How to Determine the Effectiveness of Generator Differential Protection

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Overview

- Generator Stator Winding
- Typical Stator Winding Faults
- Differential Protection
- Detecting Stator Winding Faults
- CT Selection for Differential Protection
- Differential Protection Recommendations
- Conclusions

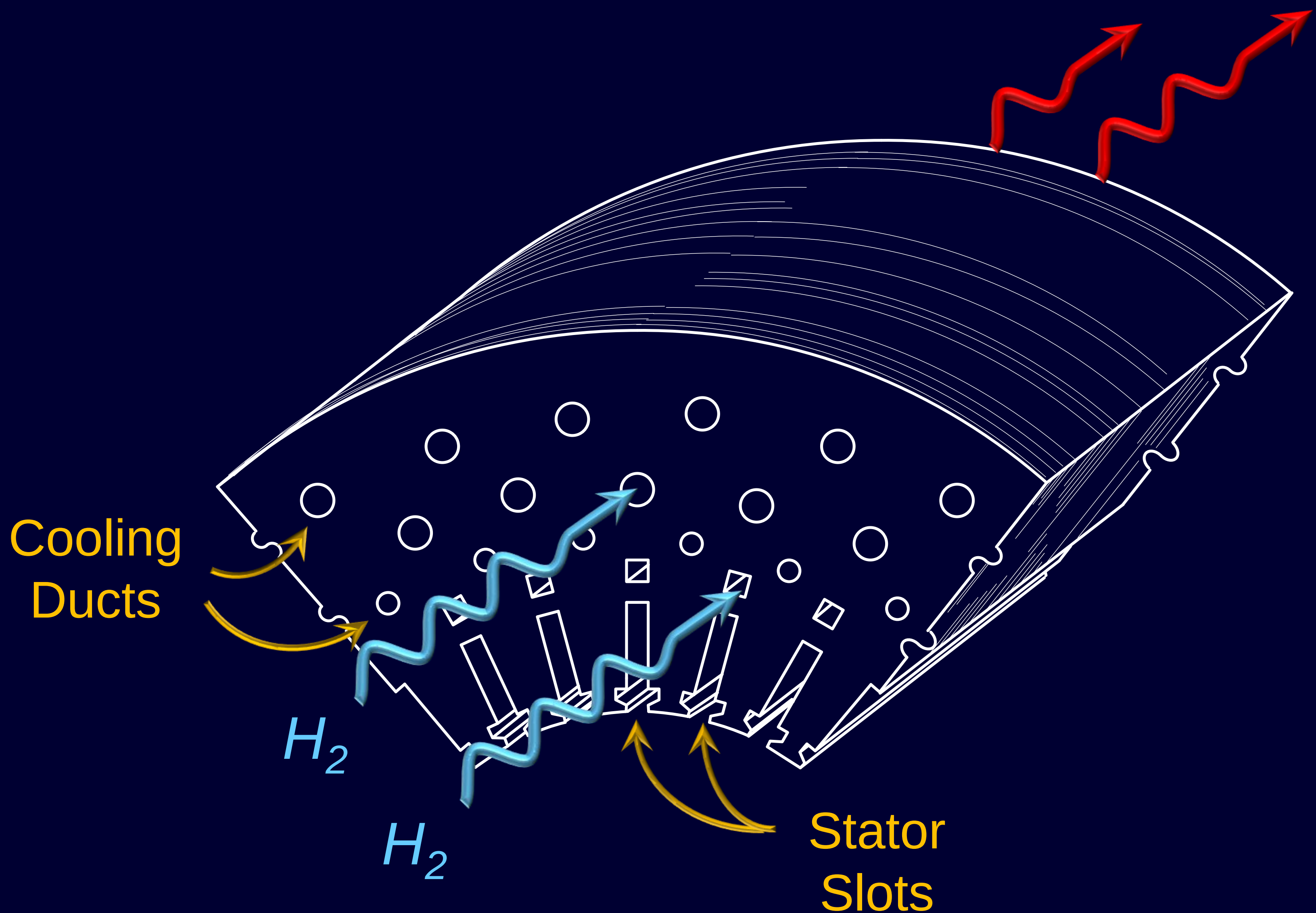
The Generator Stator

Stator Core

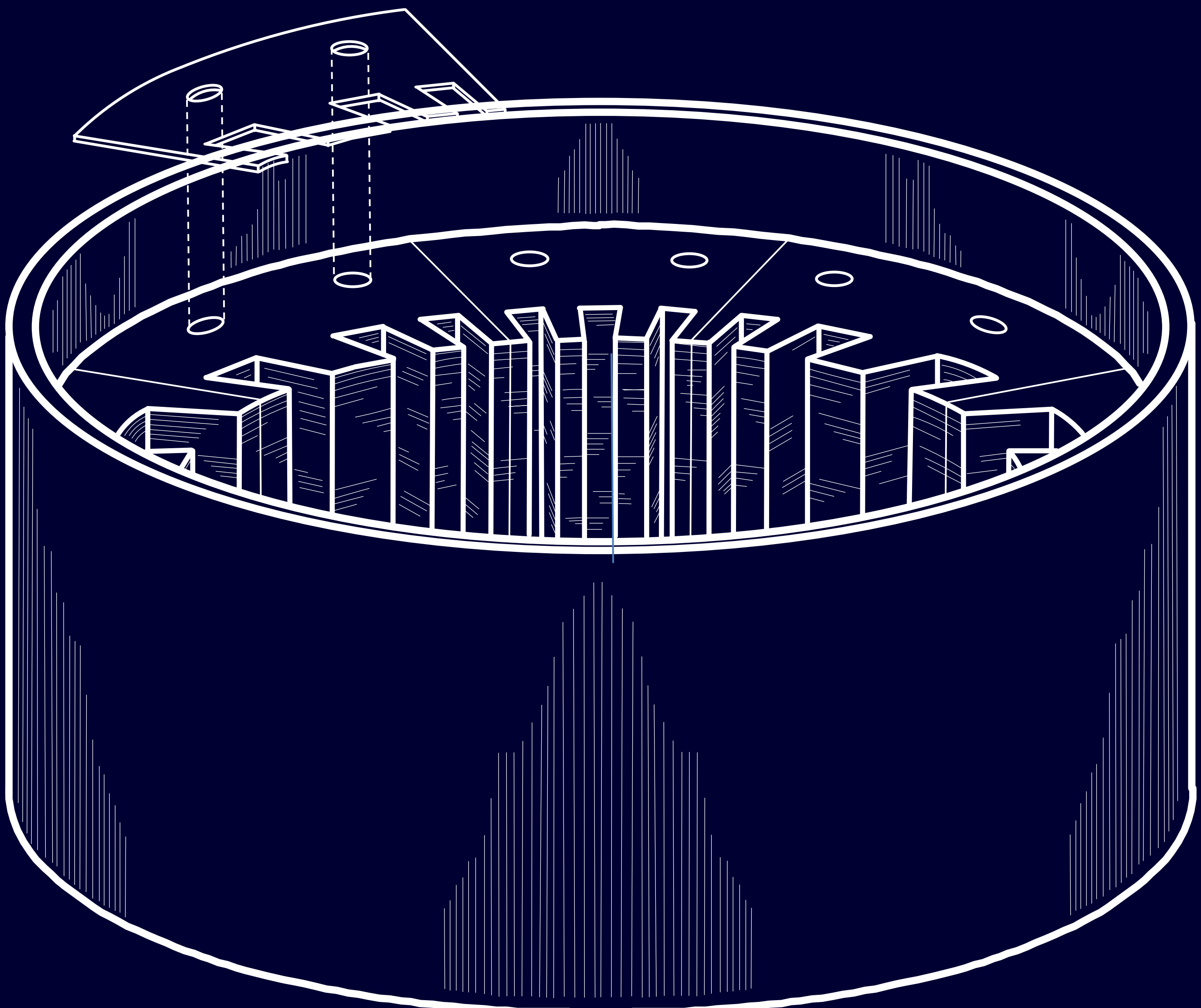
Stator Windings

Insulation

The Stator Core (Cylindrical)



The Stator Core (Hydro)

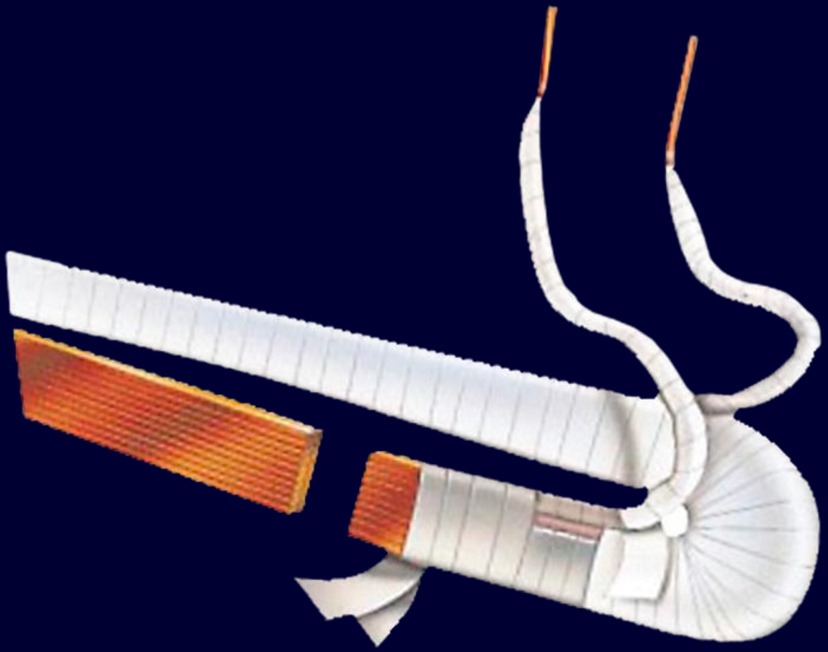


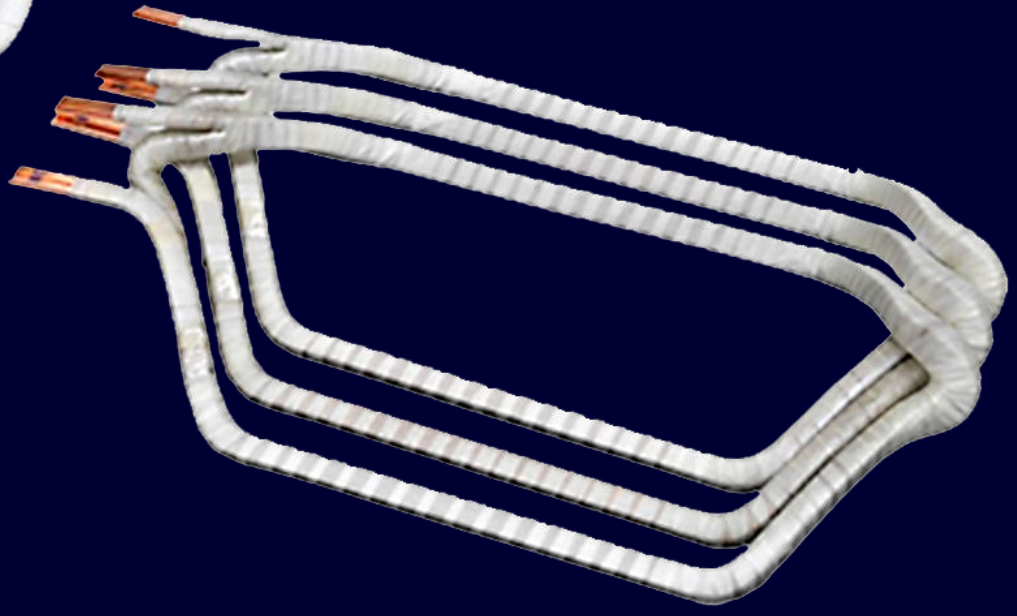
Example of Hydrogenerator Core

Types of Winding Structures

- Random-wound stators (< 300 kW)
- Form-wound stator using multiturn coils (< 100 MW) ✓
- Form-wound stator using Roebel bars (> 100 MW) ✓

Multiturn Coils





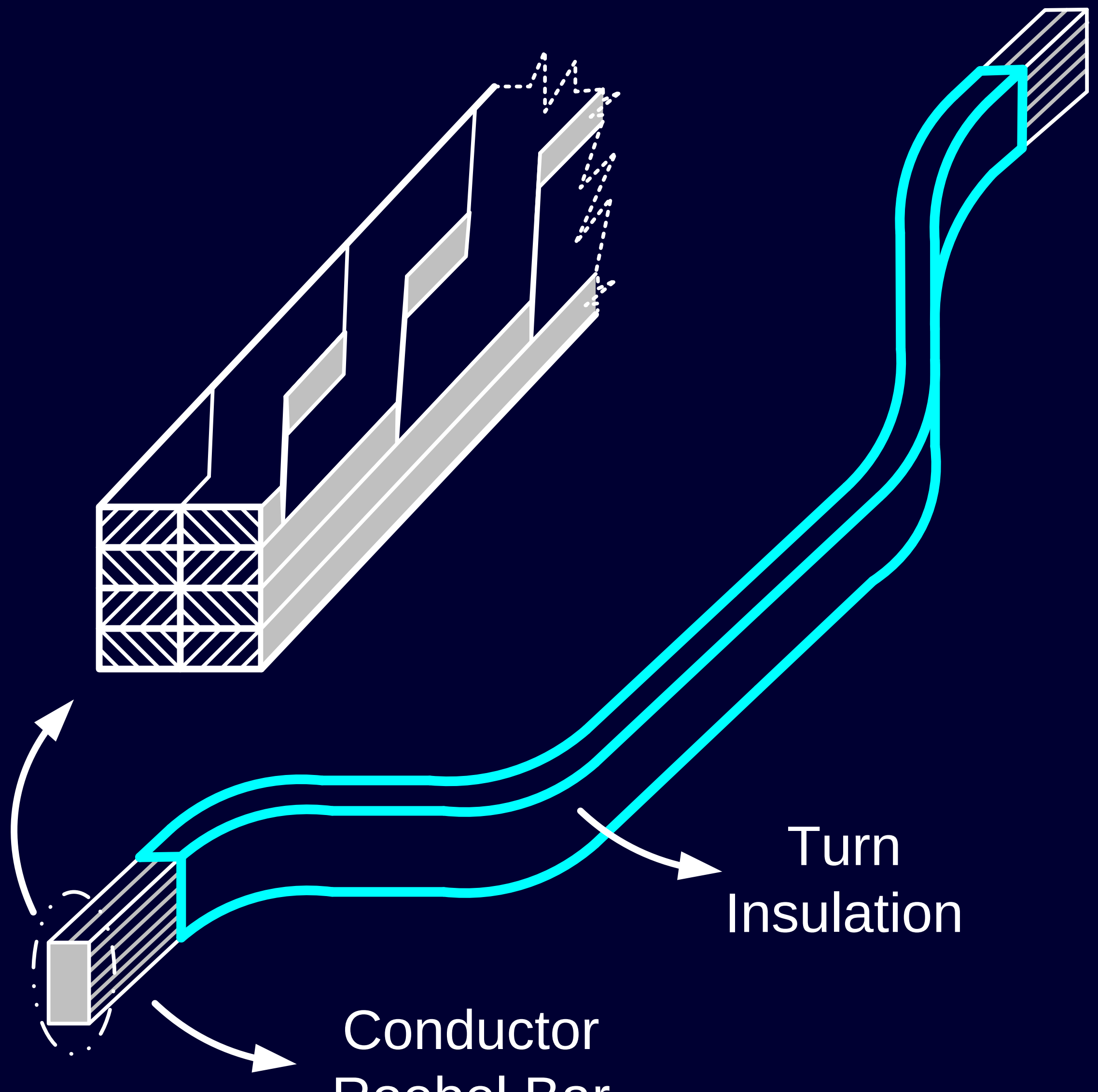
Insertion of a Multiturn Coil

Ludwig Roebel

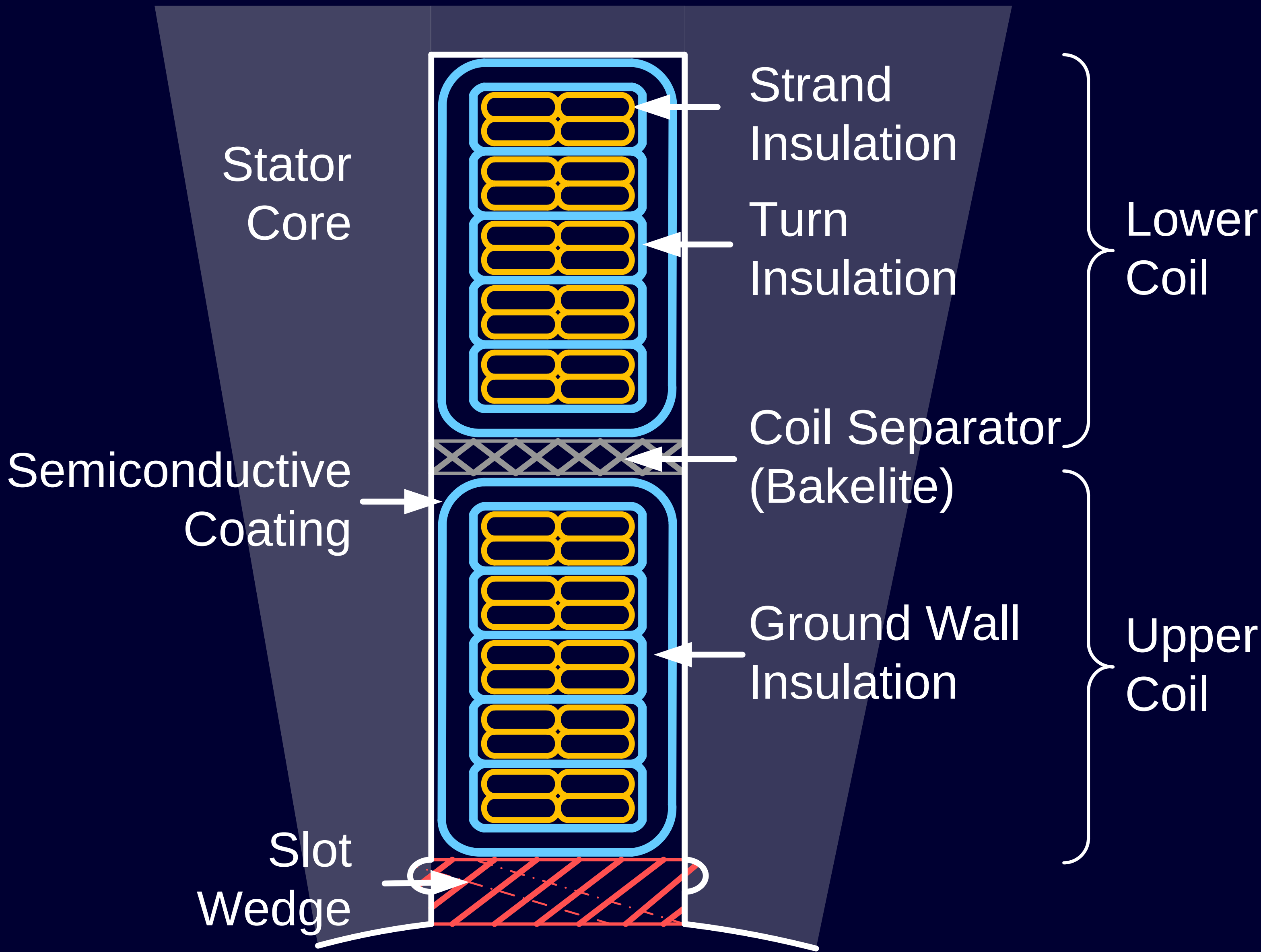
1912

20 MW

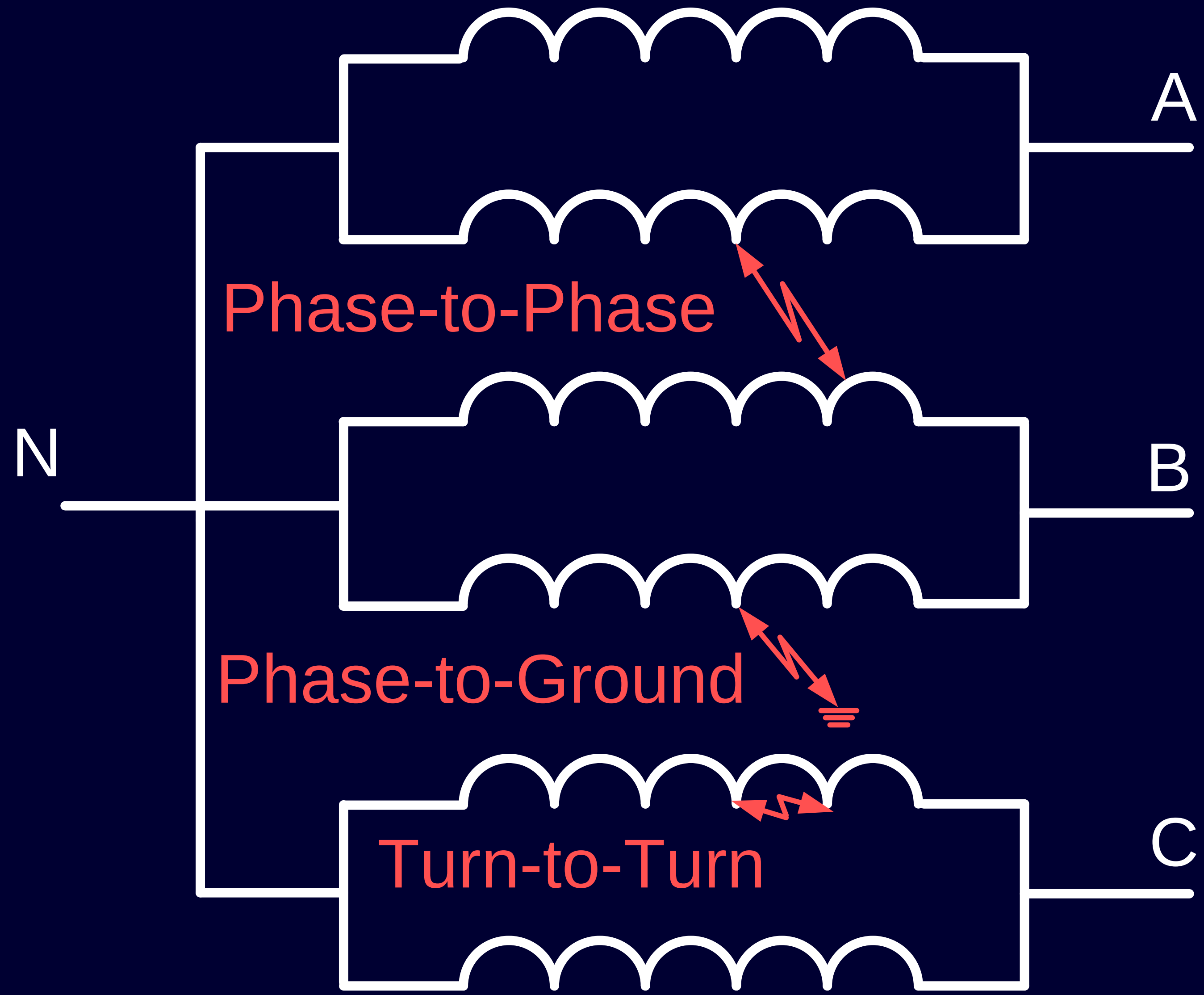
Roebel Bars



Insulation Material



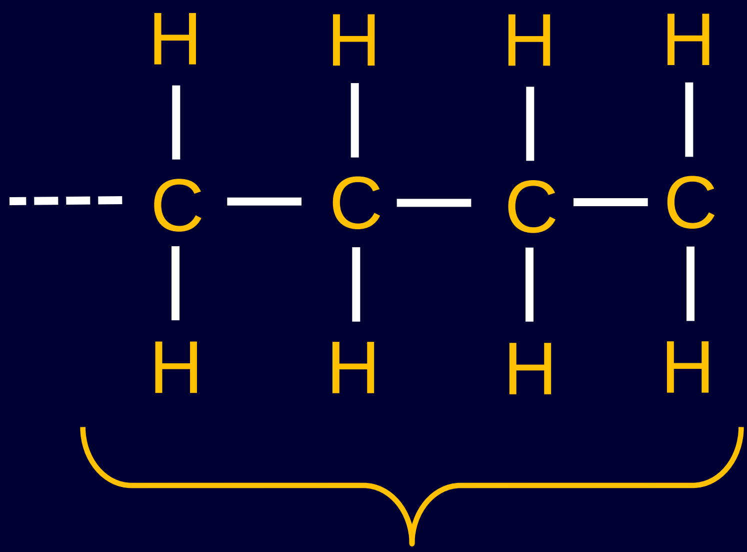
Typical Stator Winding Faults



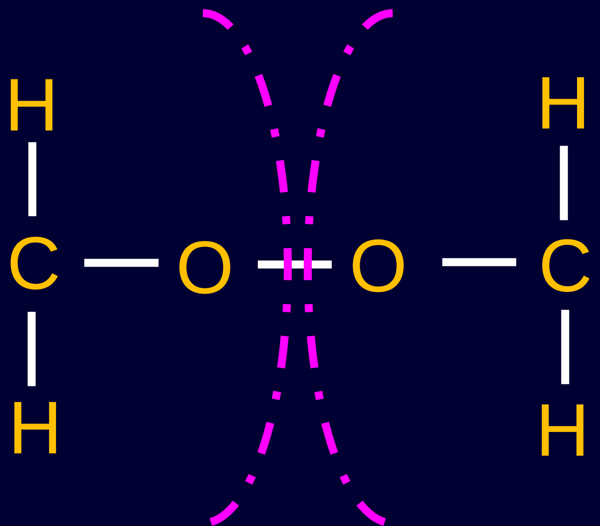
Causes of Insulation Failure

- Thermal Deterioration
- Electrical Deterioration
- Mechanical Deterioration
- Environmental Deterioration

Thermal Deterioration



Polymer



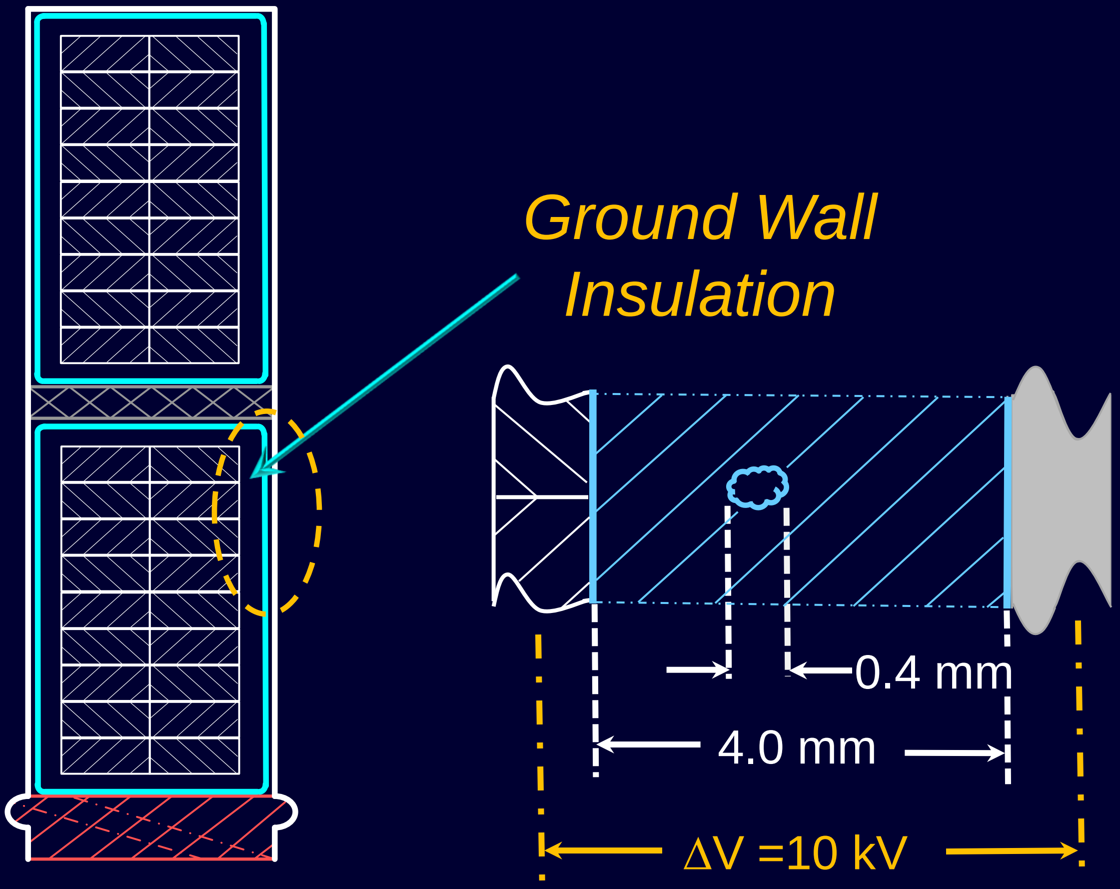
Oxidation

10°C increase temp = 50 % decrease life

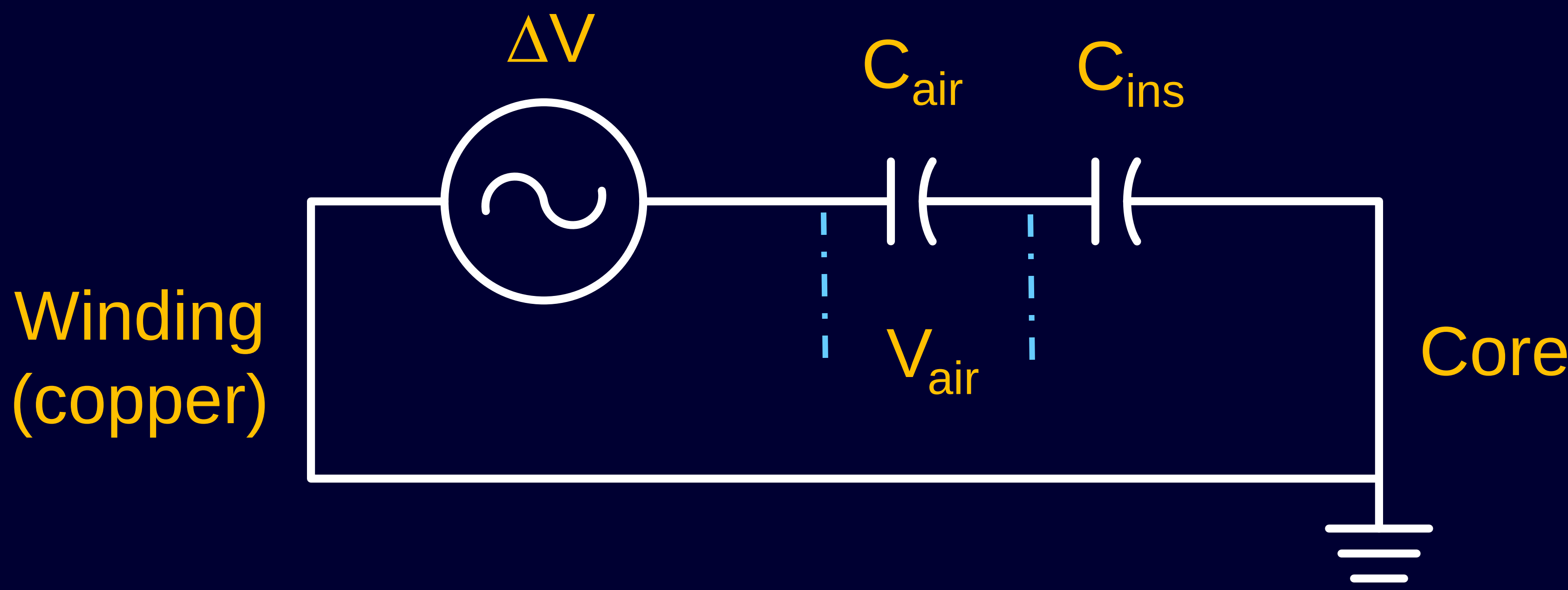
$$L = Ae^{\frac{B}{T}}$$

Electrical Deterioration

Result of electrical stress within small voids in the insulation



Calculating the Electrical Stress (E) in the Void



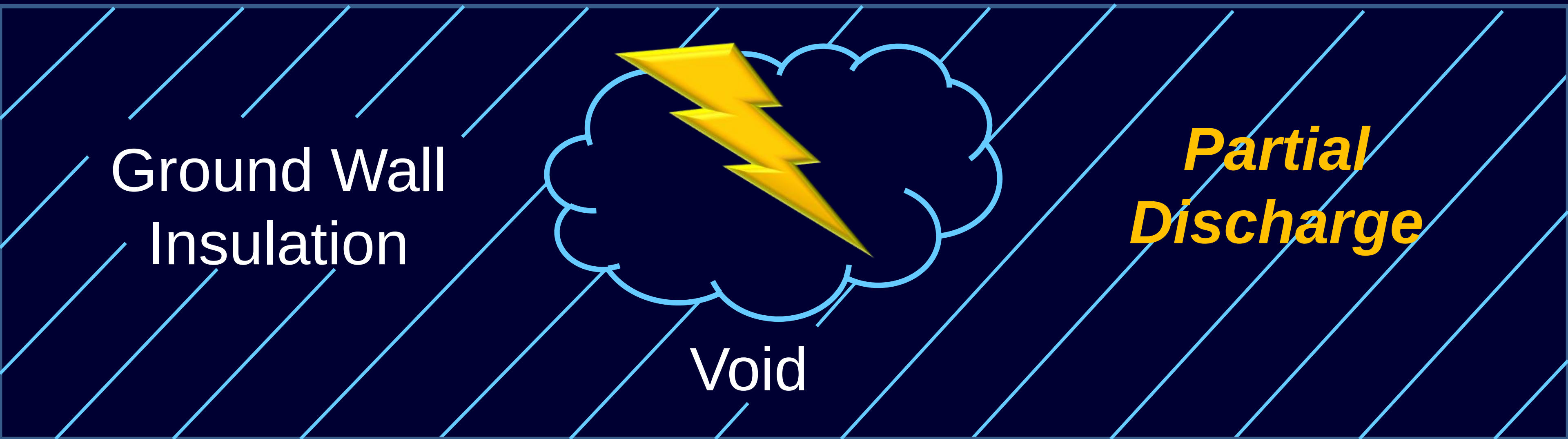
$$C_{air} = \frac{\varepsilon_0 \varepsilon_r A_{air}}{d_{air}}$$

1st Approx. // plate

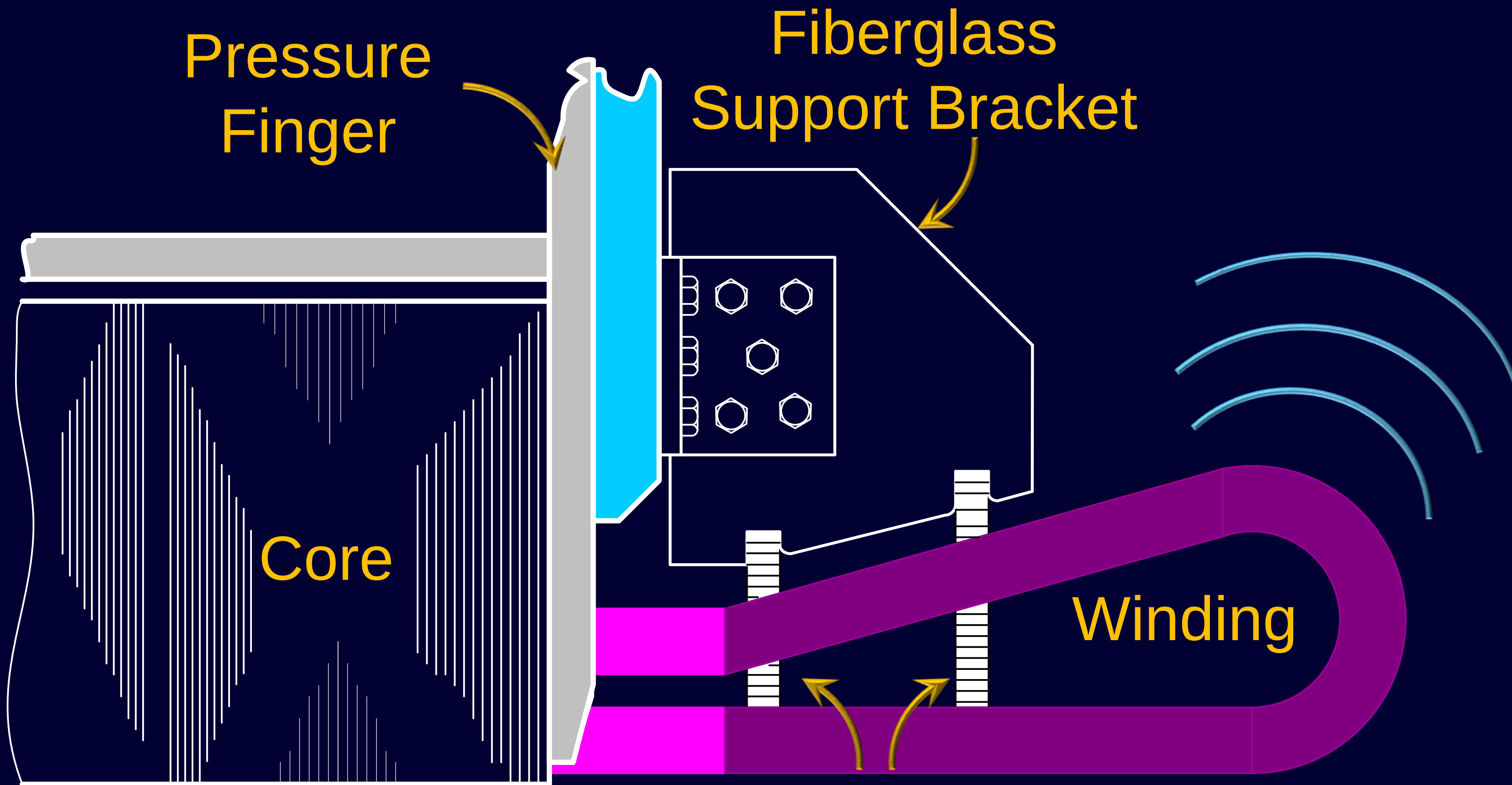
Calculate Electrical Stress in Void

$$V_{air} = \frac{C_{ins}\,\Delta V}{C_{ins} + C_{air}} \qquad V_{air} = \frac{\tfrac{3}{4} \cdot 10\ \text{kV}}{\tfrac{3}{4} + {}^{1}/_{0.4}} \qquad V_{air} = 2.31\ \text{kV}$$

$$E_{void} = \frac{V_{air}}{d_{air}} \qquad \boldsymbol{E_{void} = 5.78\ \textbf{kV/mm}}$$

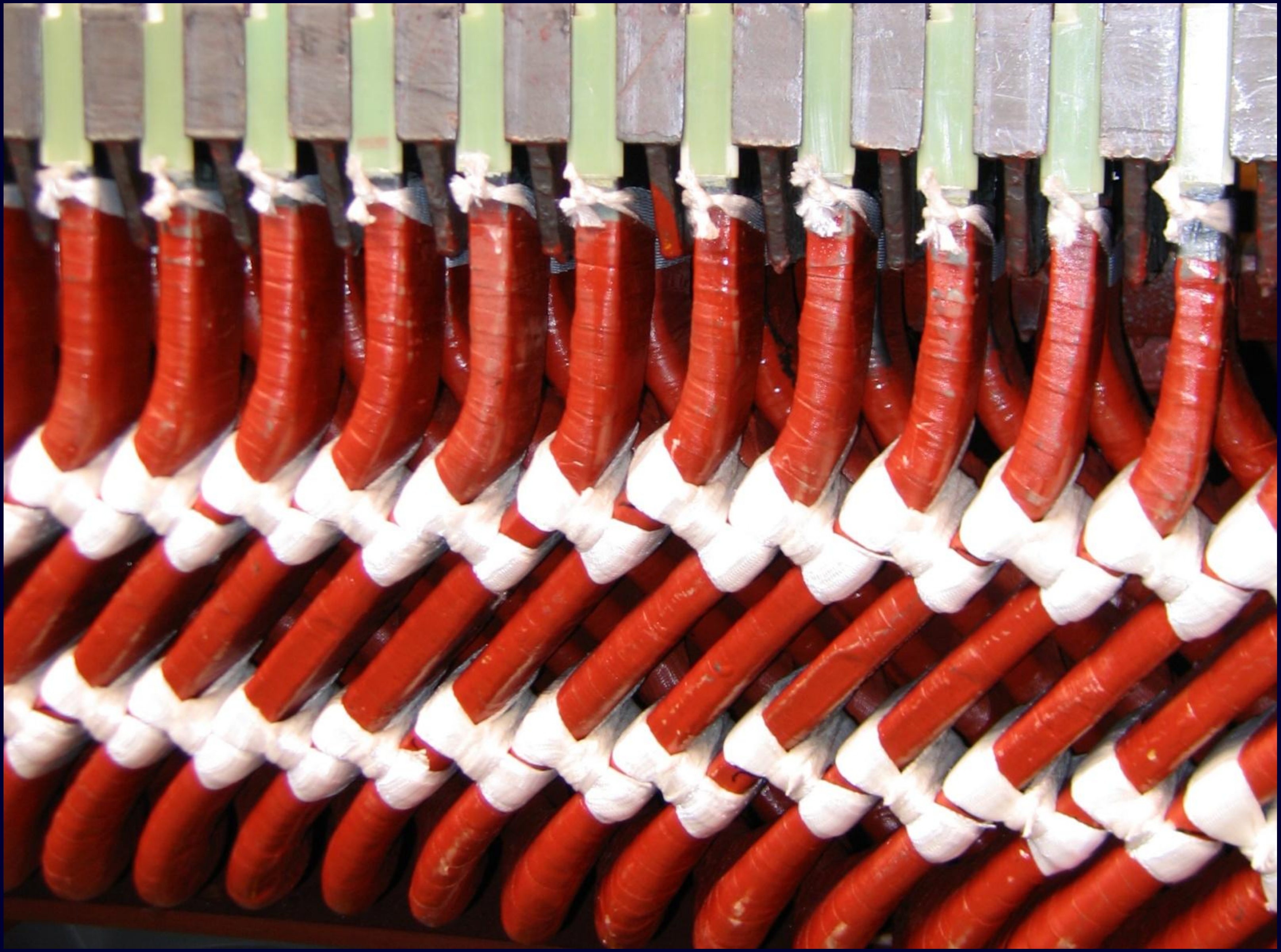


Mechanical Deterioration



$$F = \frac{k \cdot A^2 (1 - \cos 2\omega t)}{d}$$

Stator End Windings Support



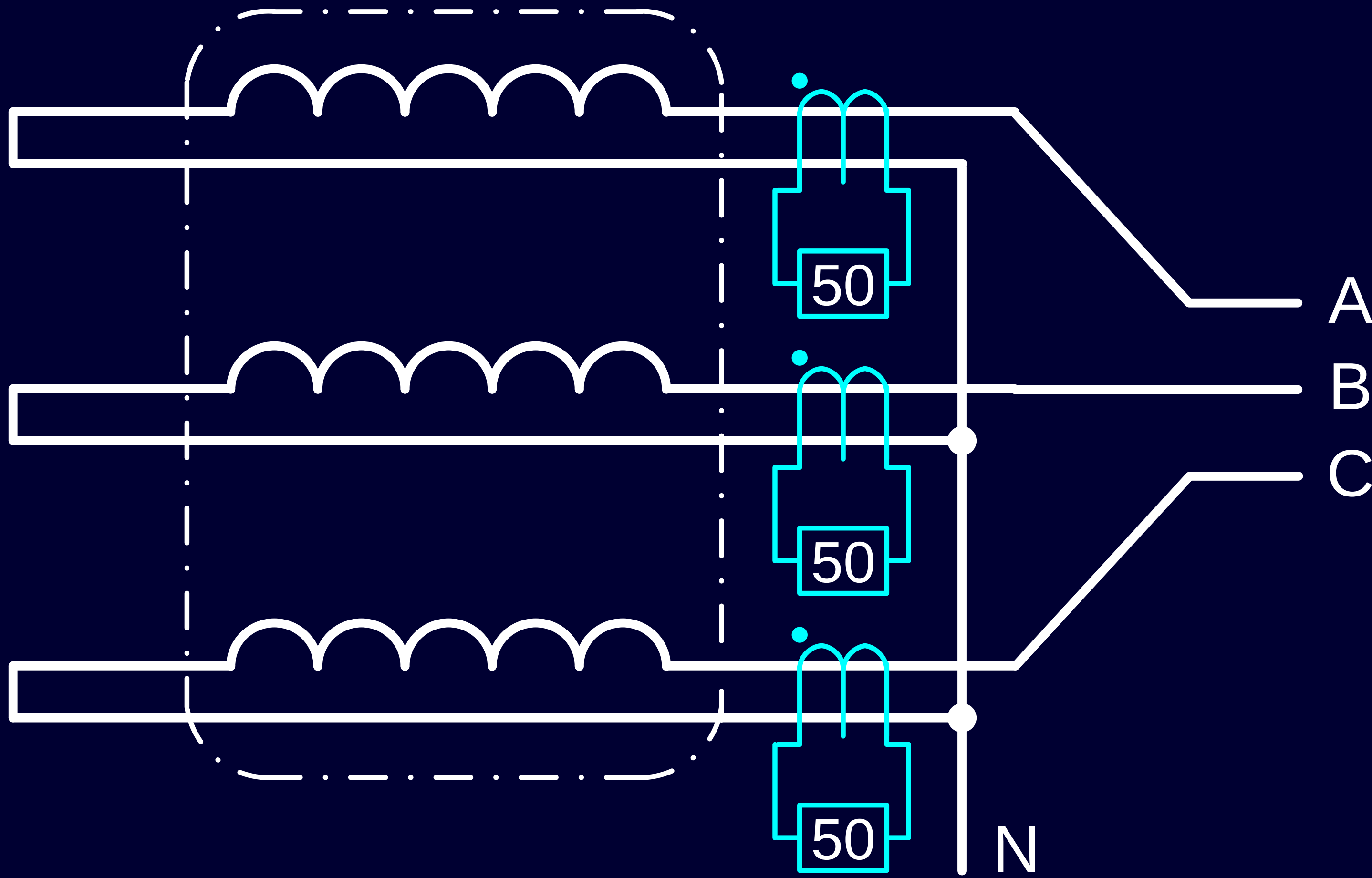
Environmental Deterioration

Oil and Dust Contamination

Differential Protection Schemes

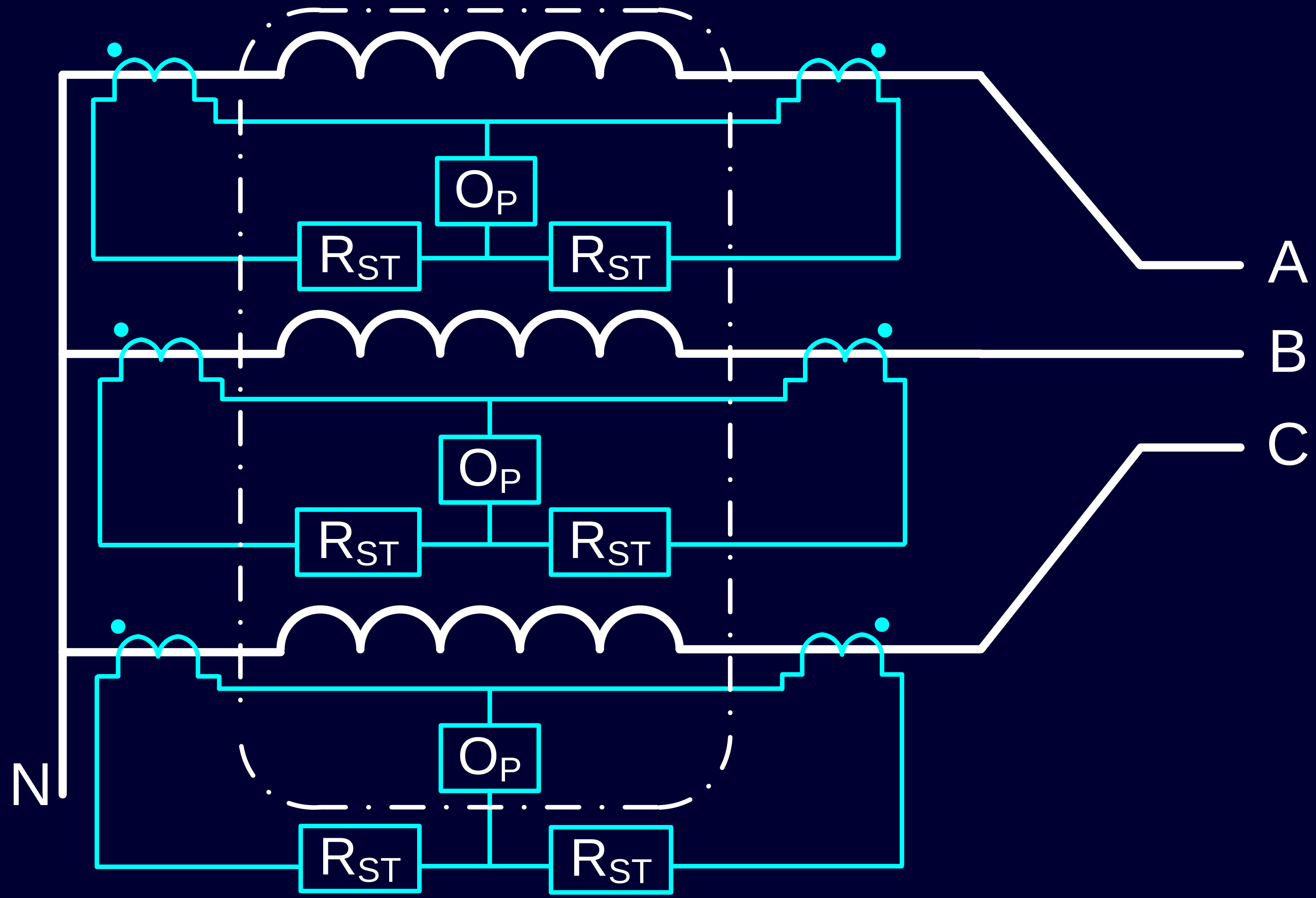
- Self-balancing differential
- Biased differential
- High-impedance differential
- Negative- and zero-sequence differential
- Restricted earth fault

Self-Balancing Differential



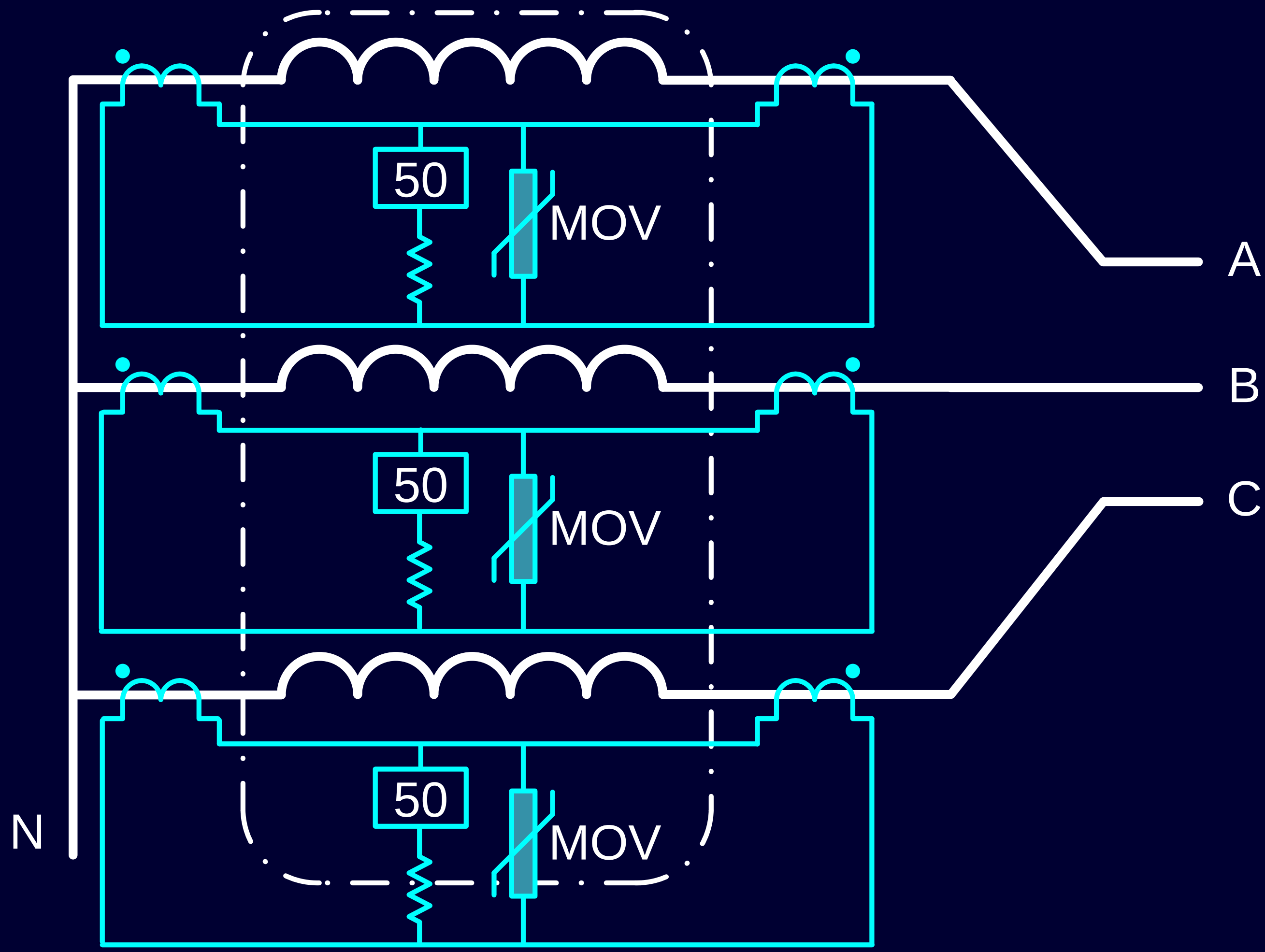
$$I_{MIN\_SB} = CTR_{CB} \bullet I\_PU_{SB}$$

Biased Differential



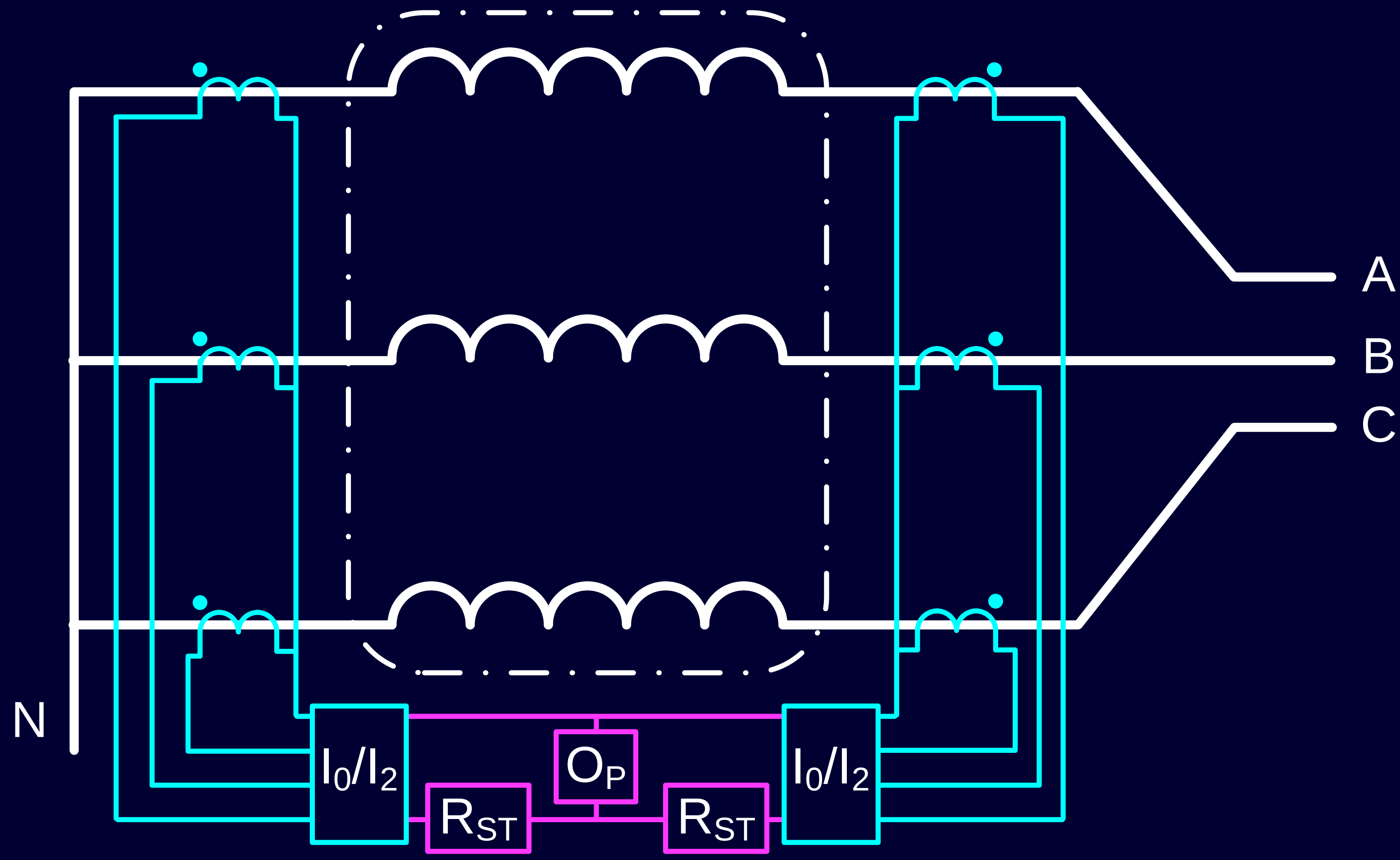
$$I_{MIN\_BD} = 2 \bullet CTR_{BD} \bullet K_{BD} \bullet I_{RATED}$$

High-Impedance Differential



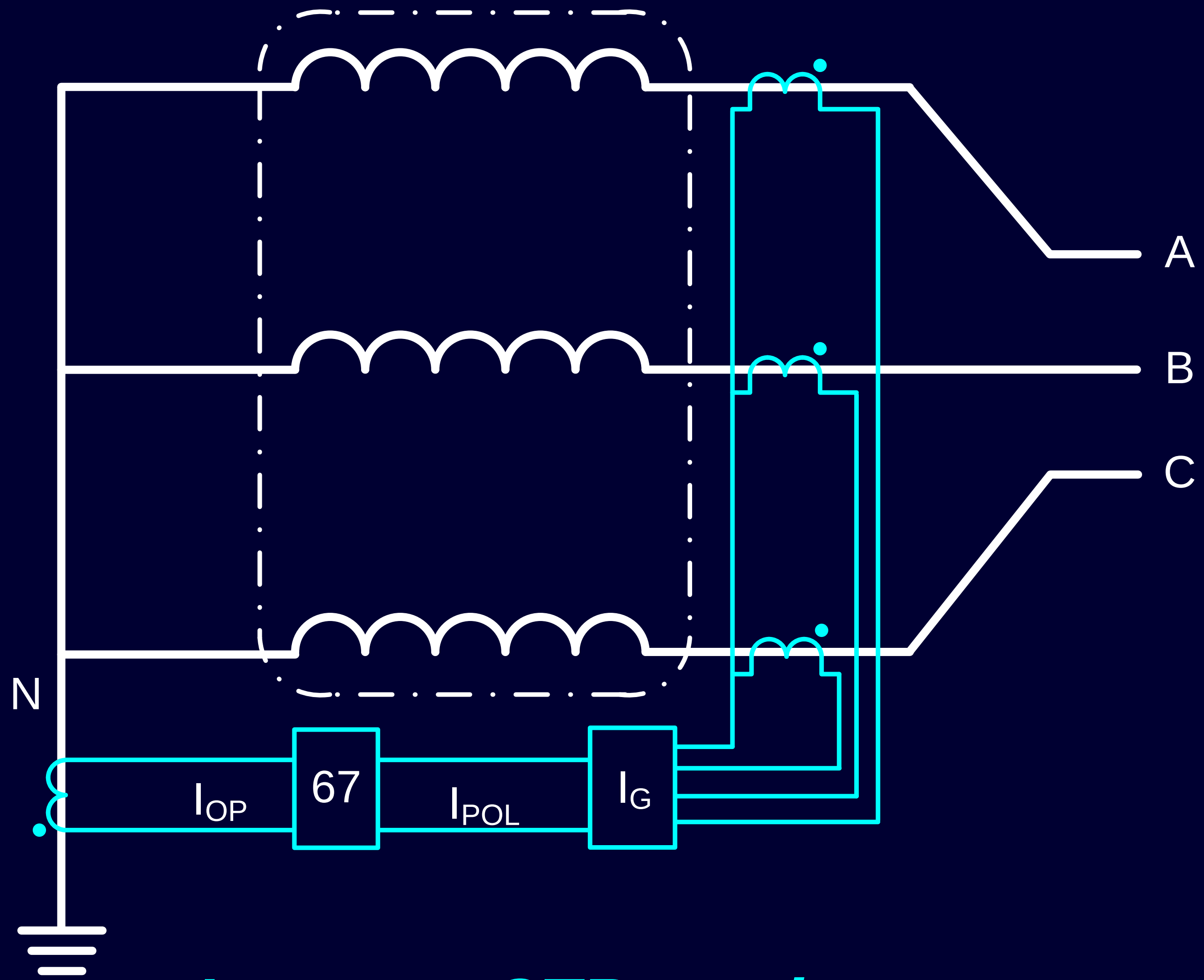
$$I_{MIN\_HZ} = CTR_{HZ} \bullet I\_PU_{HZ}$$

Negative- and Zero-Sequence Differential



$$I_{MIN\_QG} = CTR_{QG} \bullet I\_PU_{QG}$$

Restricted Earth Fault



$$I_{MIN\_REF} = CTR_{REF} \bullet I_{POL\_REF}$$

Comparison of Scheme Sensitivities

Assumed values

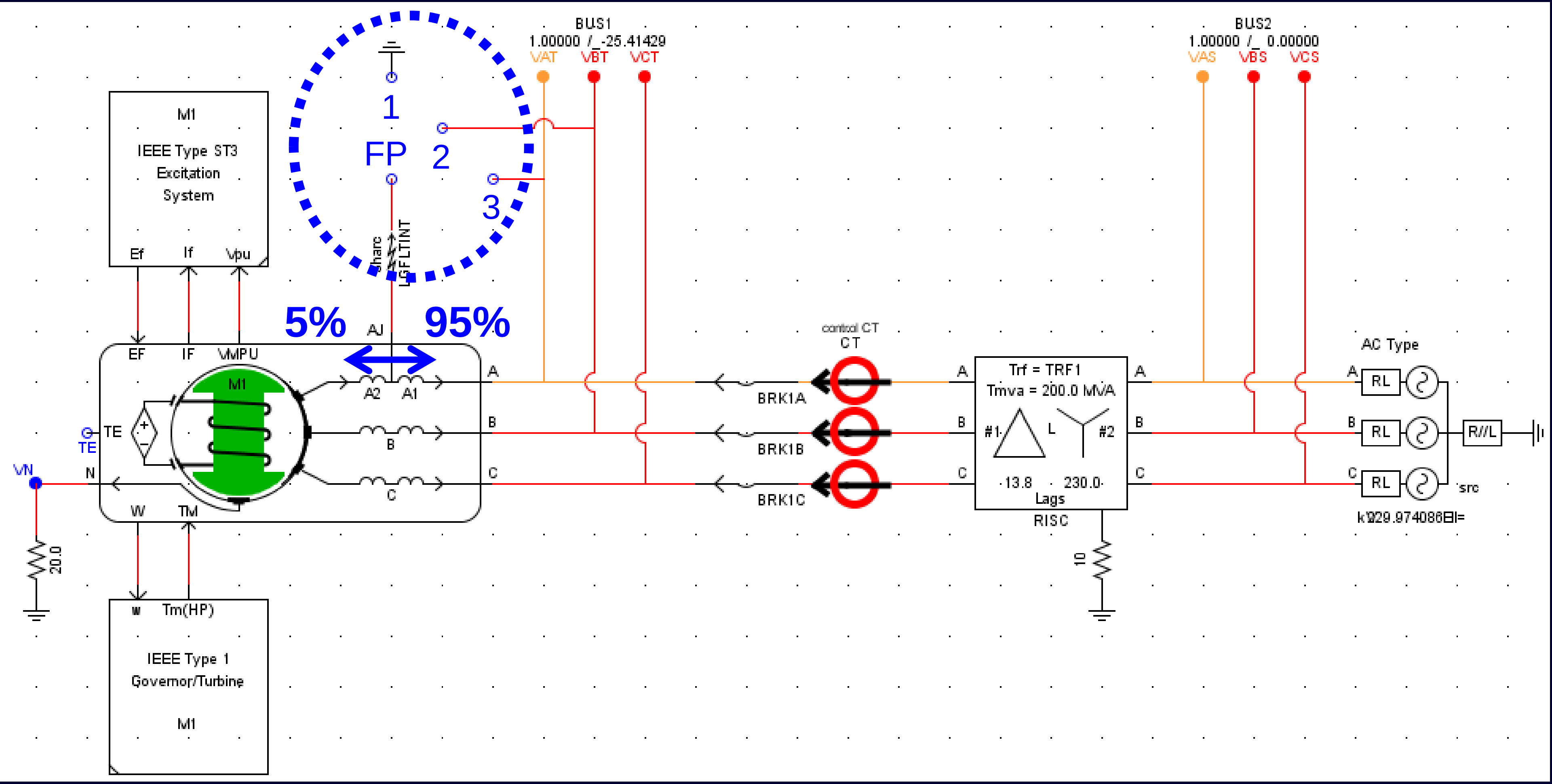
Scheme Variable	Value
CTR_{PH}	1200/5
CTR_{CB}	100/5
$Ipkp_{SB}$	0.25 A sec.
K_B	25%
$Ipkp_{HZ}$	0.1 A sec.
$Ipkp_Q$	0.25 A sec.
$Ipol_{REF}$	0.25 A sec.

Sensitivities in amperes primary

Scheme Type	Imin
Self-Balancing	5
Biased	600
High Impedance	24
Negative Sequence	60
Restricted Earth Fault	60

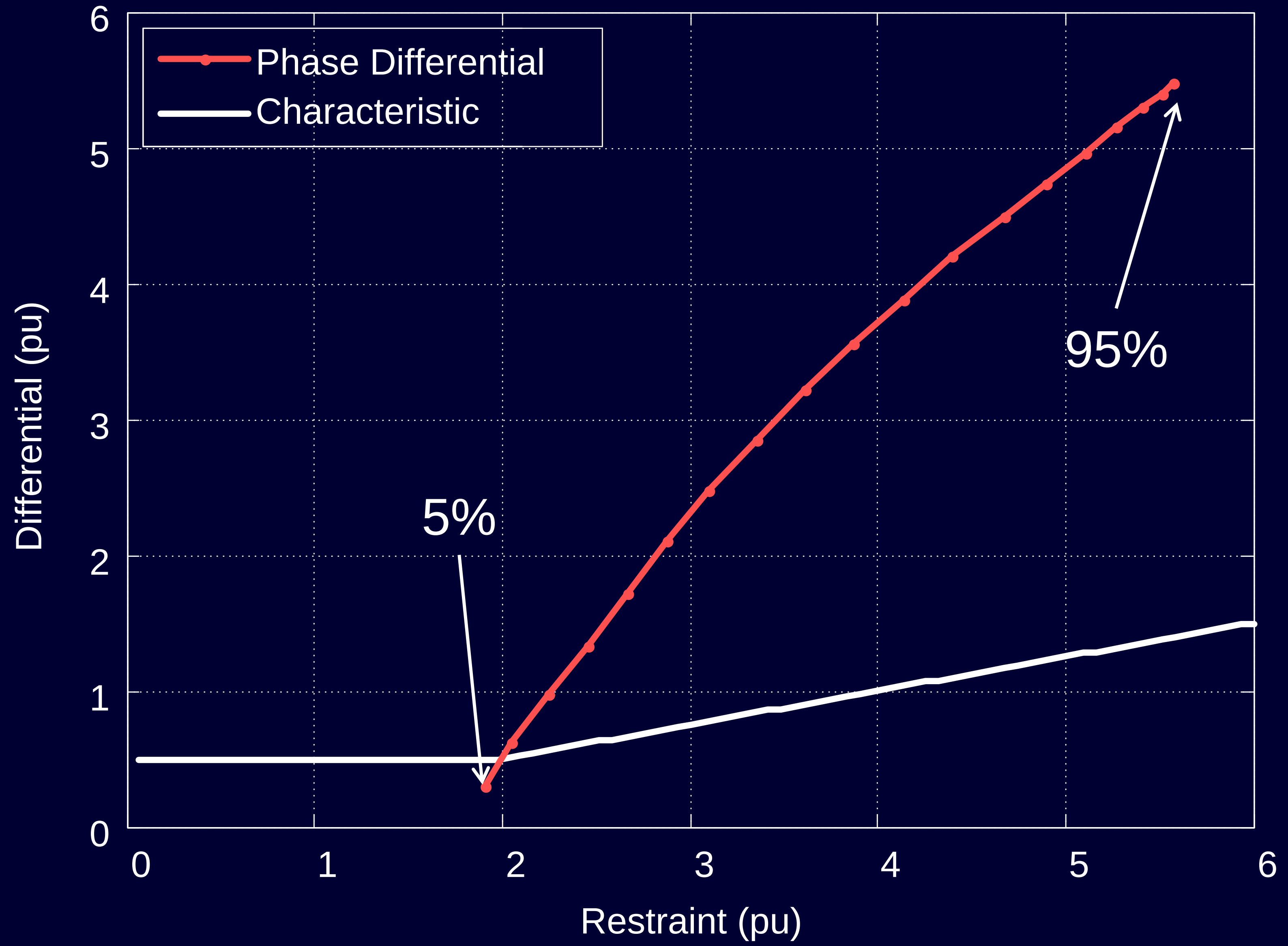
Detecting Stator Winding Faults

RTDS Model

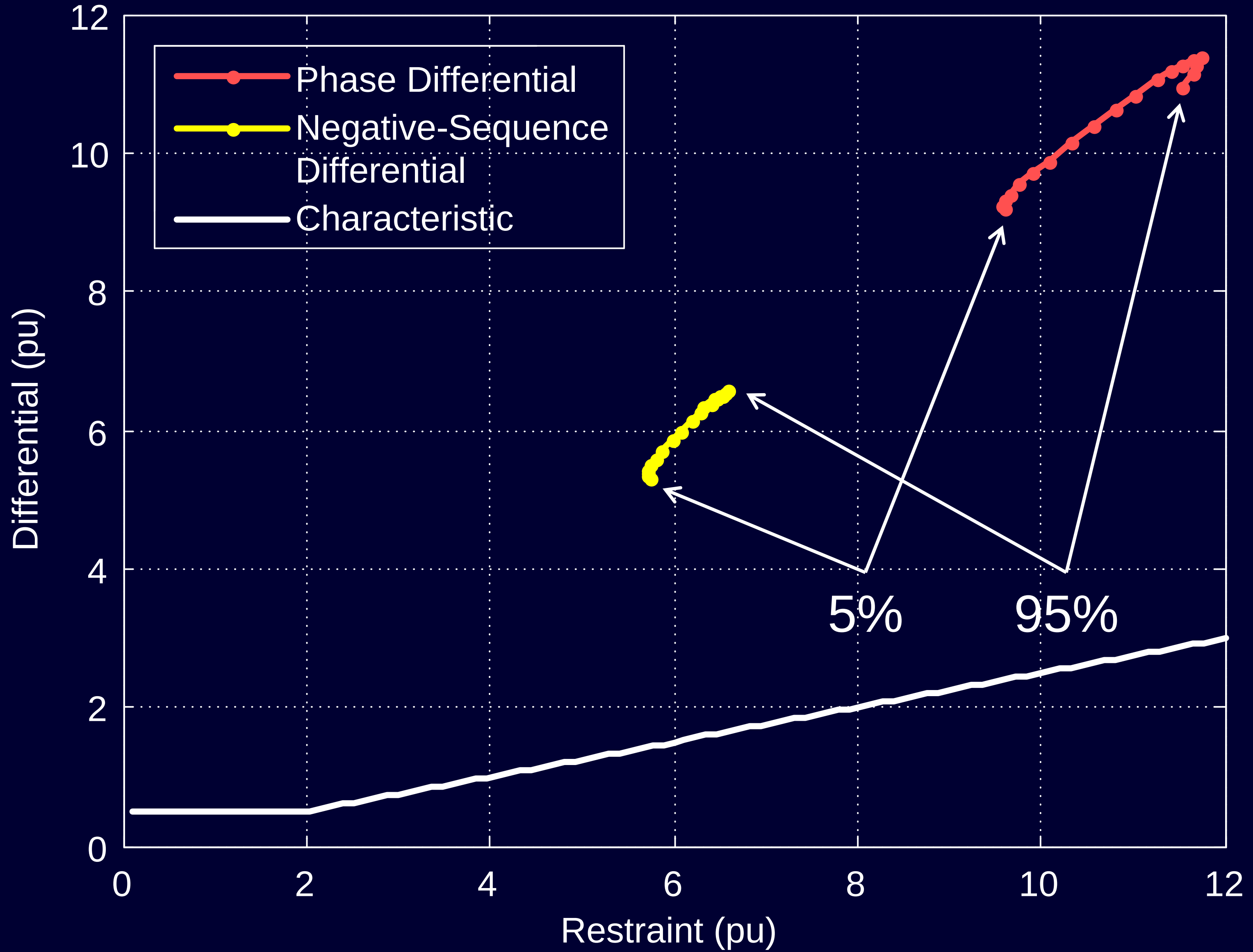


BUS1
1.00000 /_-25.41429
VAT VBT VCT
BUS2
1.00000 /_ 0.00000
VAS VBS VCS
M1
IEEE Type ST3
Excitation
System
Ef If Vpu
1
FP
2
3
5%
95%
AJ
EF IF VMPU
M1
A2 A1
B
C
TE
N
VN
20.0
W TM
w Tm(HP)
IEEE Type 1
Governor/Turbine
M1
A
B
C
CT
BRK1A
BRK1B
BRK1C
Trf = TRF1
Tmva = 200.0 MVA
#1
L
#2
13.8
230.0
Lags
RISC
10
AC Type
RL
R//L
src

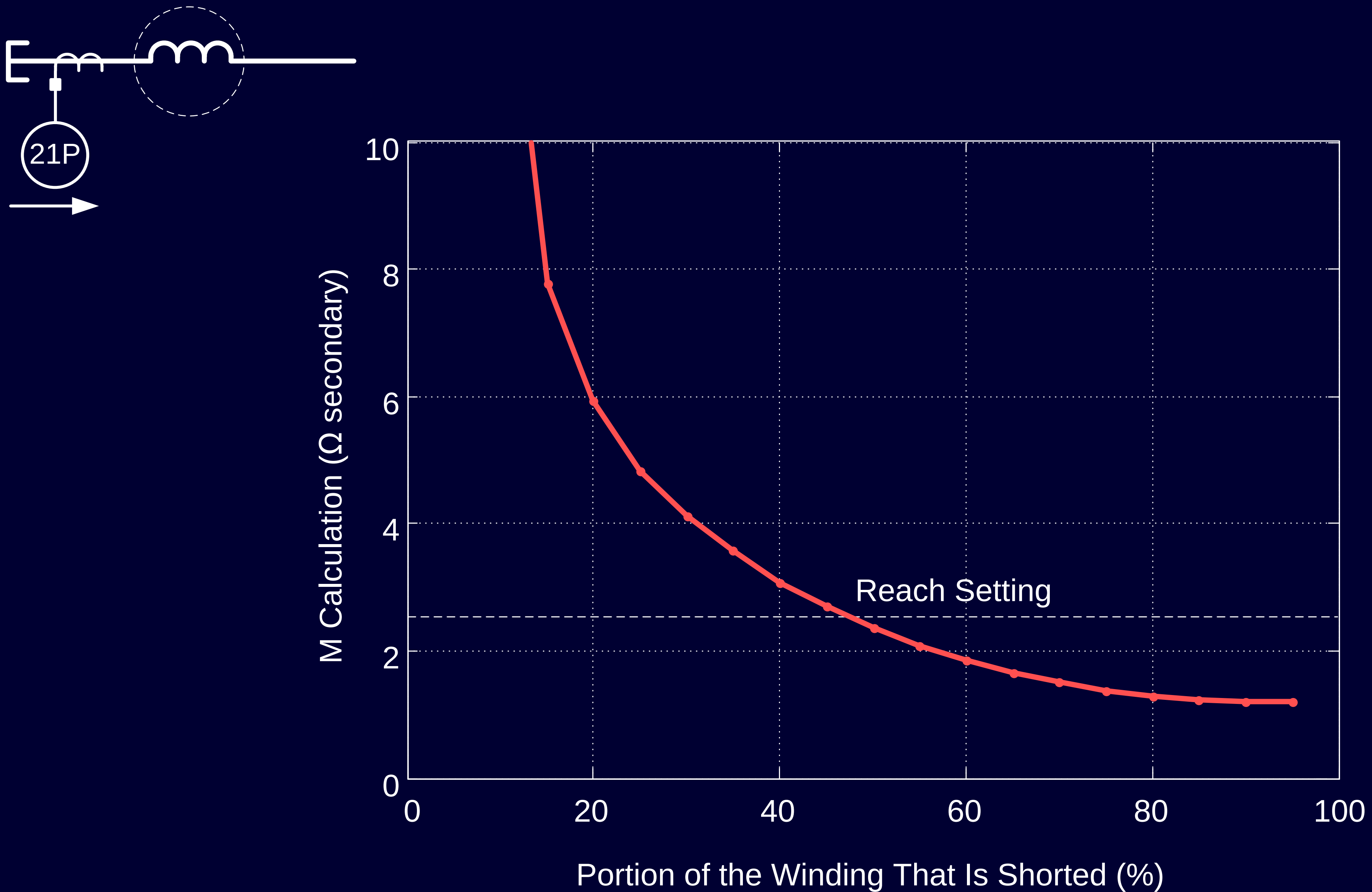
Phase-to-Ground Faults



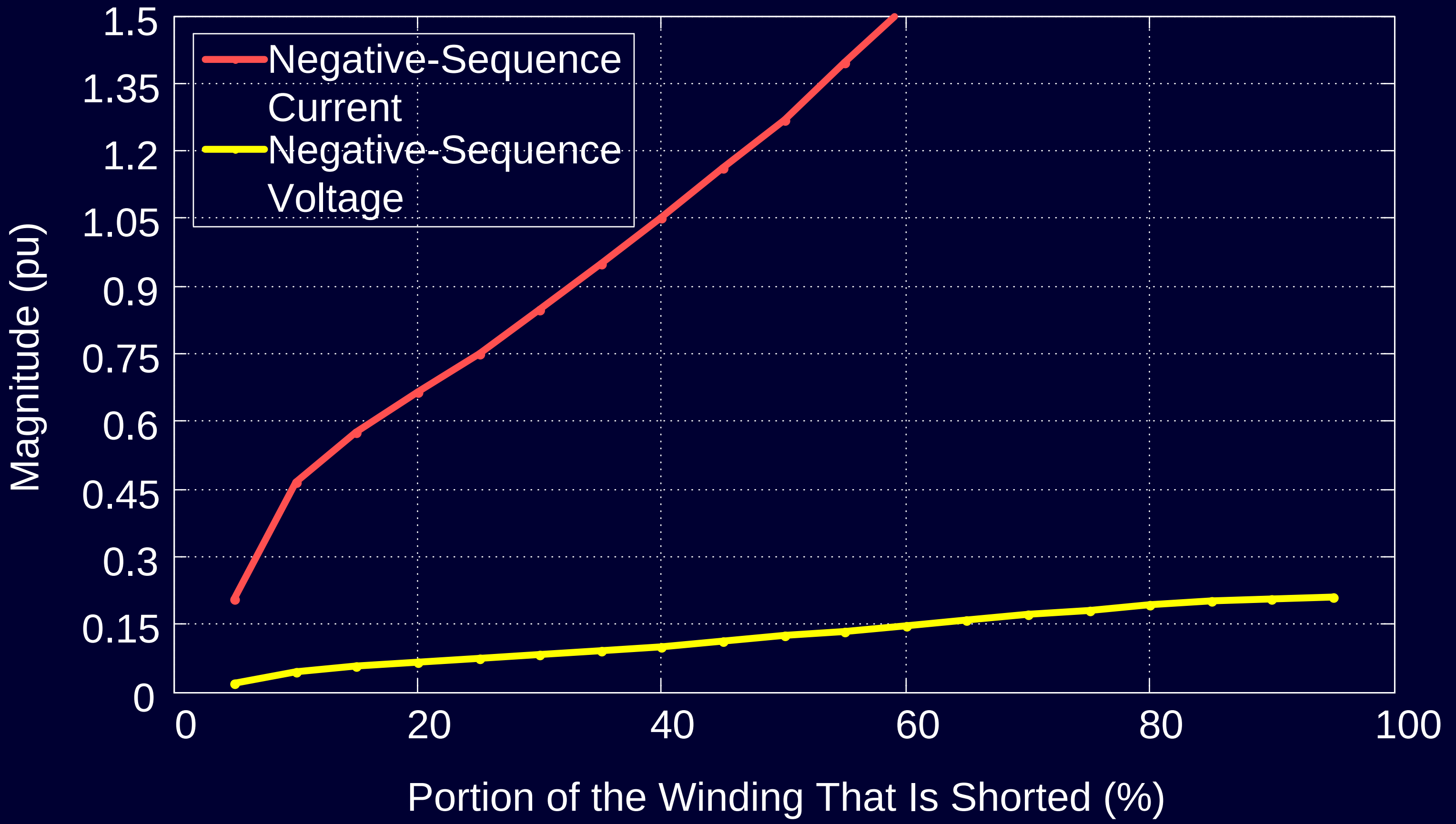
Phase-to-Phase Faults



Turn-to-Turn Faults



Turn-to-Turn Faults



CT Selection for Differential Protection

- CT ratio
  - Sensitivity vs security
  - Full load current ≈ nominal CT current
- CT voltage rating
  - Ideal $V_{KNEE} > (1 + X/R)$
  - Minimize burden impedance (Z_{MIN})
  - Select highest possible V_{KNEE}

Differential Protection Application Recommendations

- Use identical CTs for machine neutral and terminal
- Set minimum pickup current below minimum fault current
- Slope setting determined by maximum CT error for a through fault

$$\text{Worst case: } IOP_{ERR} = (1 + \varepsilon)I_{NEU} - (1 - \varepsilon)I_{TERM}$$

$$= 2\varepsilon$$

Recommendations if CT Saturation Occurs for Through Faults

- Increase slope setting to greater value
  (sacrifices sensitivity)
- Employ relay with ac and dc external fault detection logic
  (maintains sensitivity and adds security)

Conclusions

- Discussed factors that influence design of stator windings in synchronous generators
- Presented and compared various differential protection methods
- Simulated internal faults using an RTDS model
  - Phase, negative-, and zero-sequence differential elements can detect phase-to-phase faults
  - Differential elements are also effective for detecting ground faults

Conclusions

- RTDS simulation indicated that differential elements are not effective in detecting turn-to-turn faults
- RTDS model limitations
  - Cannot simulate faults close to neutral
  - Can only simulate single-winding turn faults

Questions?