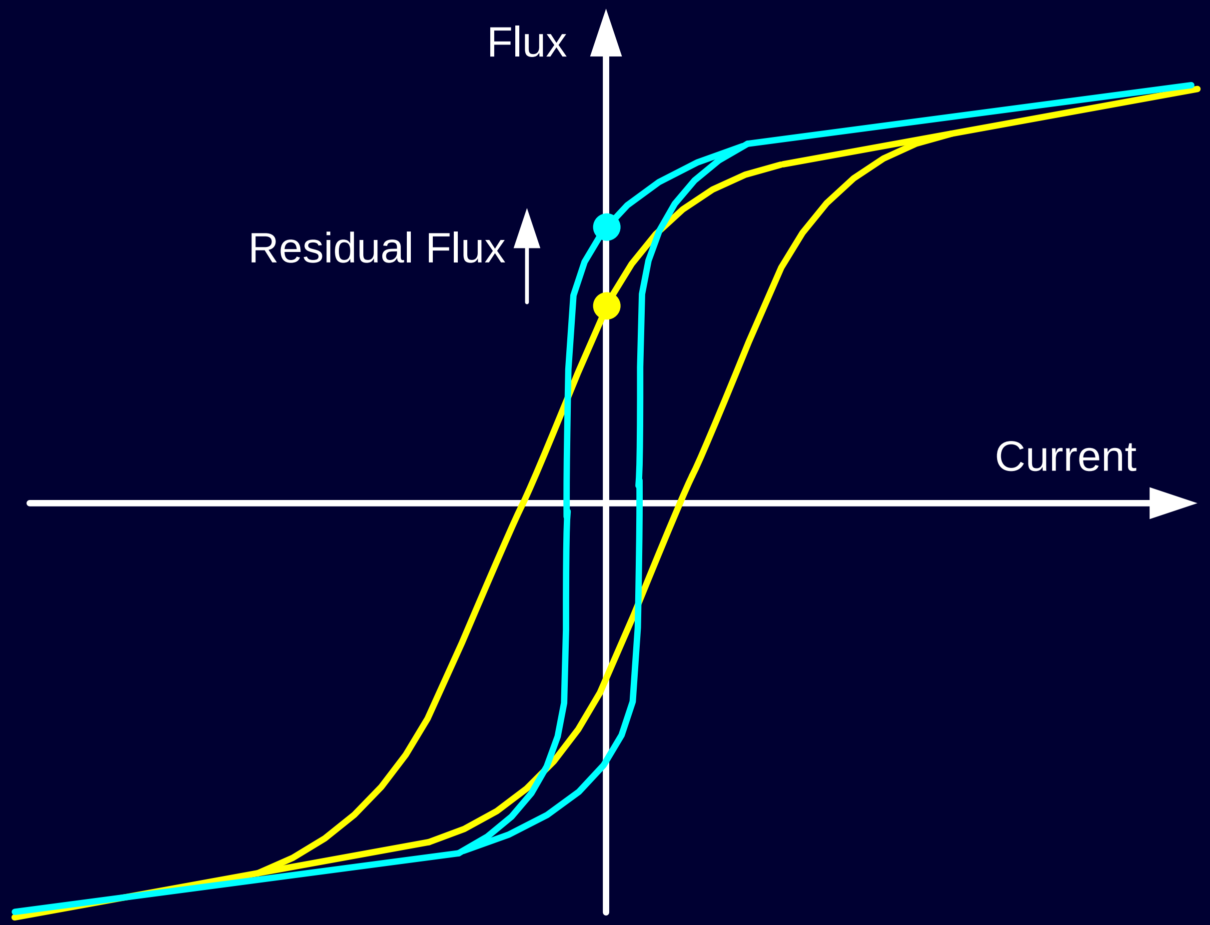
Improved Transformer Design

Lower Saturation Point



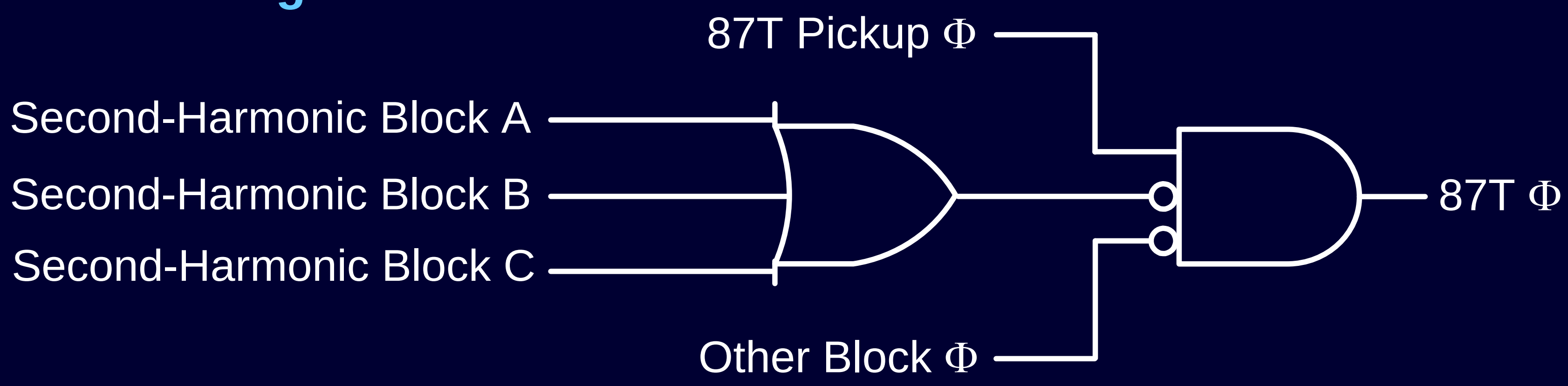
Improved Transformer Design

Lower Losses = Higher Residual Flux

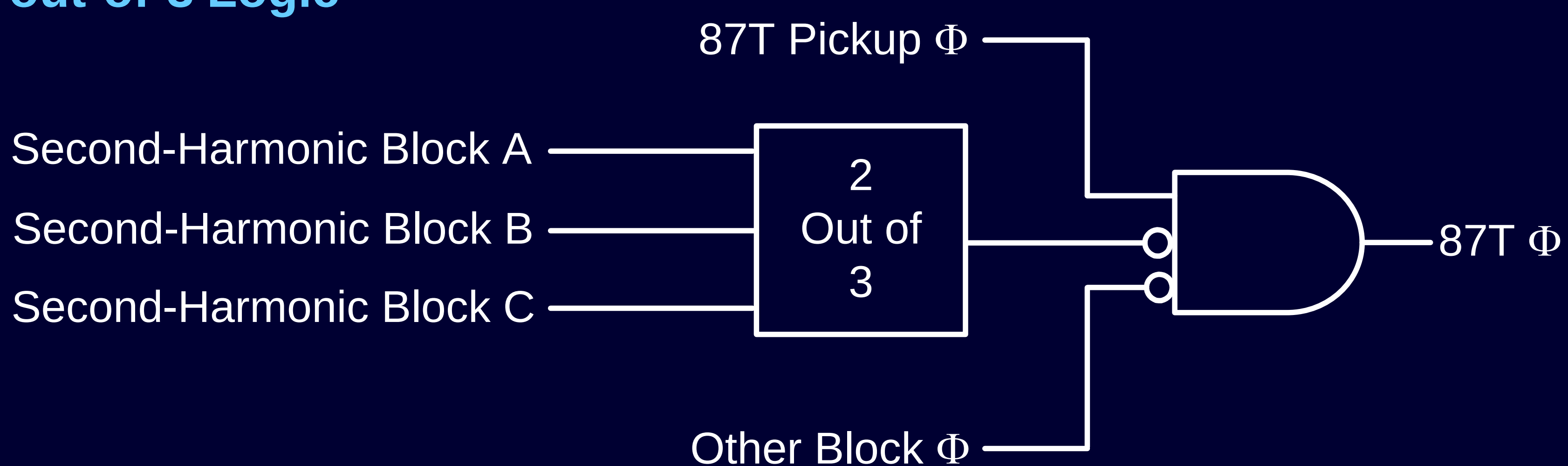


Cross-Phase Blocking

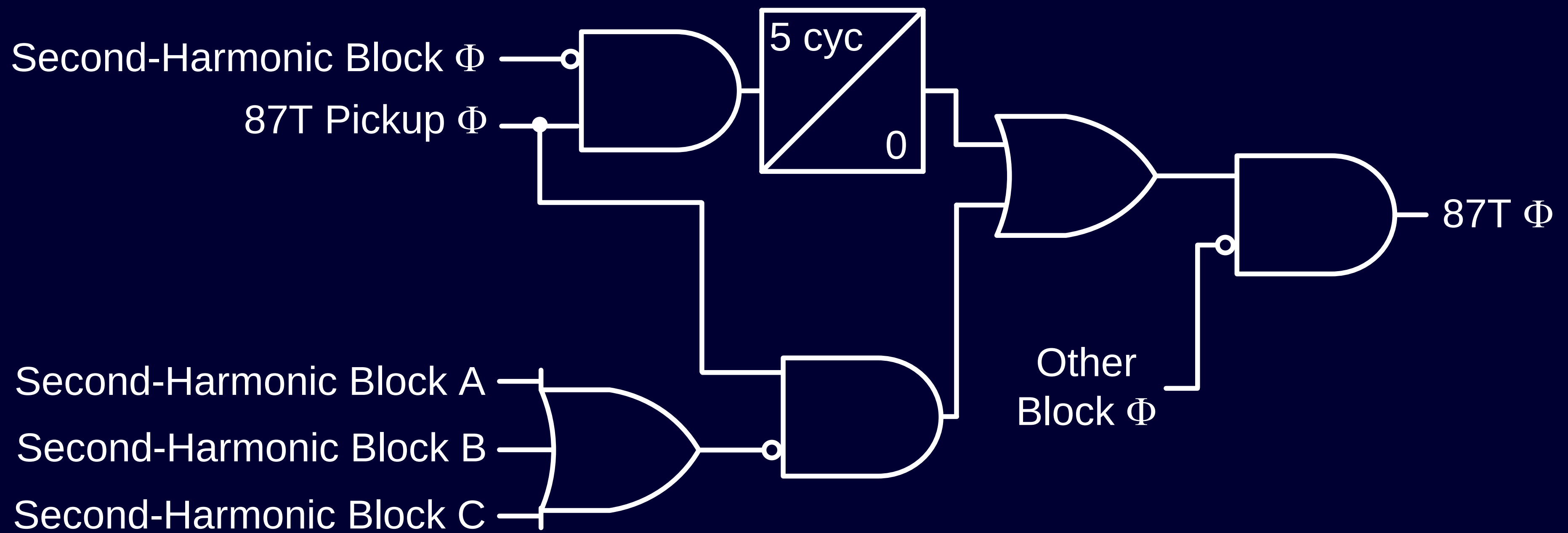
1-out-of-3 Logic



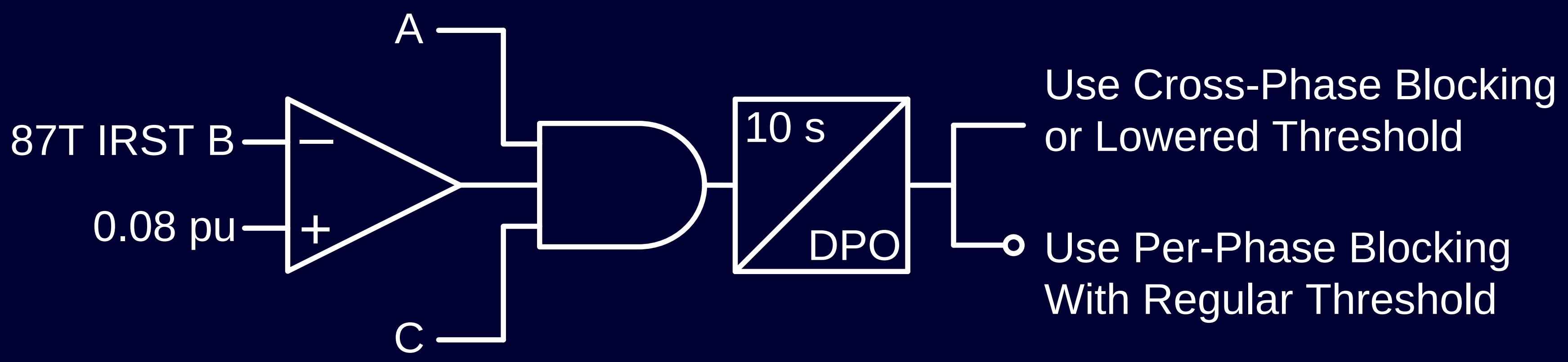
2-out-of-3 Logic



Cross-Phase Blocking With Time Override



Applying More Security When Energizing Transformer



New Inrush Detection Algorithm

In each power cycle

- Currents are small
- Currents are flat
- Periods of small and flat currents are aligned
- Dwell-time periods are longer than 2 ms

Why Are Dwell Periods Aligned?

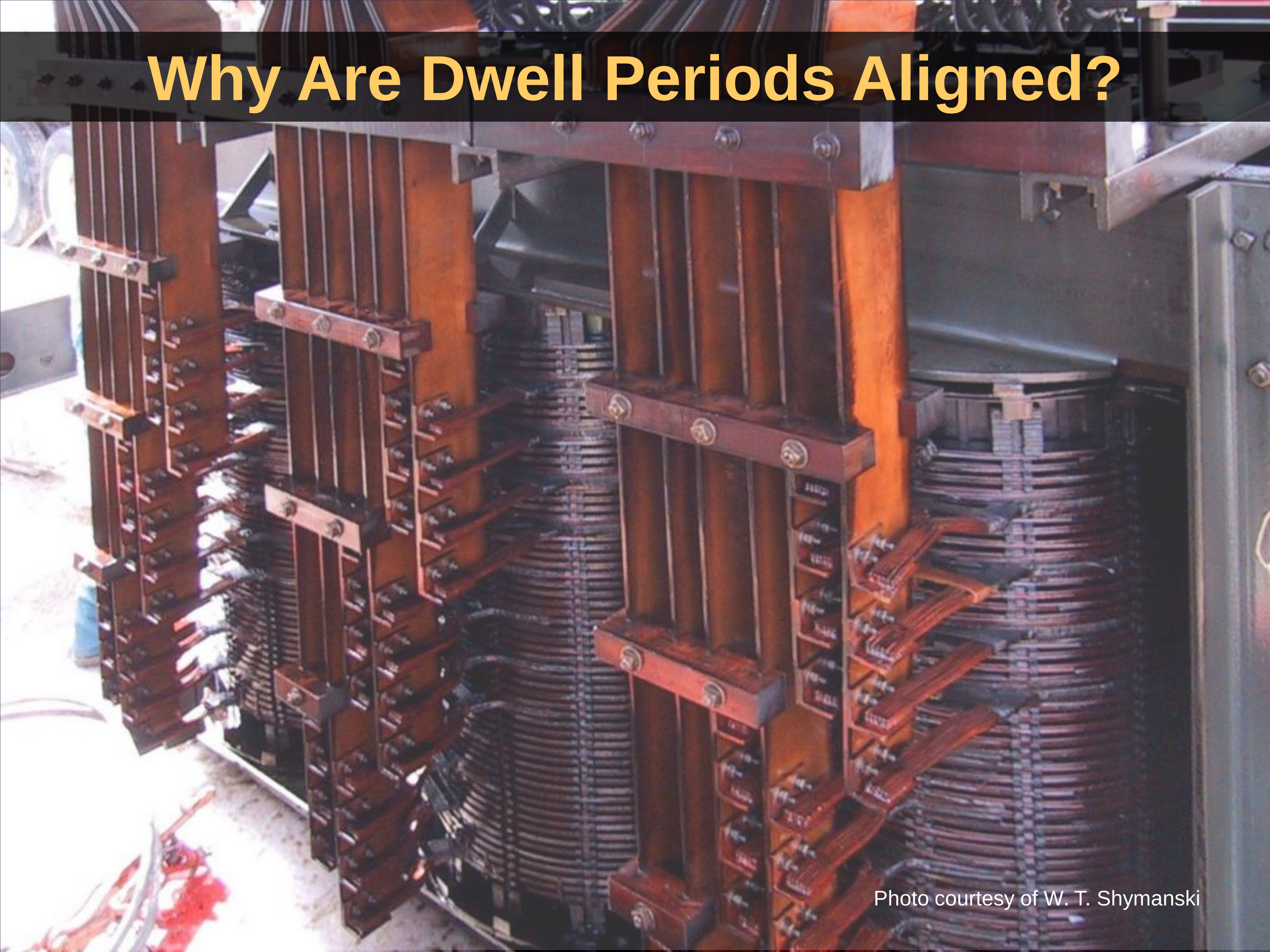


Photo courtesy of W. T. Shymanski

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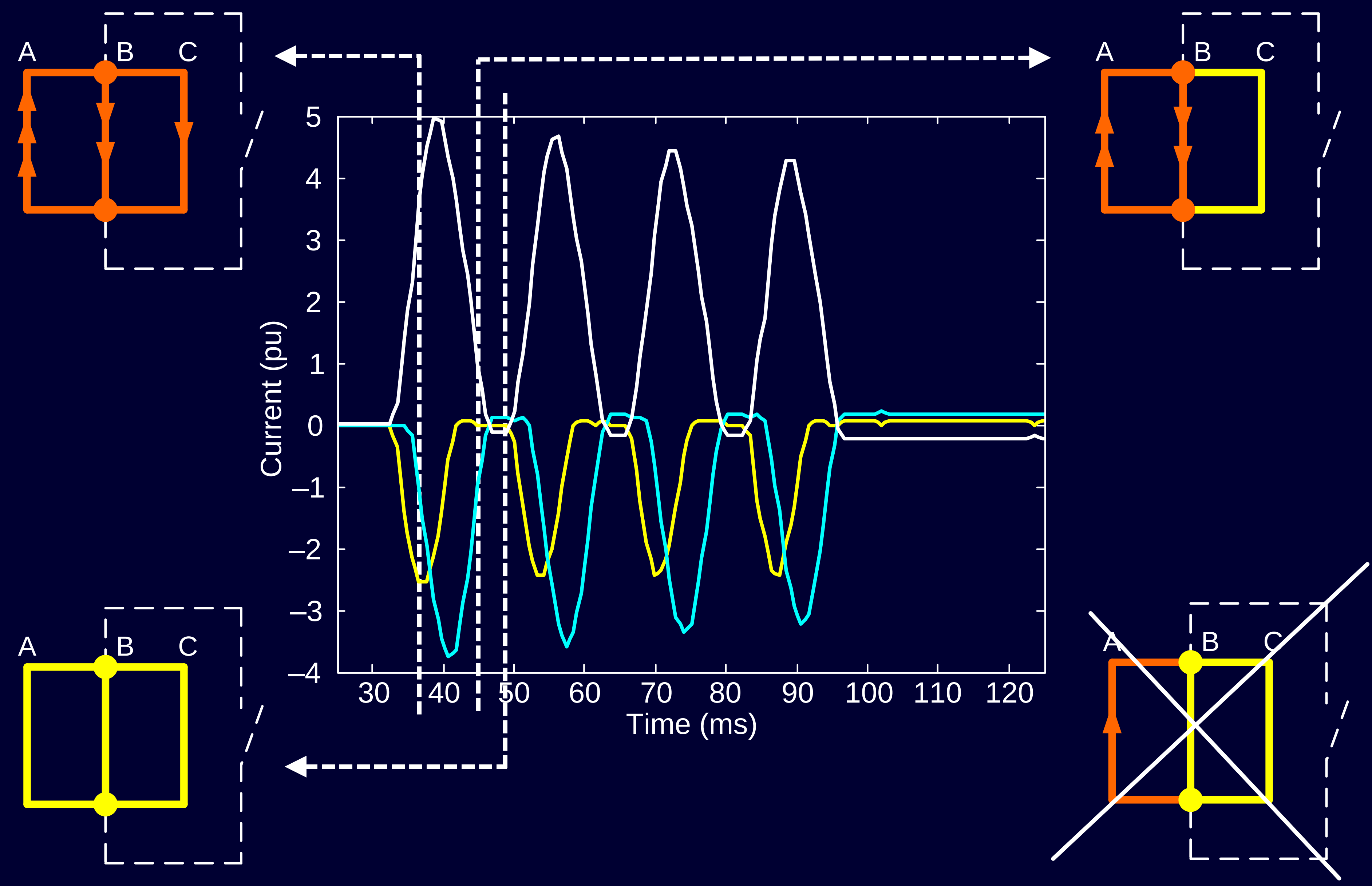

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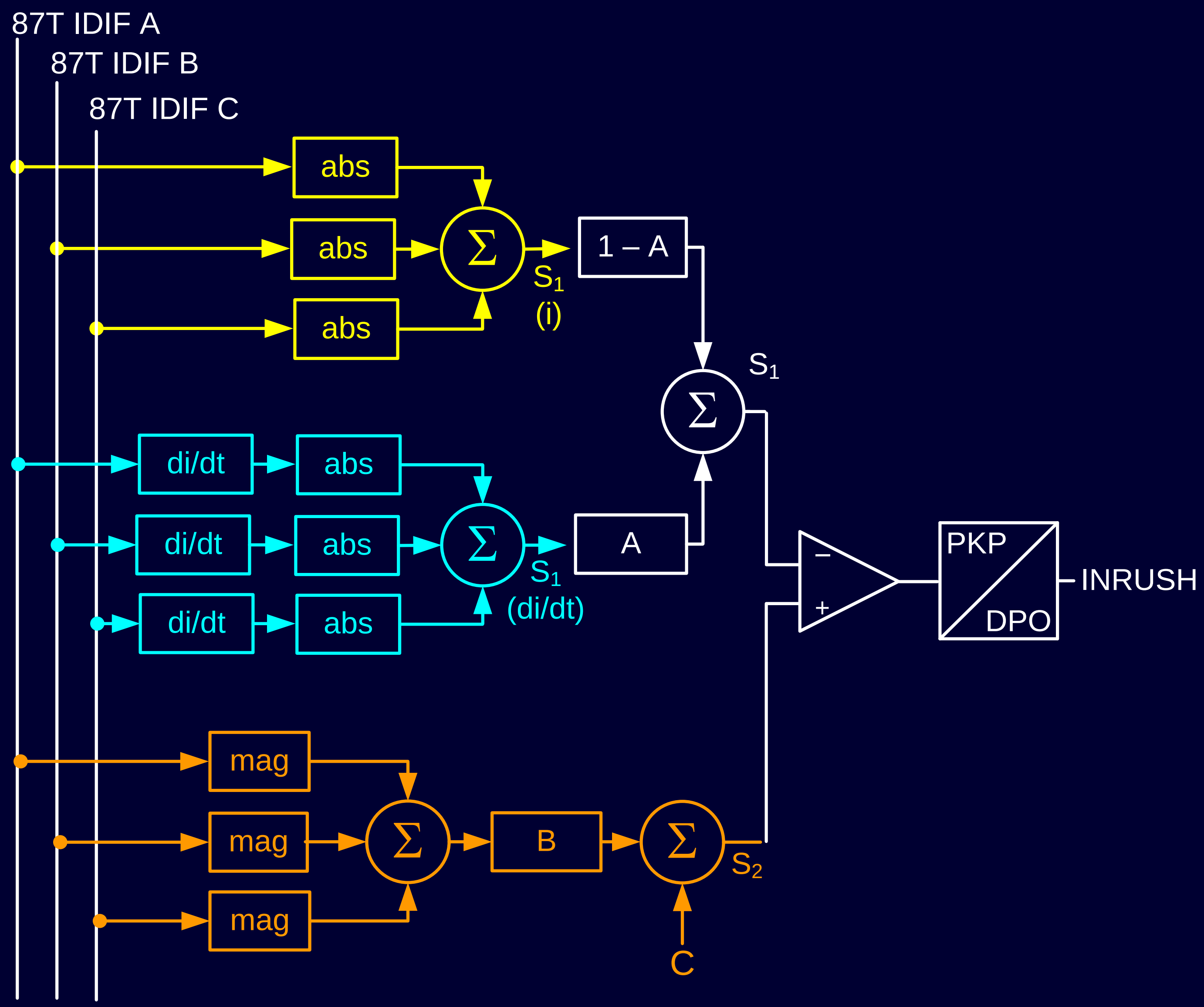
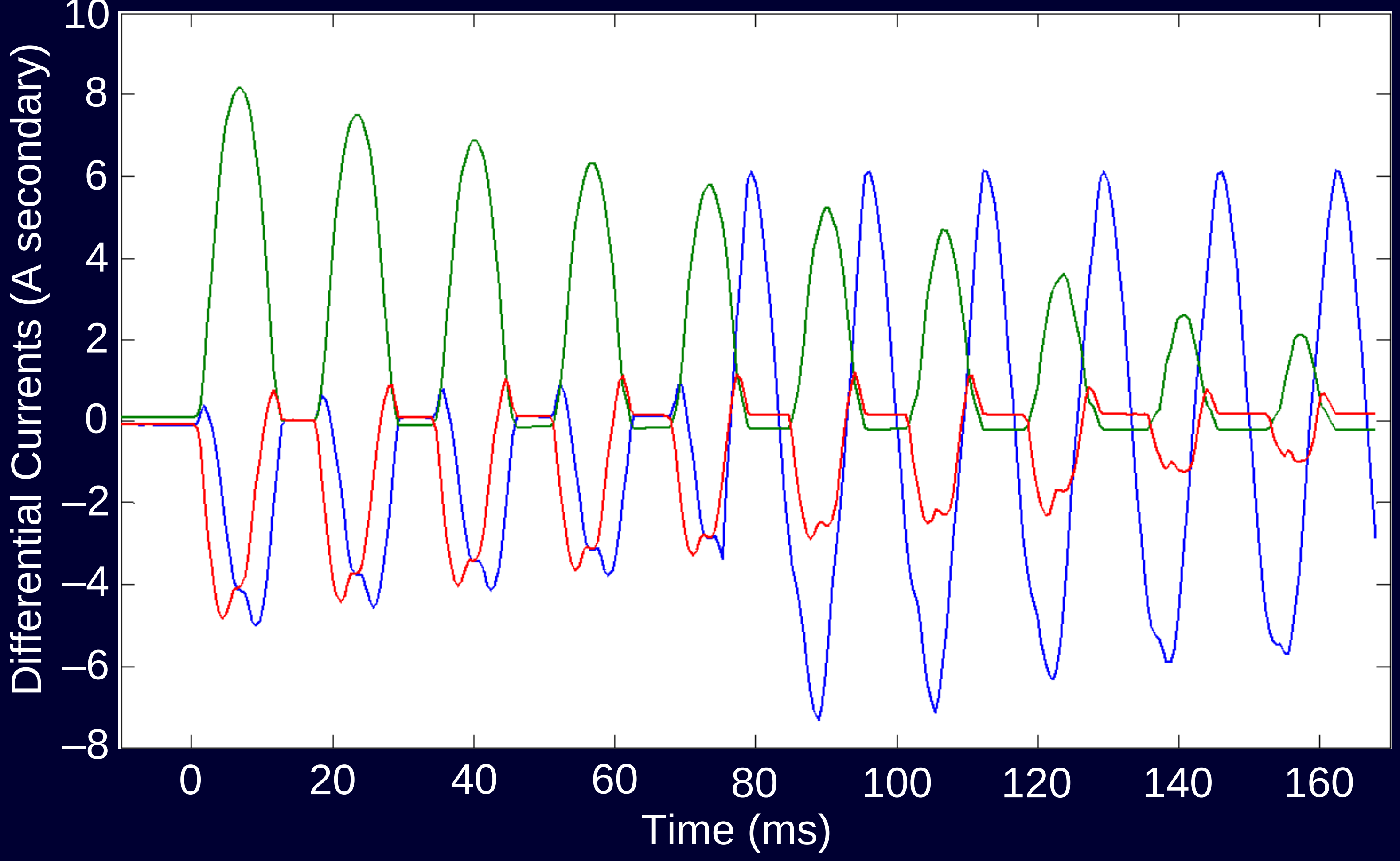


Internal Fault During Inrush Example



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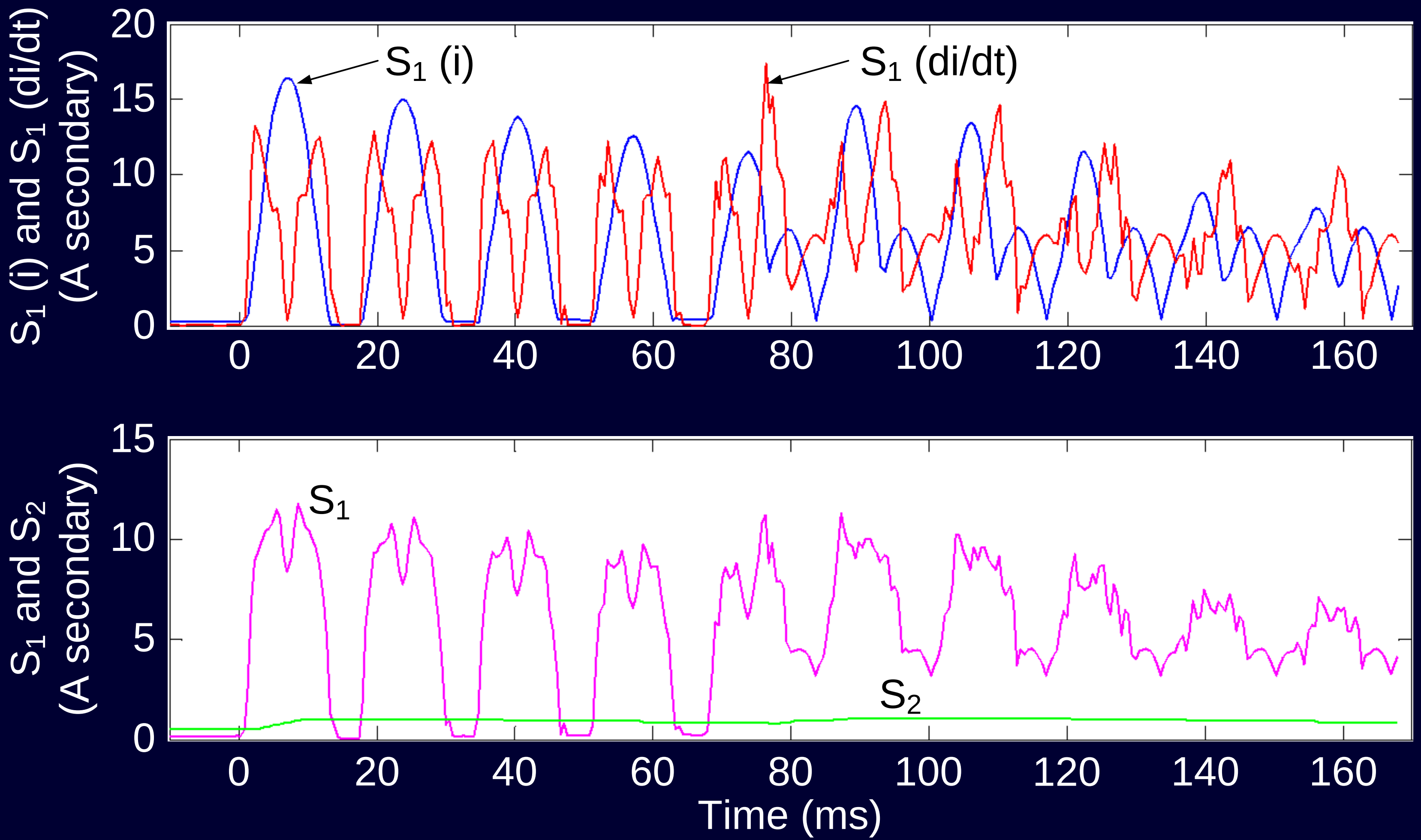
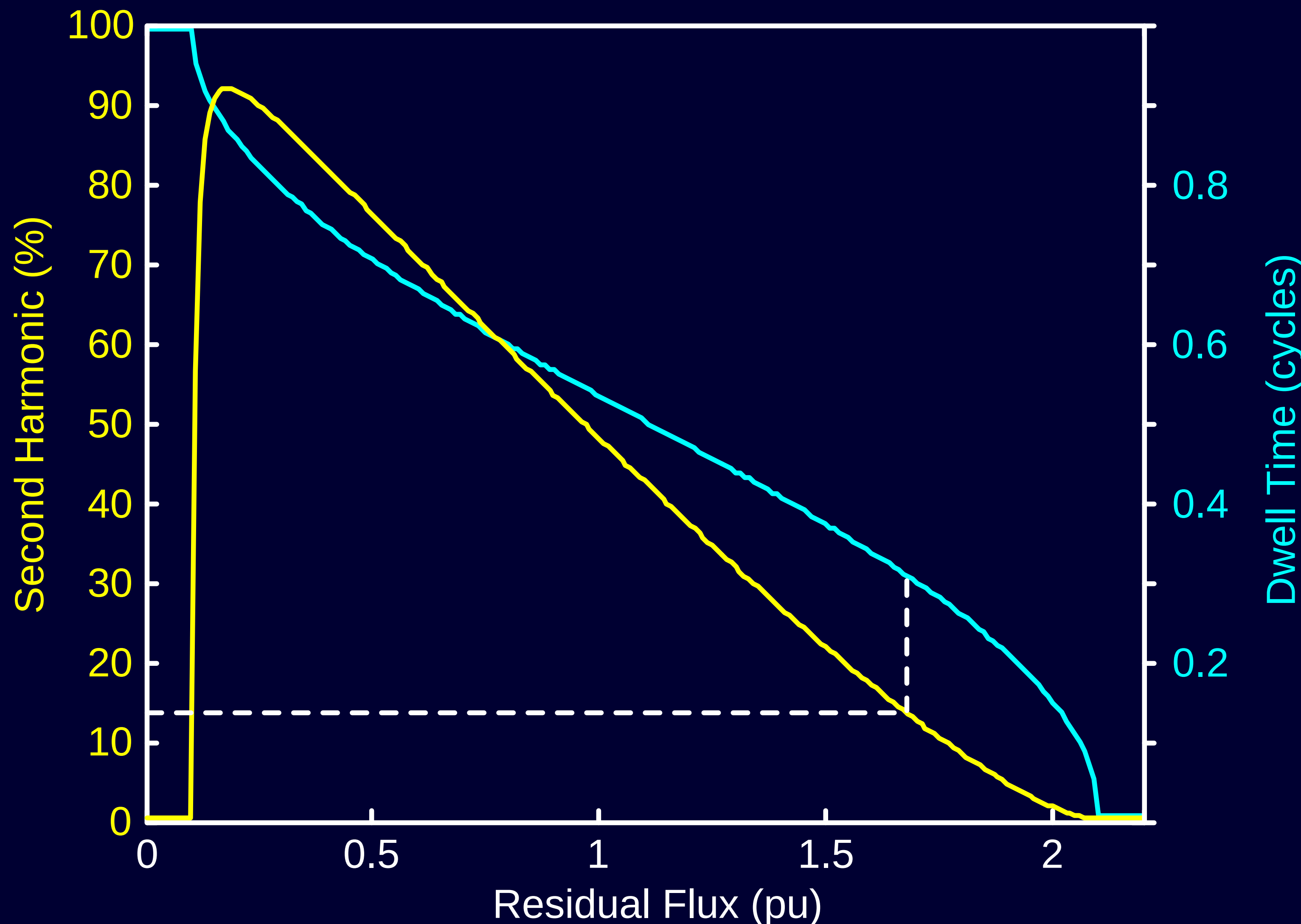


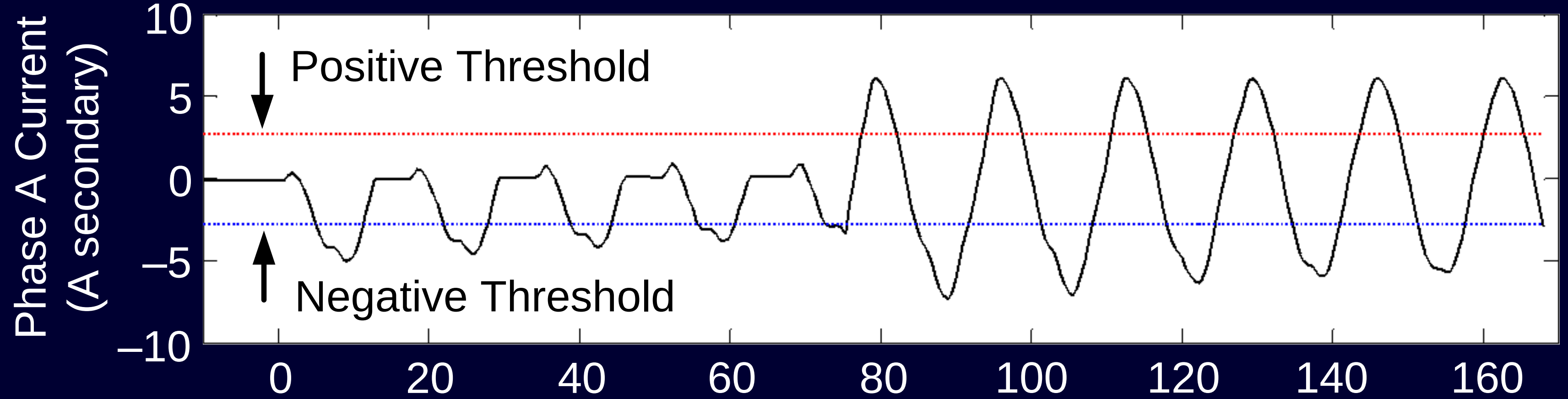
Dwell Time Versus Second Harmonic

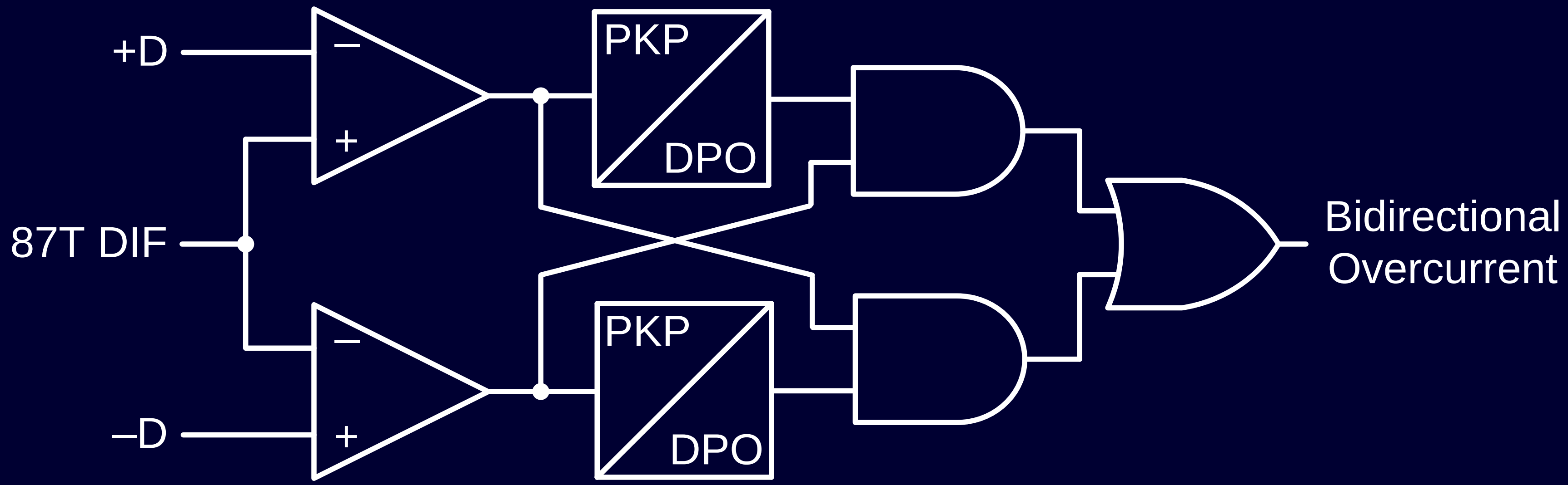


87T Speed of Operation

- Second-harmonic blocking
  - Relay digital filters settle in 1 cycle
  - Trip permission after about 1 cycle
- Second-harmonic restraining
  - Differential signal large on heavy faults
  - Potentially faster operation
- Dwell-time algorithm – intentional 1-cycle extension of block

Bidirectional Differential OC Element





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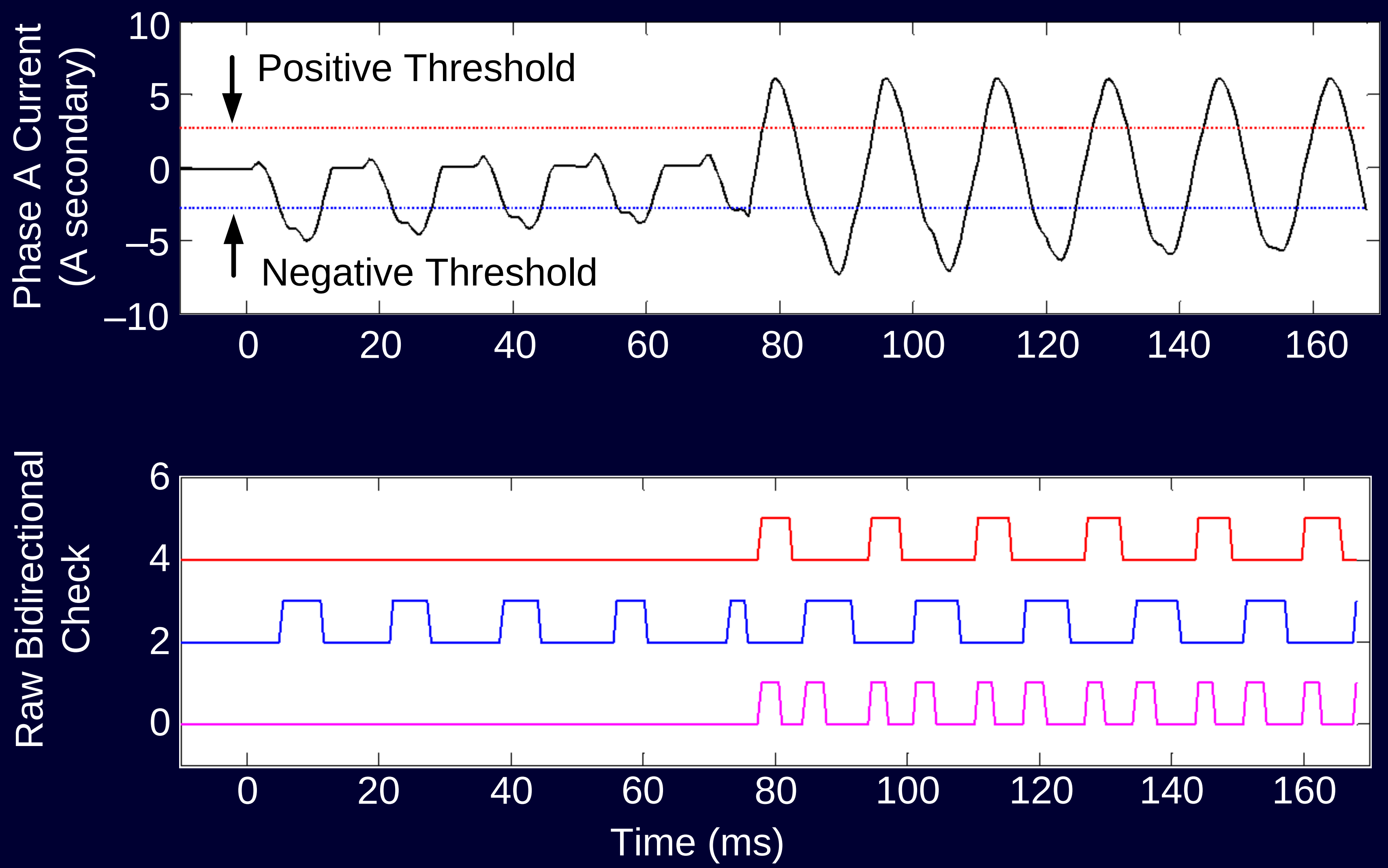
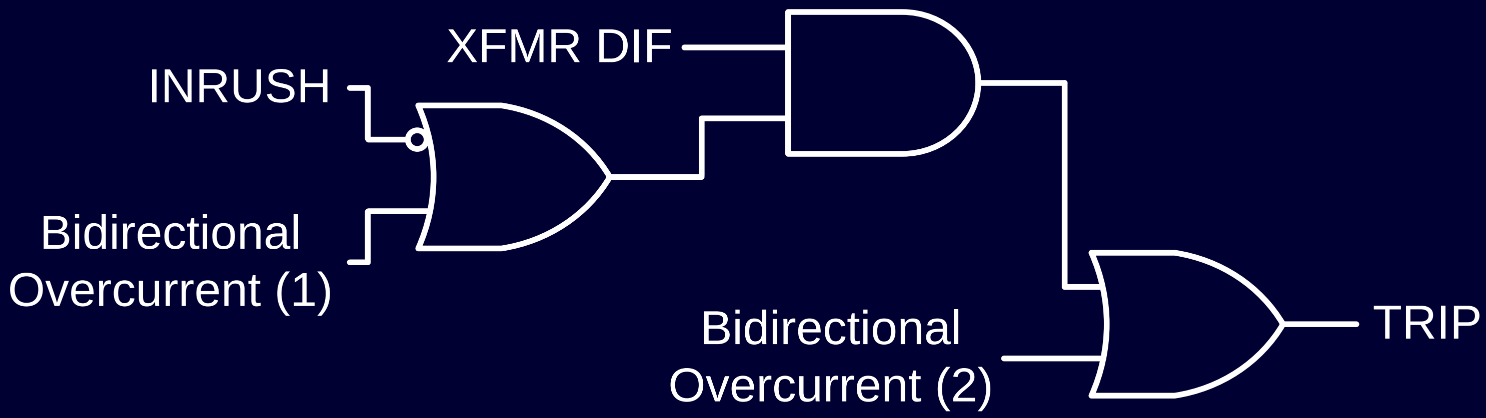


Application of New Elements



- INRUSH element blocks 87T
- Low-set bidirectional OC element cancels INRUSH block
- High-set bidirectional OC element trips unconditionally

Conclusions

- Ultrasaturation happens due to transient flux or high residual flux
- Ultrasaturation reduces second-harmonic level and jeopardizes 87T security
- New transformer designs are more prone to ultrasaturation
- Harmonic-based mitigation techniques sacrifice dependability or speed

Conclusions

- New inrush detection method is both secure and dependable
- Bidirectional OC element considerably speeds up 87T operation

Questions?