Protection Basics

TECHNOLOGY EXCHANGE
Learn. Connect. Solve.

Protection Review

- Fault types
- Electrical equipment damage
- Time versus current plot
- Protection requirements
- Protection system elements

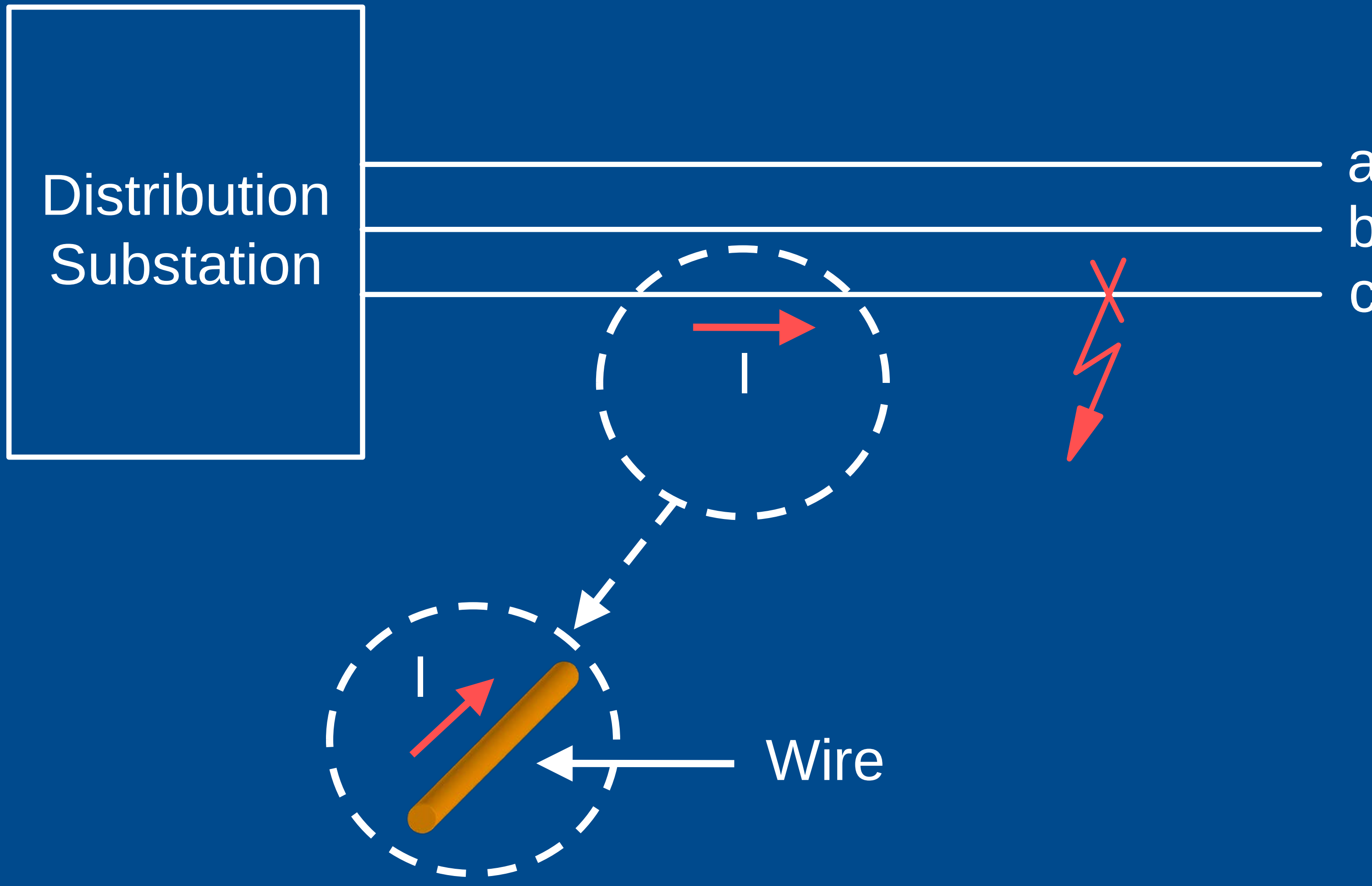
Power System Faults

- Short circuits
- Contacts with ground
    - Isolated neutral systems
    - High-impedance grounded systems
- Open phases

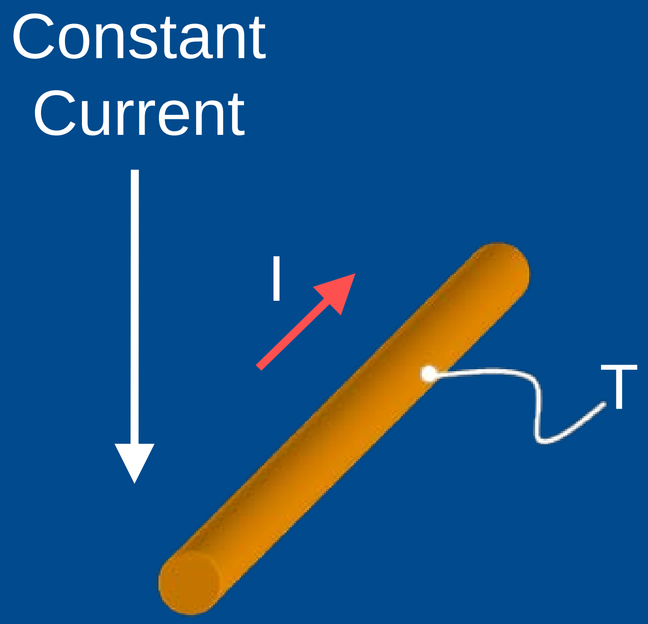
Typical Short-Circuit-Type Distribution

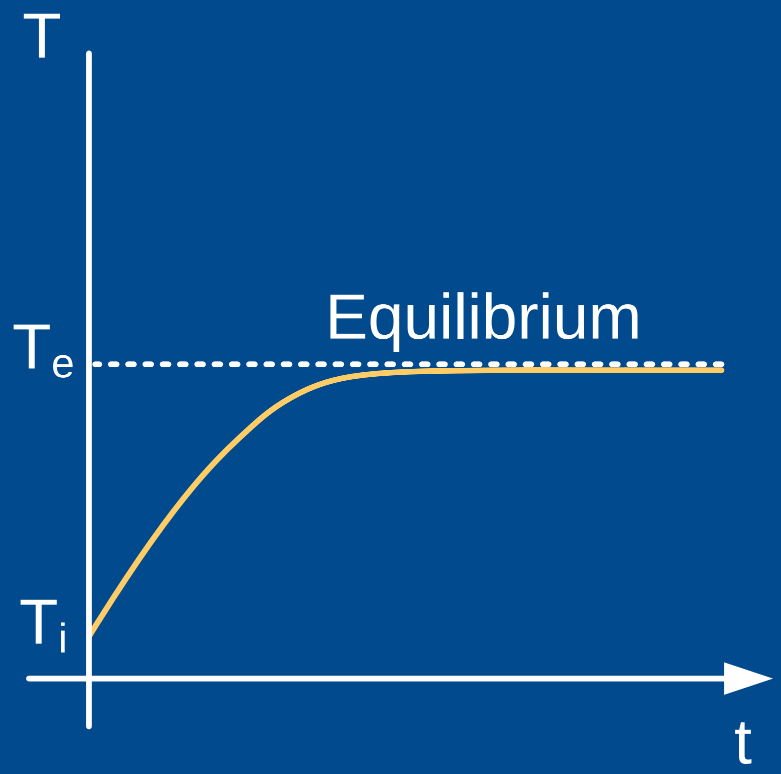
Single-phase-to-ground	70 – 80%
Phase-to-phase-to-ground	10 – 17%
Phase-to-phase	8 – 10%
Three-phase	2 – 3%

Faults in Electrical Systems Produce Current Increments



Temperature Rise From Current

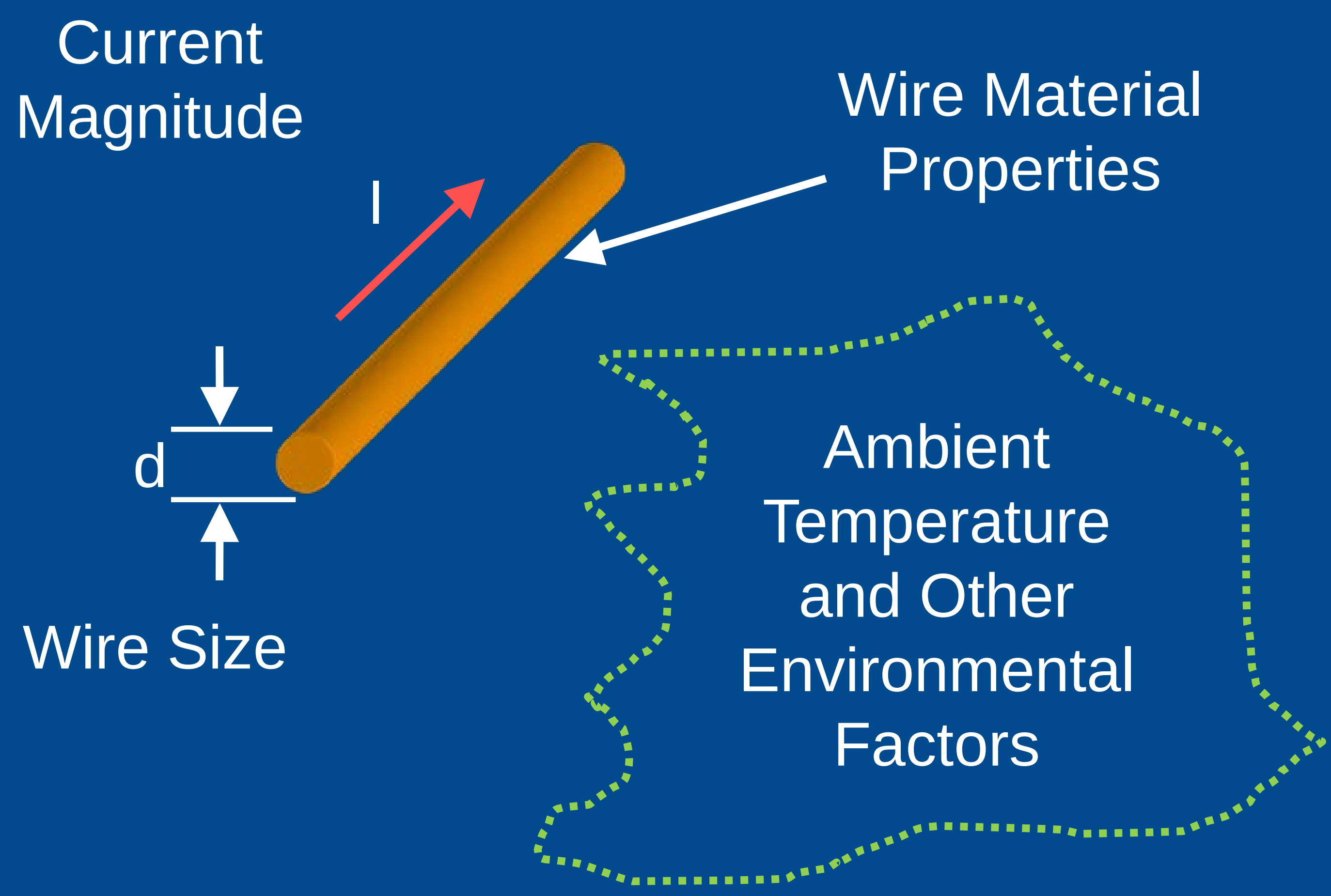




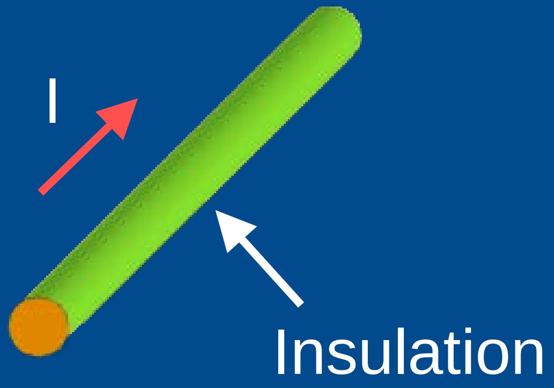
$$\frac{dW}{dt} = I^2R$$

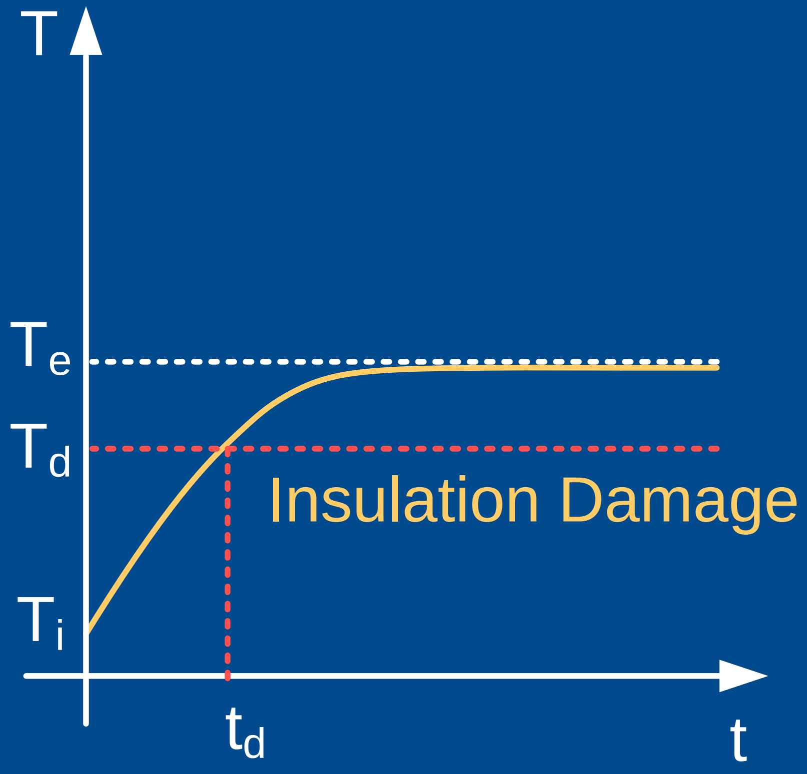
$$T(t) = (T_i - T_e)e^{-t/\tau} + T_e$$

Factors Influence Wire Heating

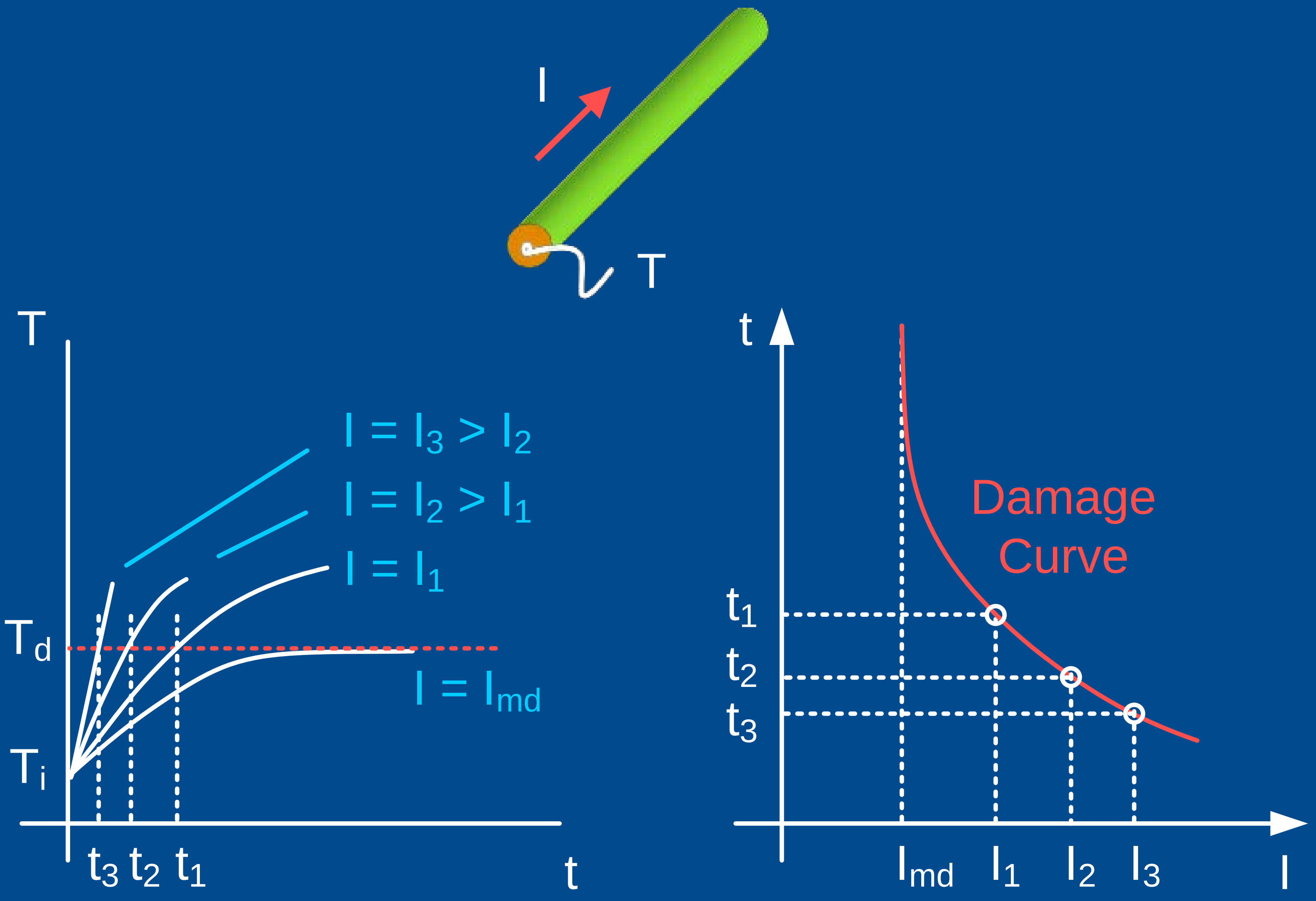


Insulated Conductor (Cable) Thermal Damage

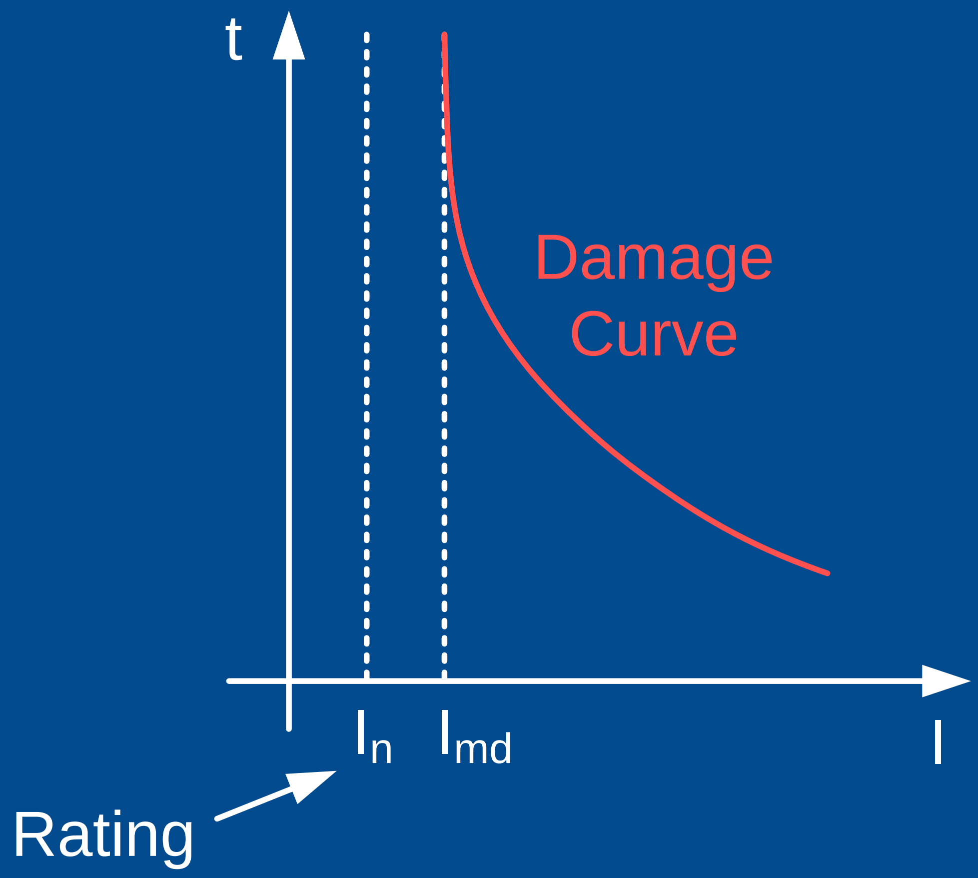




Insulated Conductor Thermal Damage

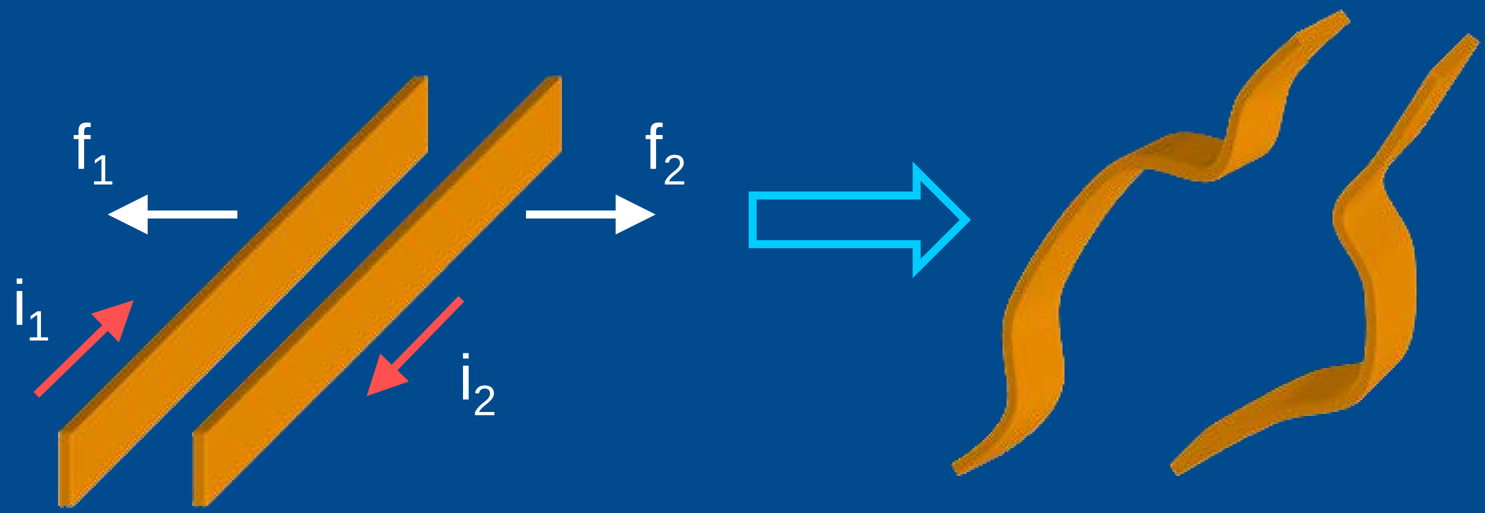


Electrical Equipment Component Thermal Damage Curve



Mechanical Damage

Mechanical forces (f_1 and f_2) produced by short-circuit currents cause instantaneous damage to busbars, insulators, supports, transformers, and machines



$$f_1\,(t) = k\, i_1\,(t)\, i_2\,(t)$$

Real-World Mechanical Damage

Power System Protection Requirements

- Reliability
  - Dependability
  - Security
- Selectivity

Power System Protection Requirements

- Speed
  - System stability
  - Equipment damage
  - Power quality
- Sensitivity
  - High-impedance faults
  - Dispersed generation

Protection Functions

- Fault detection
- Faulted element disconnection
- Fault indication

Protective Devices

- Fuses
- Automatic reclosers
- Sectionalizers
- Circuit breakers
- Protective relays

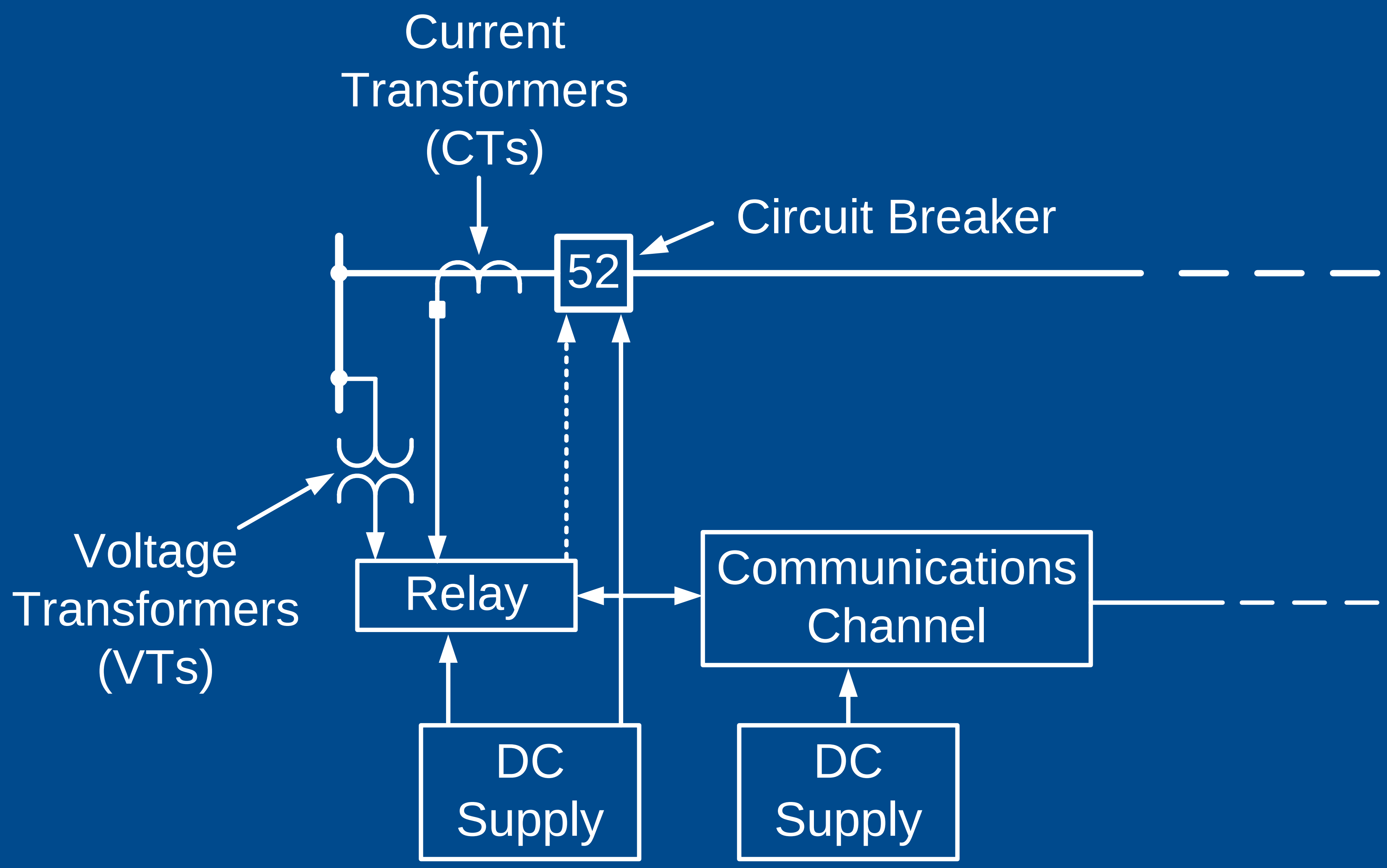
Relay Classification

- Protective
- Regulating
- Reclosing and synchronism check
- Monitoring
- Auxiliary

IEEE C37.2 Device Numbers

51	Time-overcurrent relay
50	Instantaneous-overcurrent relay
67	Directional-overcurrent relay
21	Distance relay
87	Differential relay
52	Circuit breaker

Protective Relaying System



Protection System Elements

- Protective relays
- Circuit breakers
- CTs and VTs (instrument transformers)
- Communications channels
- DC supply system
- Control cables

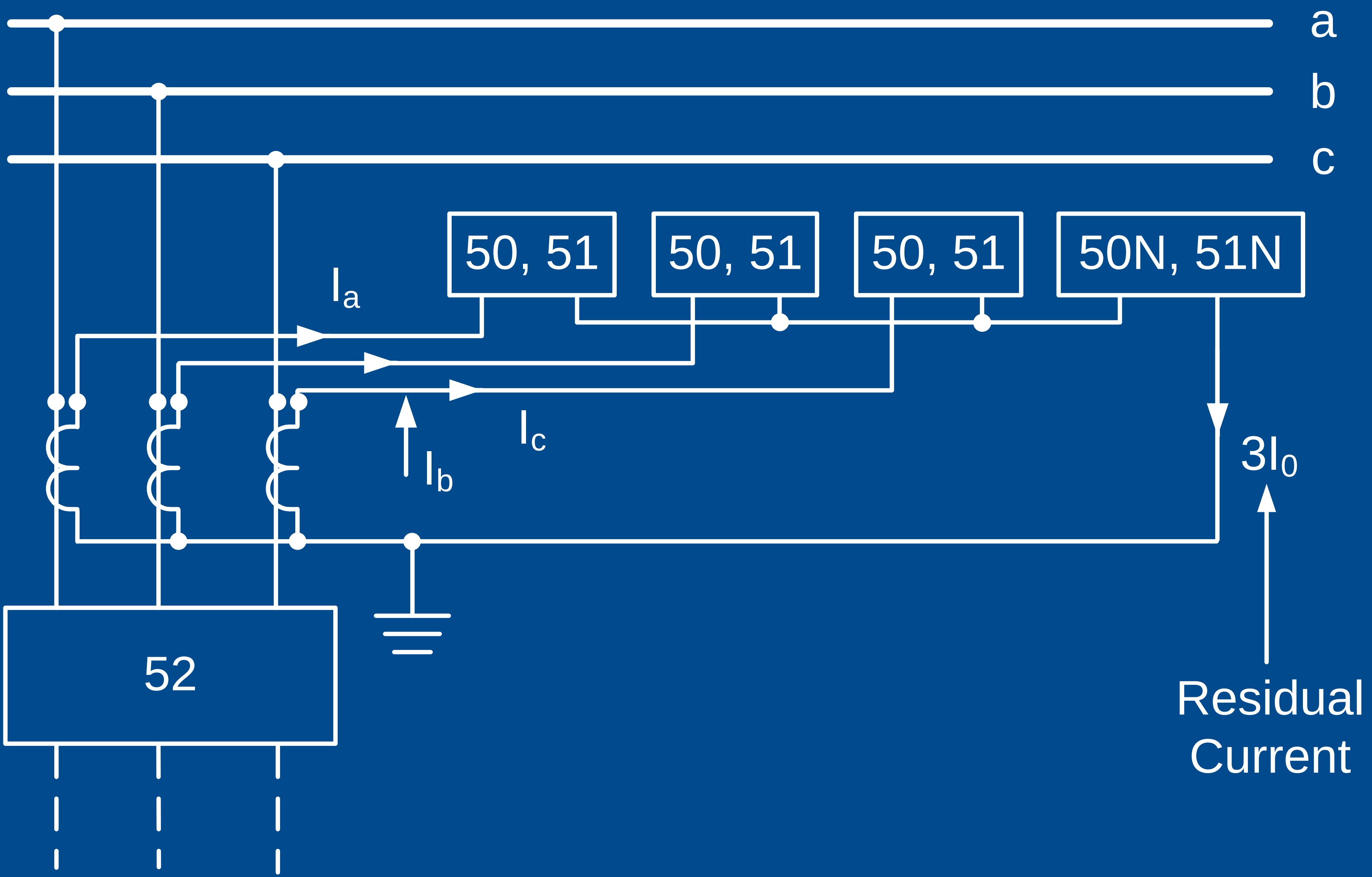
Protection System Elements

- Protective relays
  - Monitor
  - Detect
  - Report
  - Trigger
- Circuit breakers
  - Interrupt
  - Isolate from abnormal condition

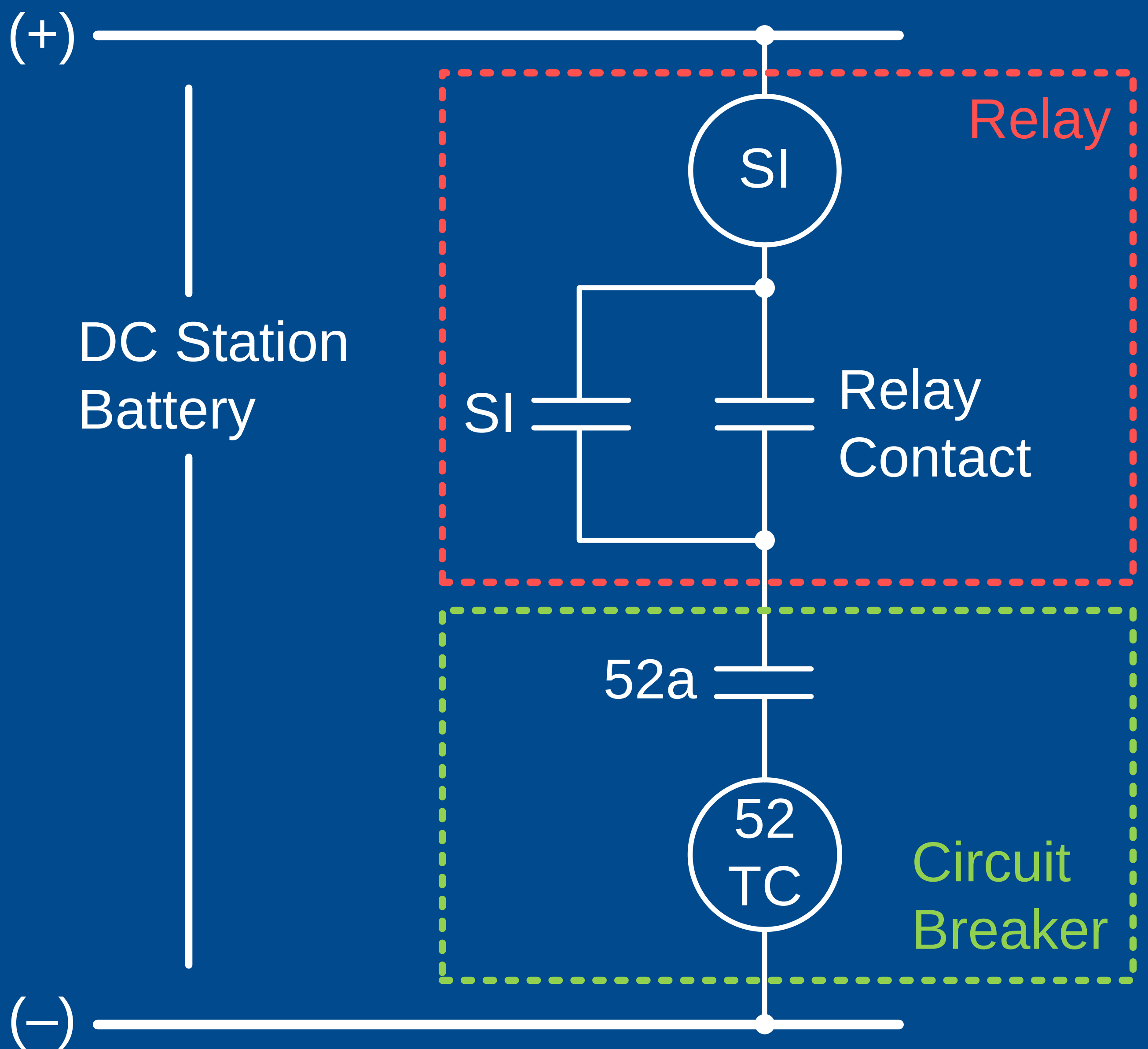
Instrument Transformers

- CTs
  - Current scaling
  - Isolation
- VTs
  - Voltage scaling
  - Isolation

Overcurrent Relay Connections



DC Tripping Circuit



Overcurrent Relay Setting

- 51 elements
  - Pickup setting
  - Time-dial setting
- 50 elements
  - Pickup setting
  - Time delay

Review

- What is the function of power system protection?
- Name two protective devices
- For what purpose is IEEE device 52 is used?
- Why are seal-in and 52a contacts used in the dc control scheme?
- In a typical feeder OC protection scheme, what does the residual relay measure?

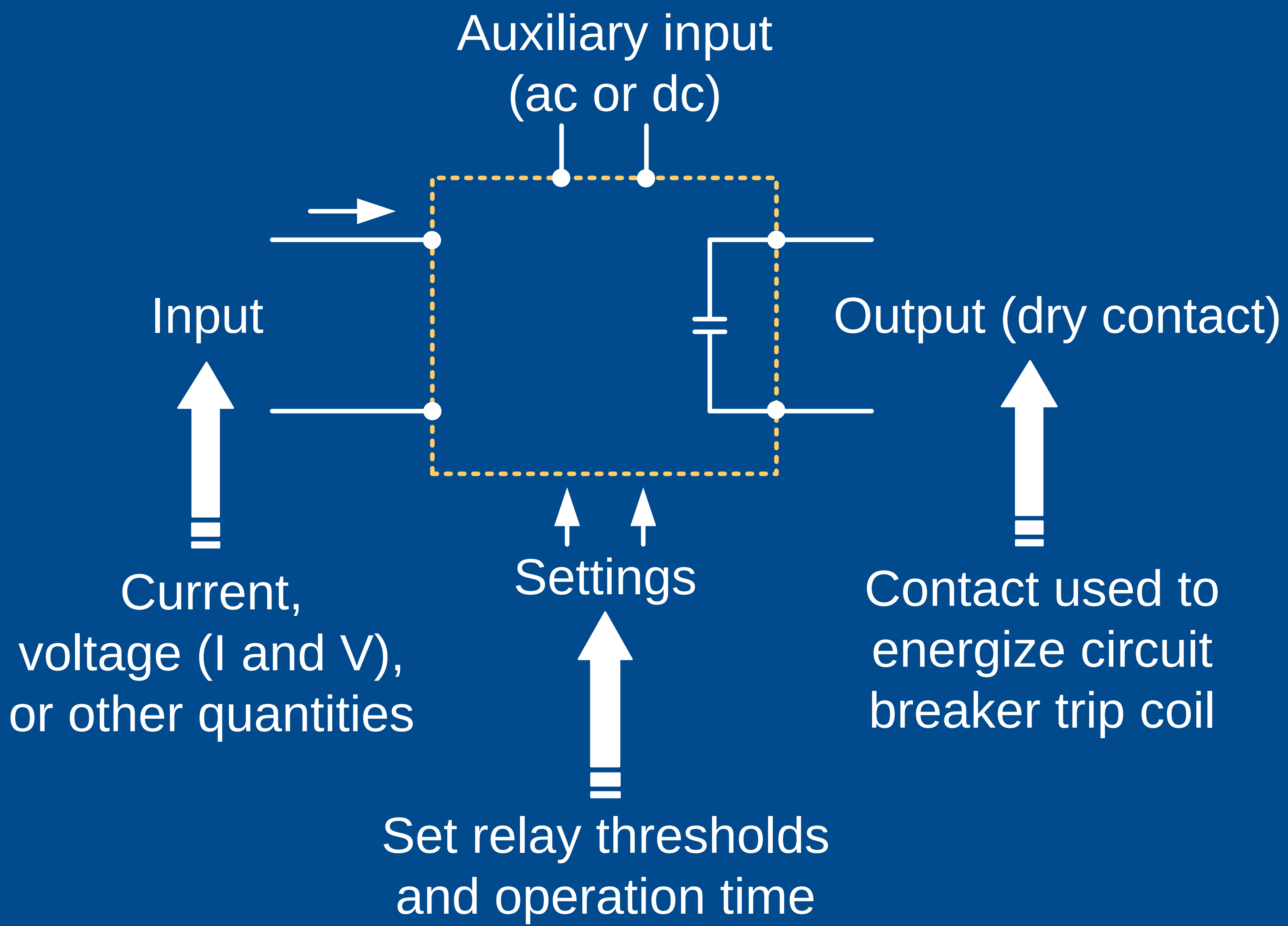
Questions?

Digital Relay Basics

SEL-751A Feeder Protection Relay

TECHNOLOGY EXCHANGE
Learn. Connect. Solve.

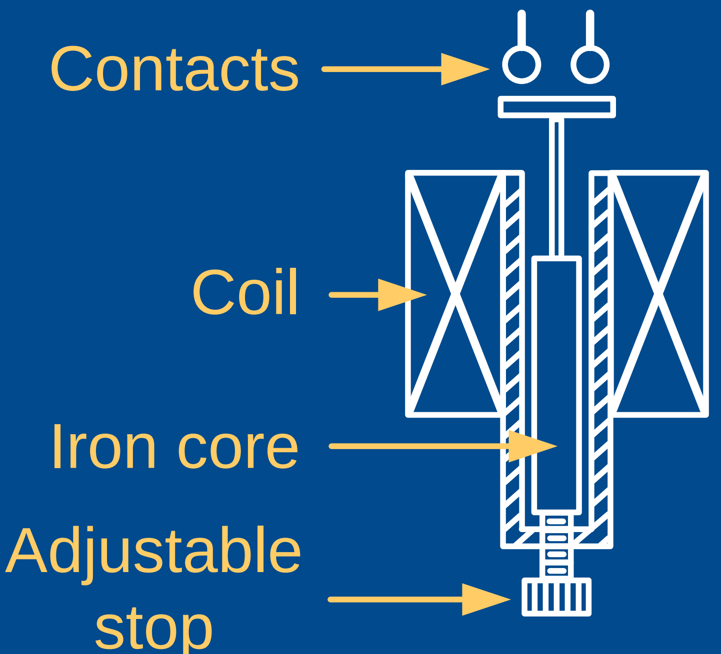
Simple Protective Relay

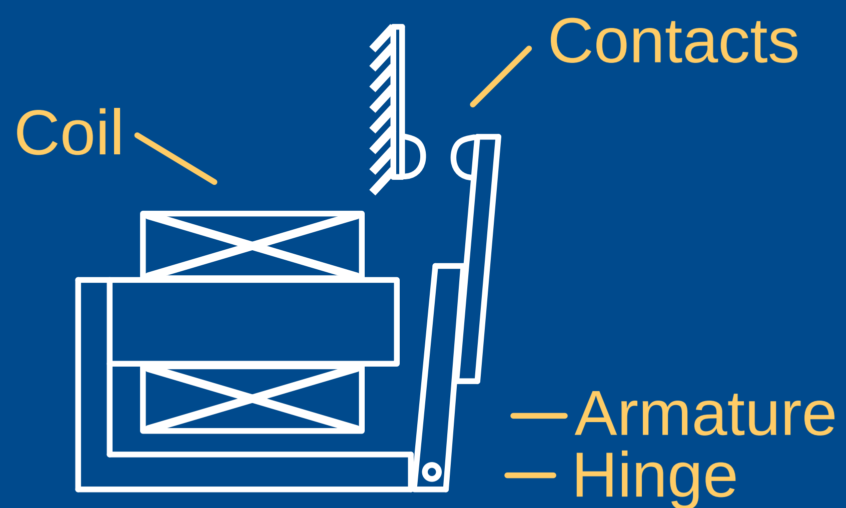


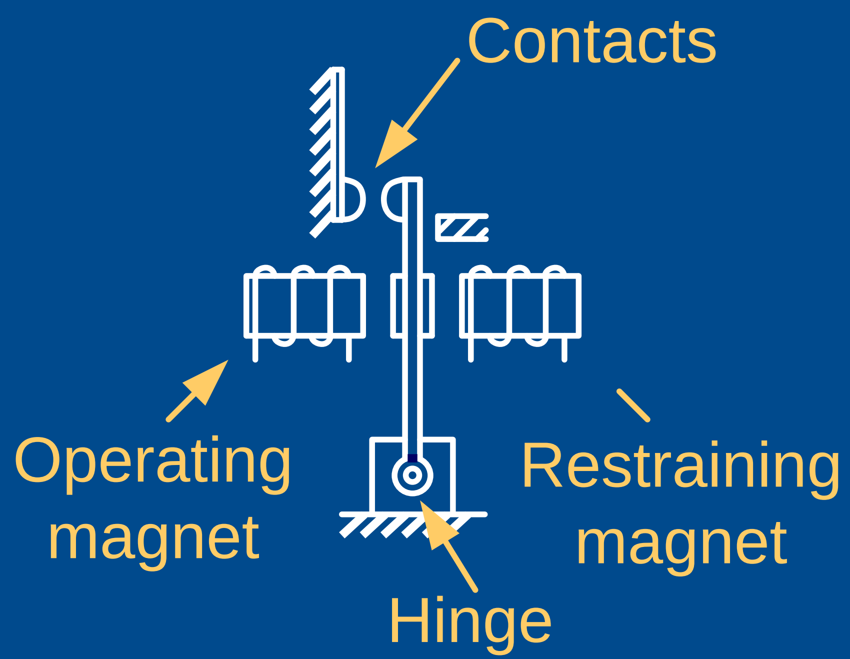
Electromechanical Instantaneous Overcurrent Elements

Magnetic Attraction Unit

Instantaneous Element







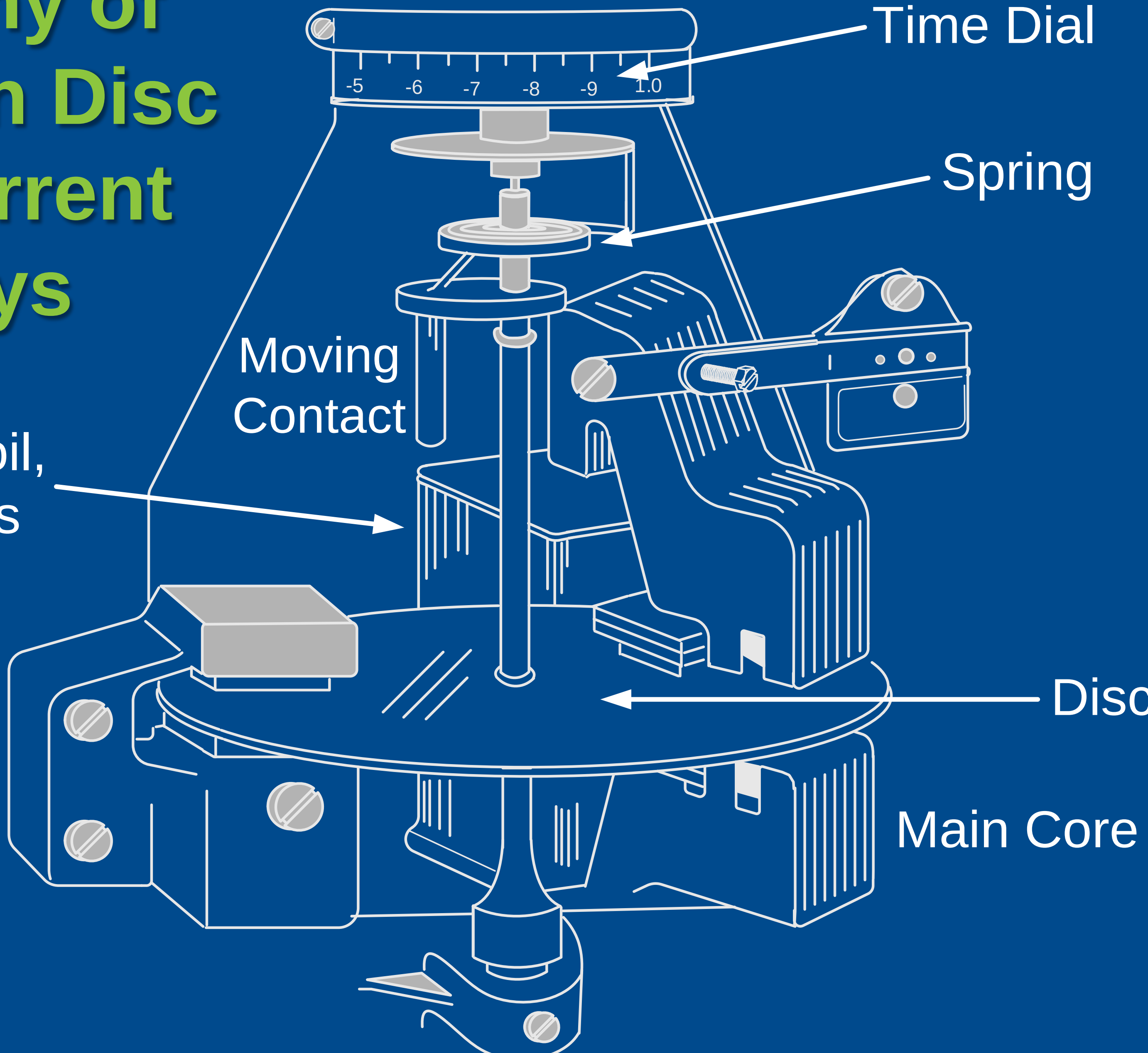
Force of contact: $F = k \bullet I^2$

Pickup Current Setting

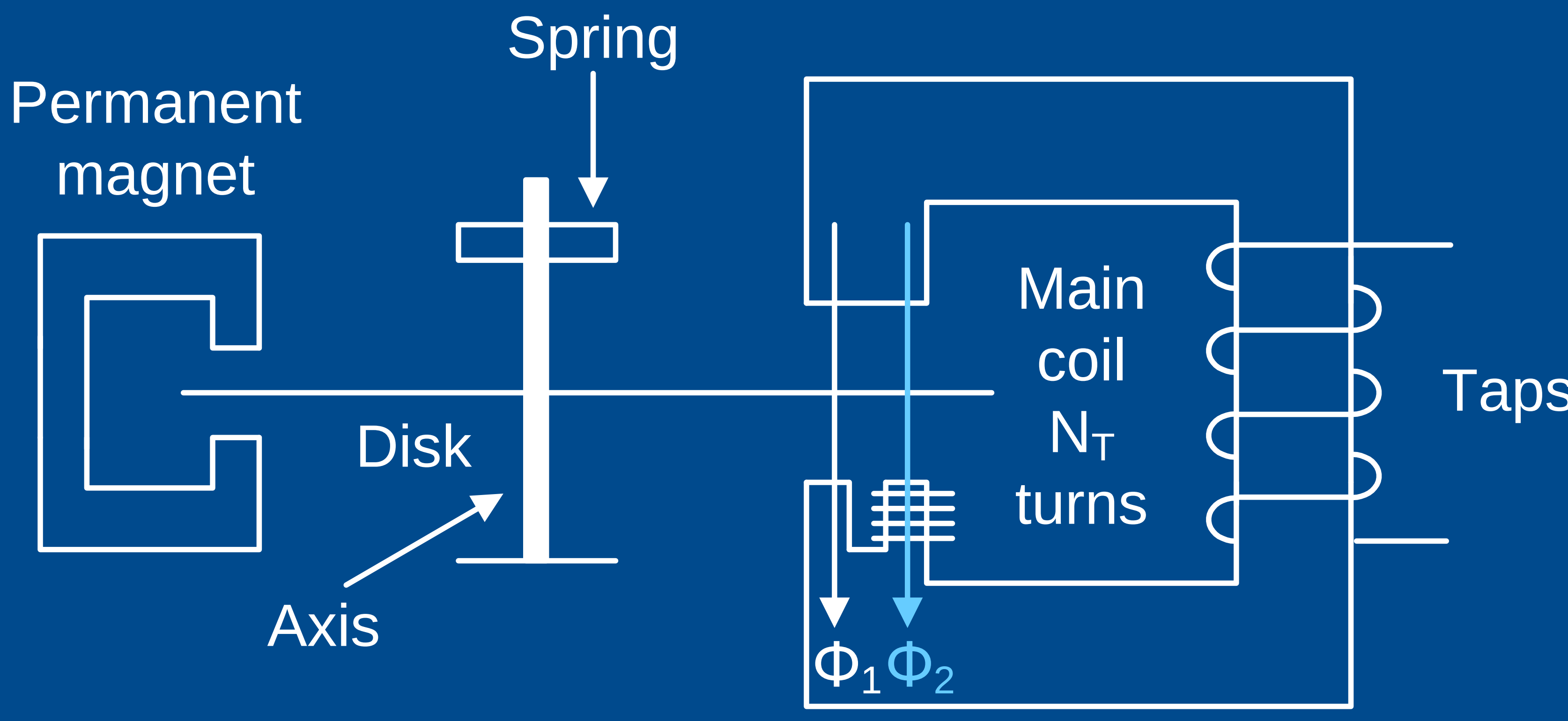
- Tap in relay current coil
- Adjust air gap
- Adjust spring

Electromechanical Inverse-Time Overcurrent Elements

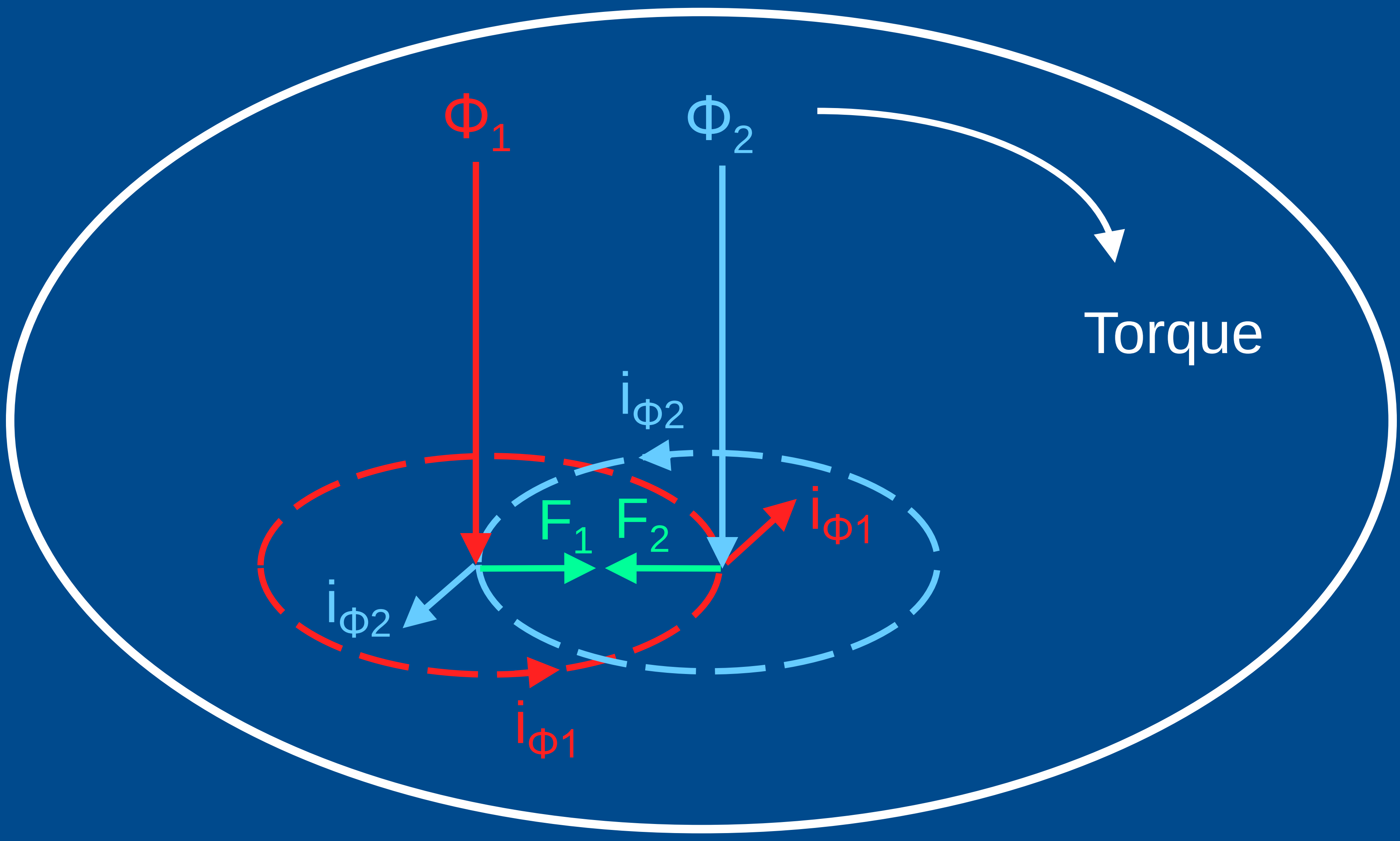
Anatomy of Induction Disc Overcurrent Relays



Simplified View
Shaded Pole Element



Electromagnetic Induction Principle

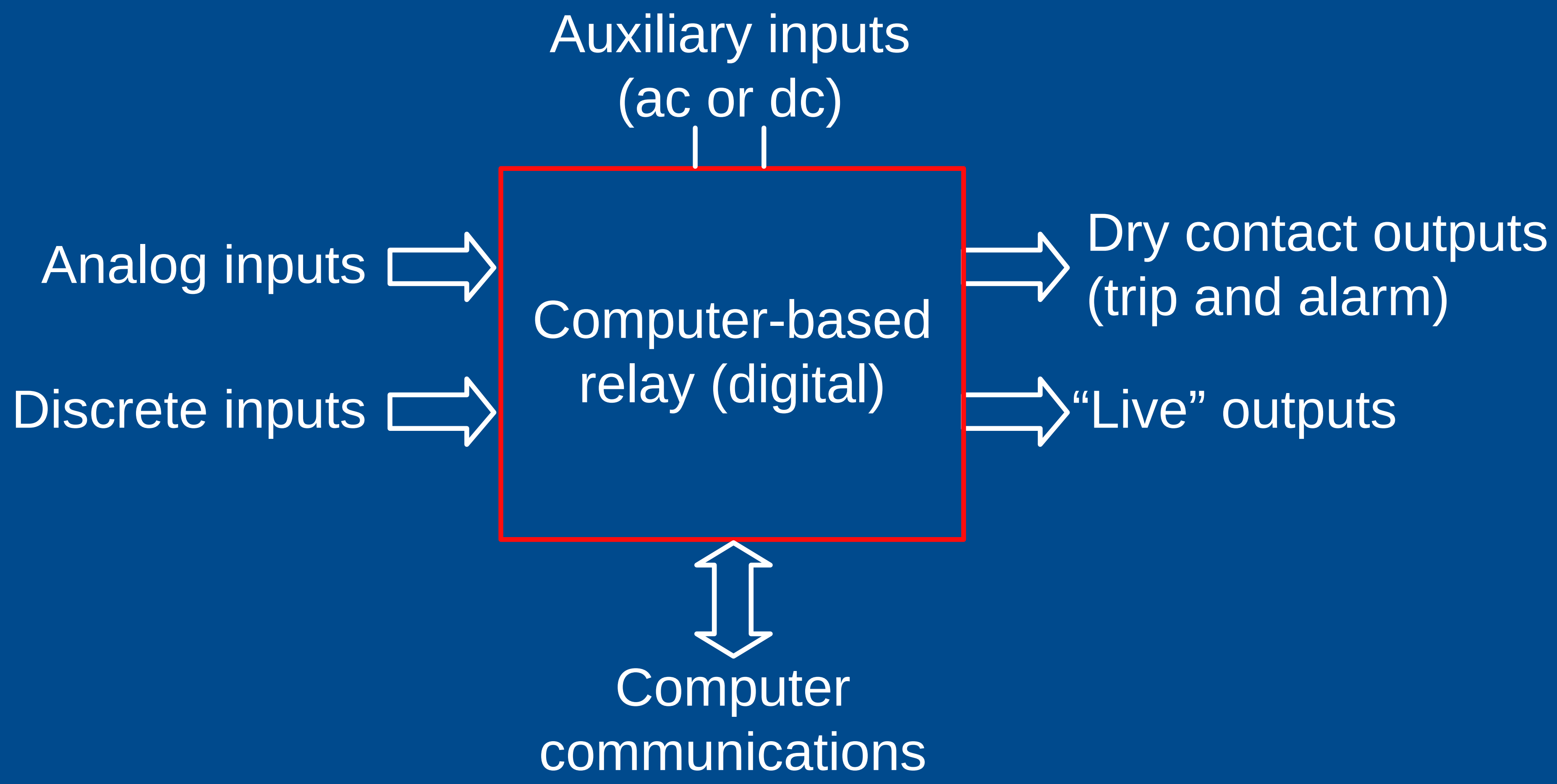


Summary of Induction 51 Element Setting

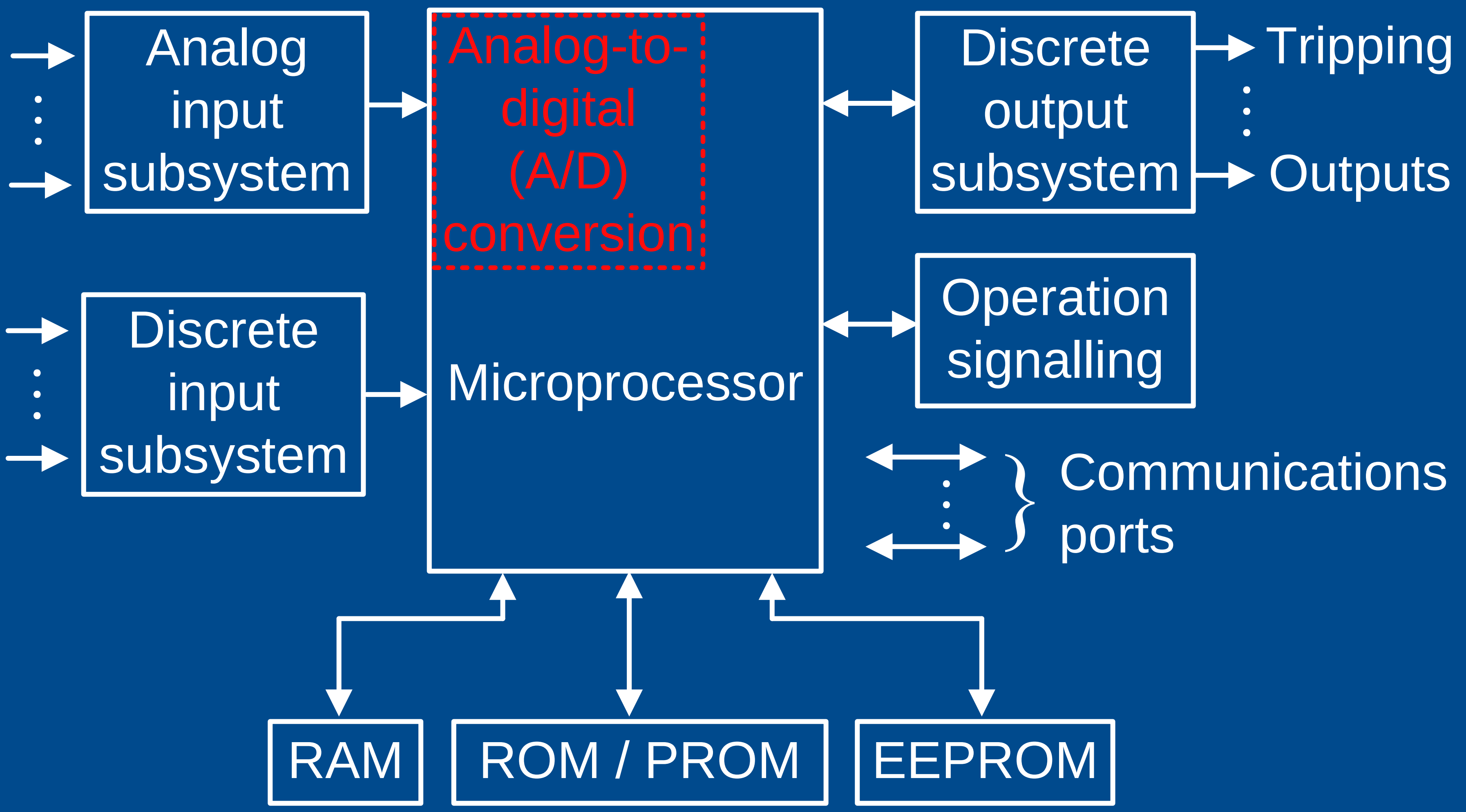
- Pickup current setting – taps in relay current coil
- Time-current curve setting – controls initial disc position (time dial setting)

Microprocessor-Based Protection

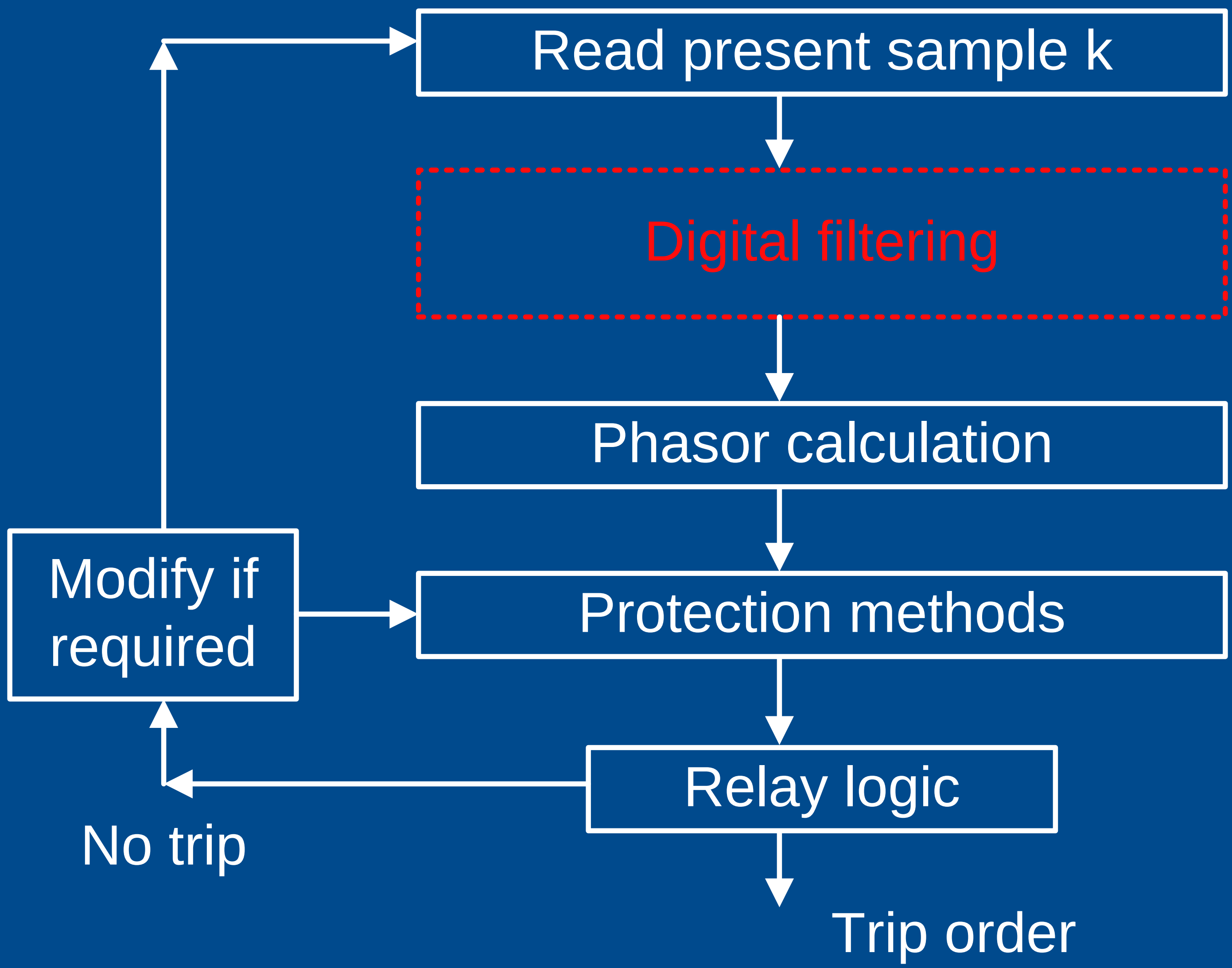
Digital Relay I/O Scheme



Digital Relay Architecture

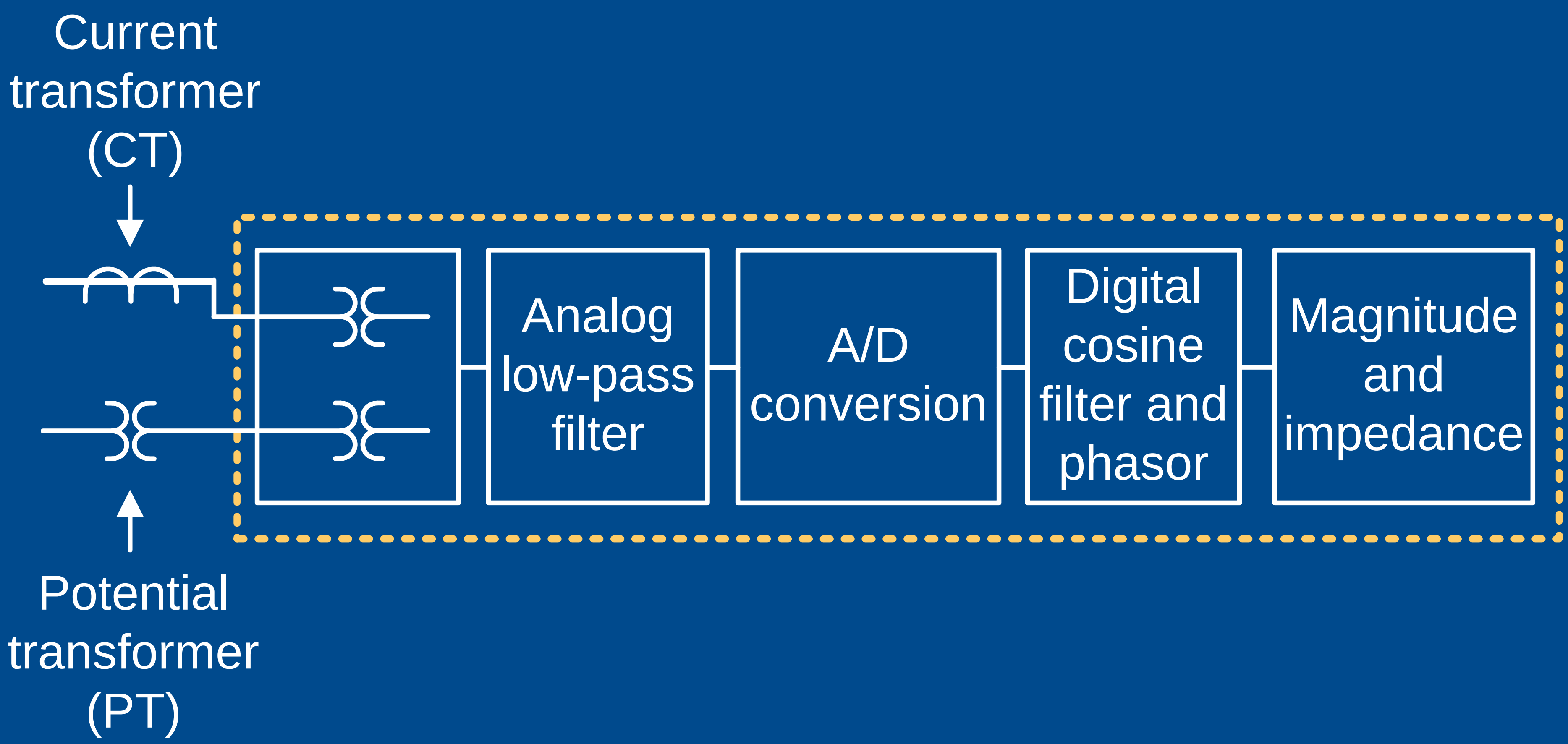


Digital Relay Algorithm

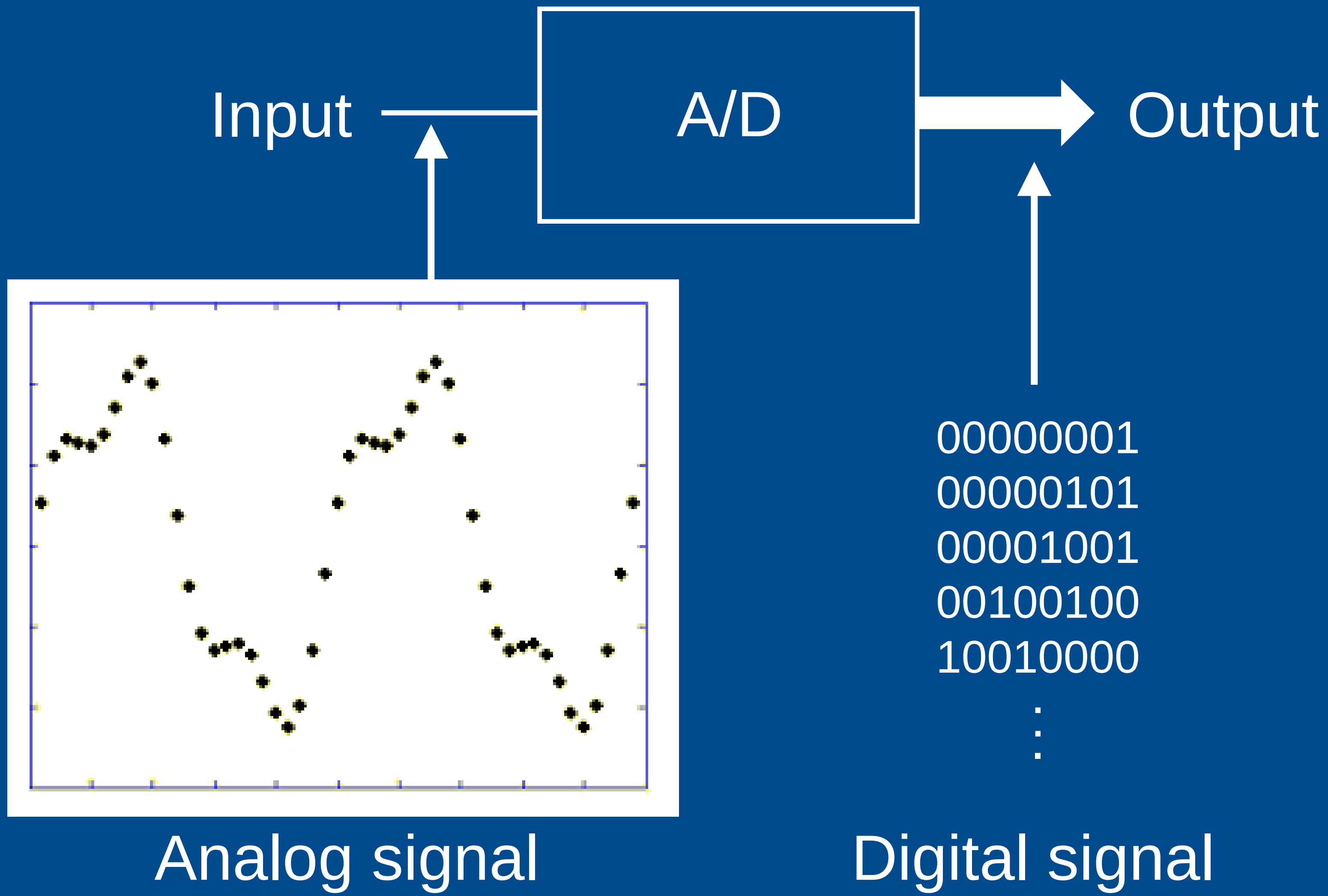


Relay Operation
Analog Inputs

Signal Path for Microprocessor-Based Relays

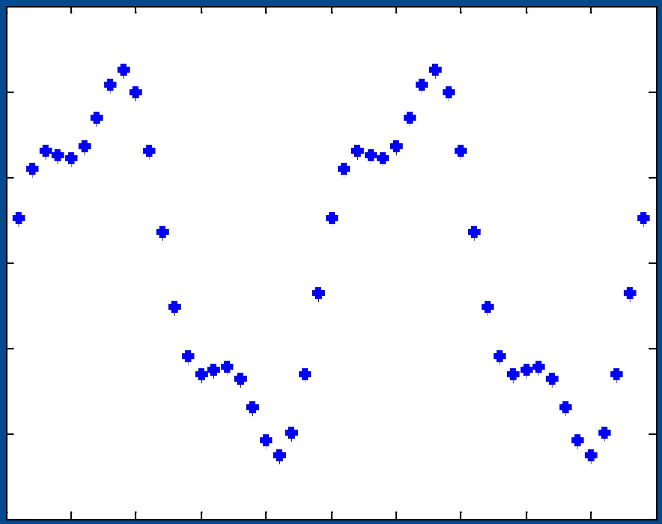


A/D Conversion



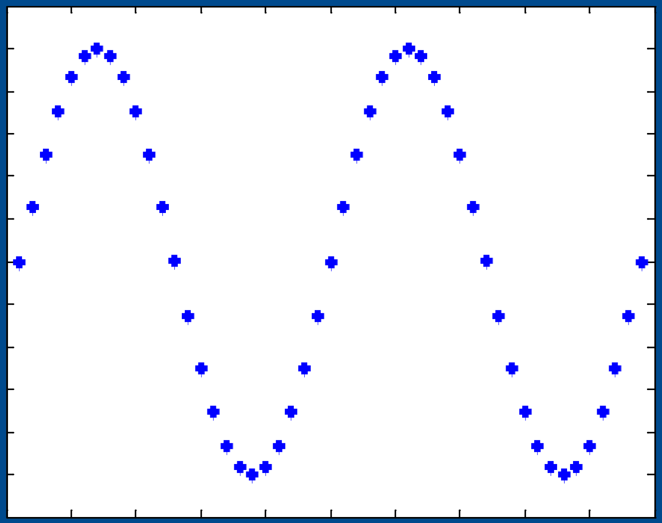
Digital Filtering

Nonfiltered signal (samples)

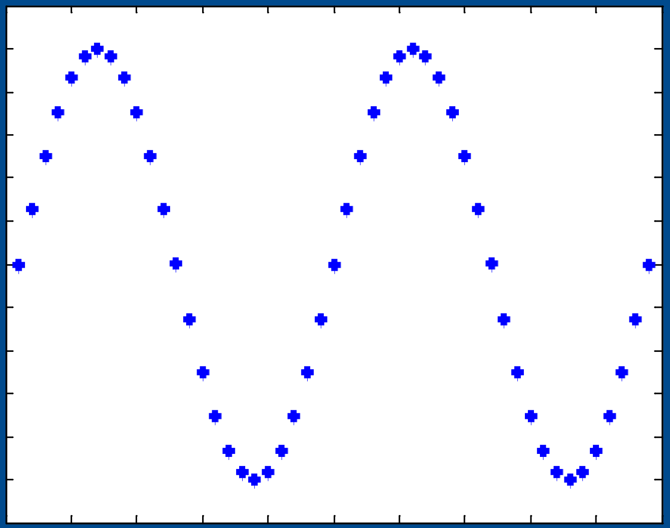


Digital filtering

Filtered signal (samples)



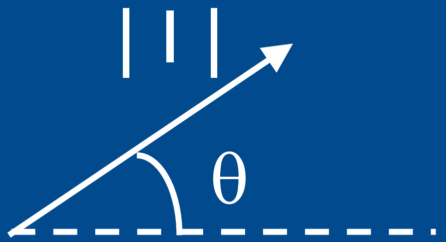
Phasor Calculation



Filtered signal
(samples)

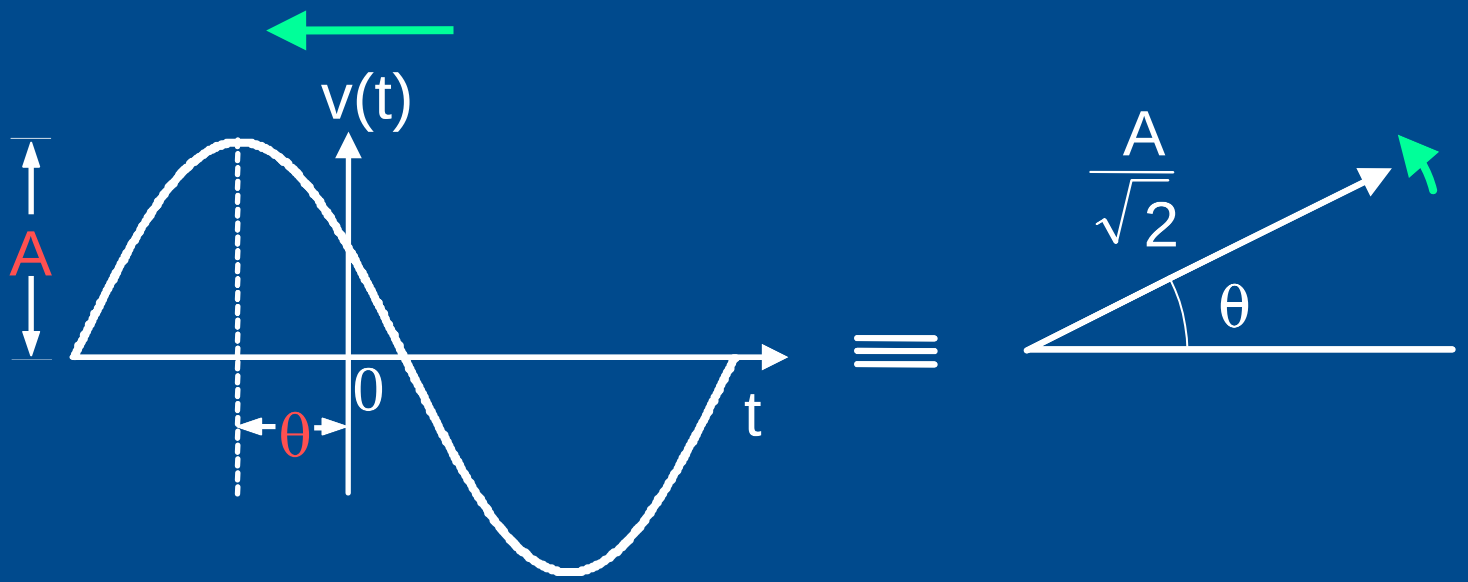
Phasor calculation

Phasor samples:
magnitude and angle
versus reference



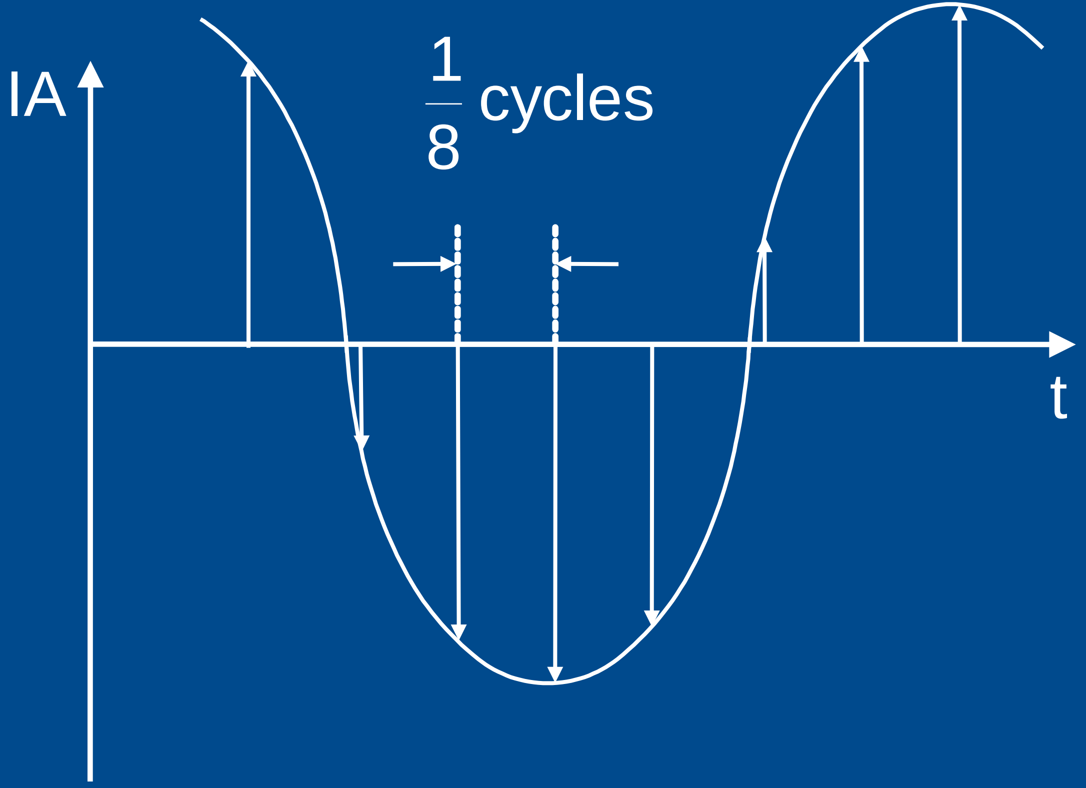
Reference

Sinusoid-to-Phasor Conversion



Sinusoid to Phasors

Current Channels Are Sampled



IA
1559
–69
–1656
–2274
–1558
70
1656
2273

Sinusoid to Phasors

- Pick quadrature samples (1/4 cycle apart)
- Pick current sample (x sample)
- Pick previous sample 1/4-cycle old (y sample)

IA	
1559	
–69	
–1656	
–2274	← y sample (1/4-cycle old)
–1558	
70	← x sample (present)
1656	
2273	

Sinusoid to Phasors

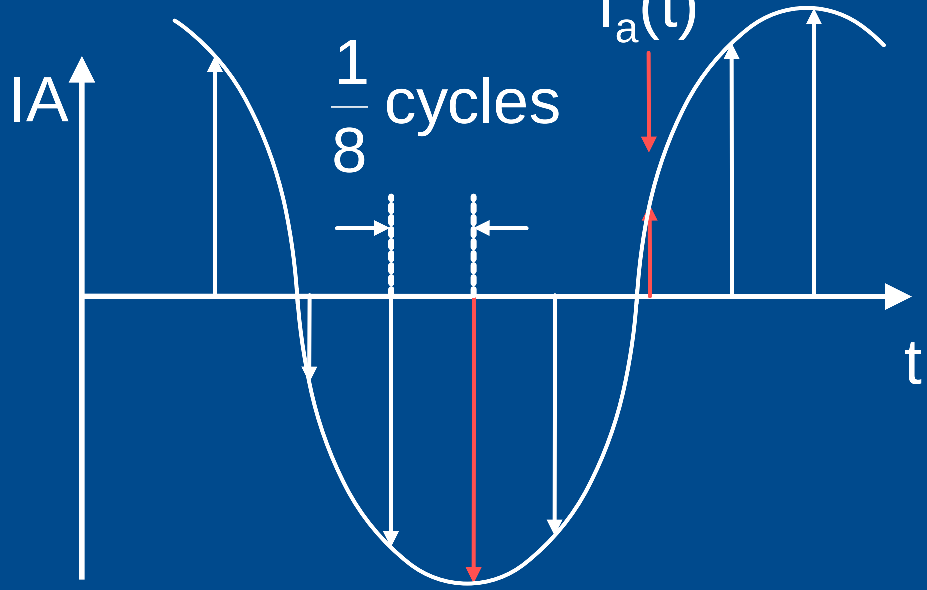
$$\text{Magnitude} = \sqrt{x^2 + y^2}$$

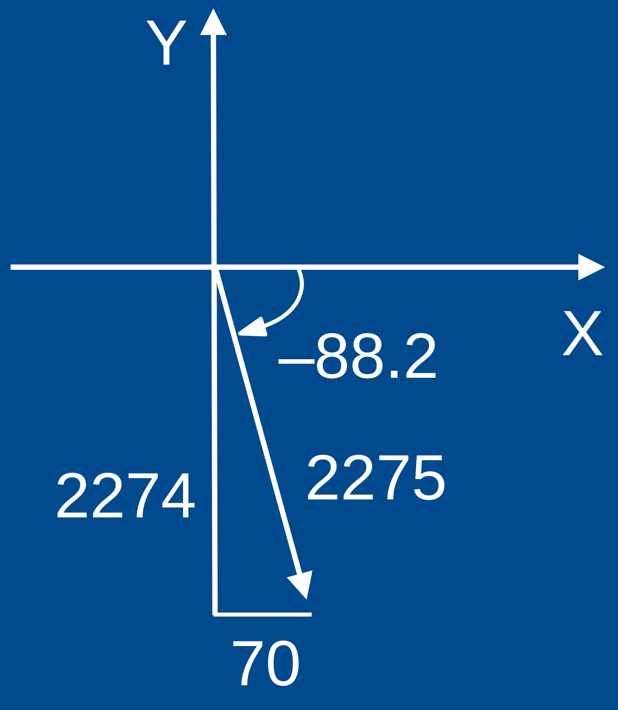
$$\text{Angle} = \arctan\left(\frac{y}{x}\right)$$

$$\text{Magnitude} = \sqrt{70^2 + (-2274)^2}$$

$$\text{Angle} = \arctan\left(\frac{-2274}{70}\right)$$

$$IA = 2275\angle -88.2^\circ$$





Relay Operation

Relay Word Bits and Logic

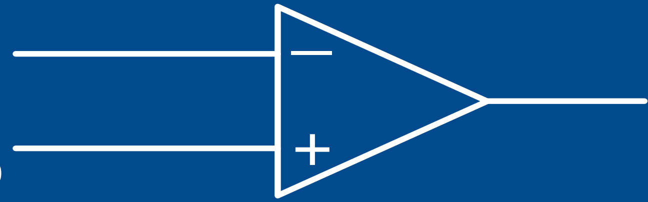
Relay Word Bits

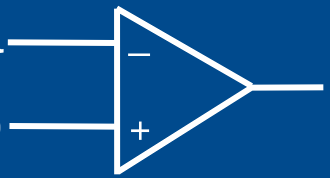
- Instantaneous overcurrent
- Time overcurrent
- Voltage elements
- Inputs
- Internal relay logic: SELOGIC® variable (SV) and latches
- Outputs

Assert to logical 1 when conditions are true, deassert to logical 0 when conditions are false

Instantaneous-Overcurrent Element

- 50P1P = instantaneous phase-overcurrent setting
- I_p = measured current of maximum phase
- 50P1P = 1 if I_p > 50PIP; 50P1P = 0 if I_p < 50P1P



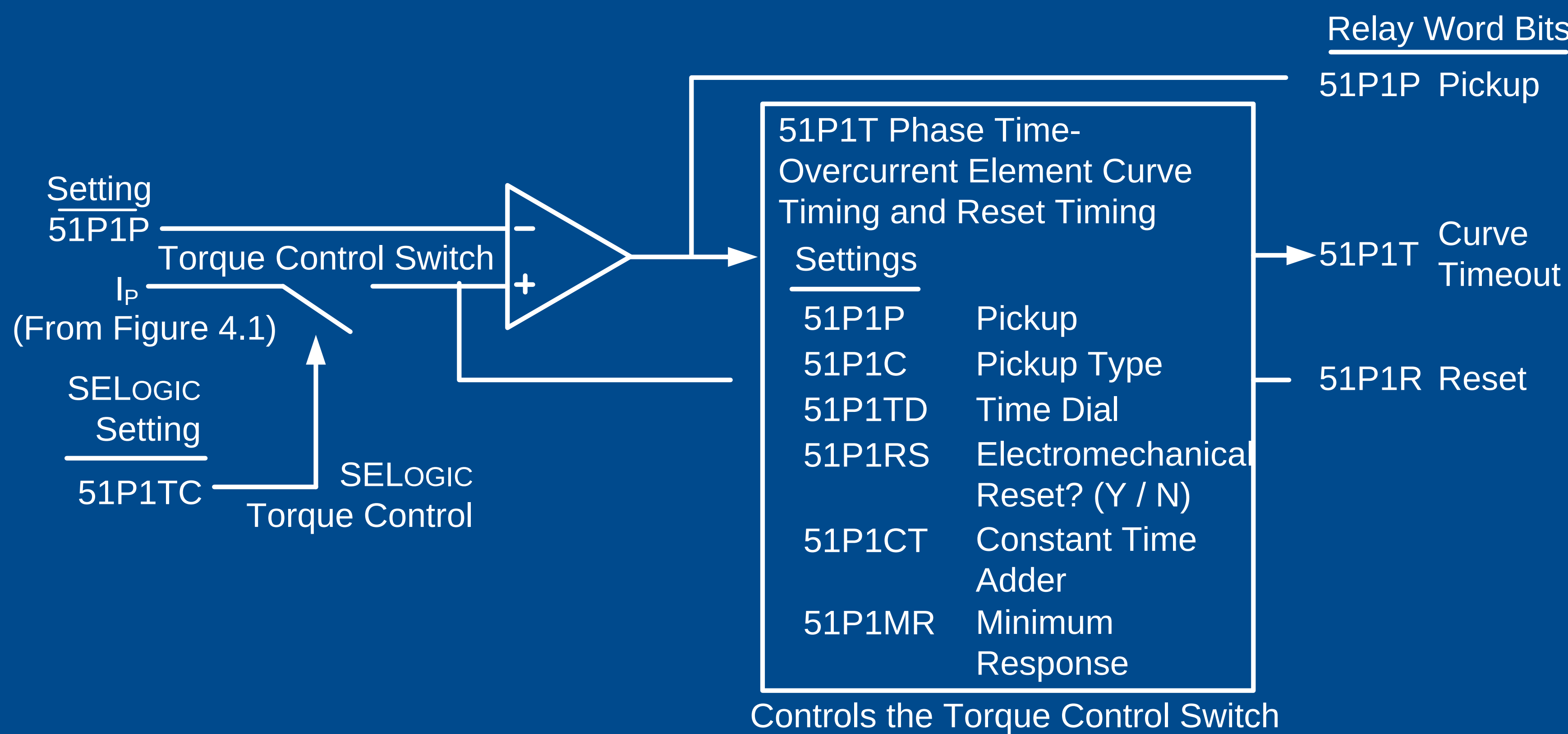


Comparator

When b (+) terminal is greater than a (–) terminal, c is logical 1

SEL-751A Protection System

Phase Time-Overcurrent Element



51P1TC State	Torque Control Switch Position
Logical 1	Closed
Logical 0	Open

Setting 51P1RS=	Reset Timing
Y	Electromechanical
N	1 Cycle

SEL-751A Protection System

ORED – Overcurrent Elements

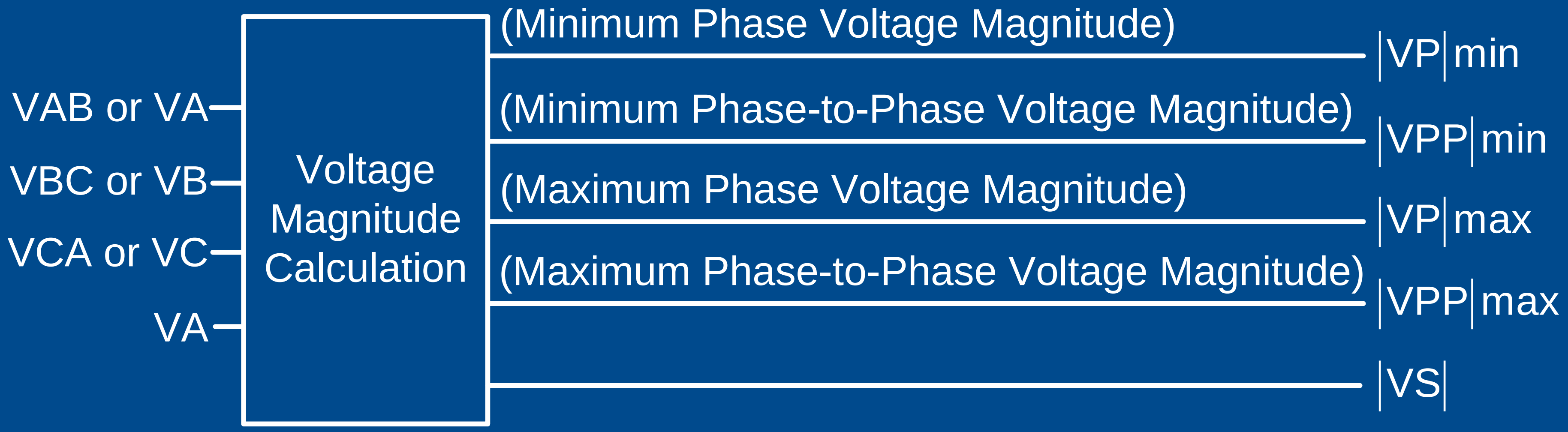
- Relay Word bit ORED50T is asserted if 50PnT, 50NnT, 50GnT, or 50QnT Relay Word bits are asserted
- Relay Word bit ORED51T is asserted if 51AT, 51BT, 51CT, 51P1T, 51P2T, 51N1T, 51N2T, 51G1T, 51G2T, or 51QT Relay Word bits are asserted

Standard Time-Current Characteristics

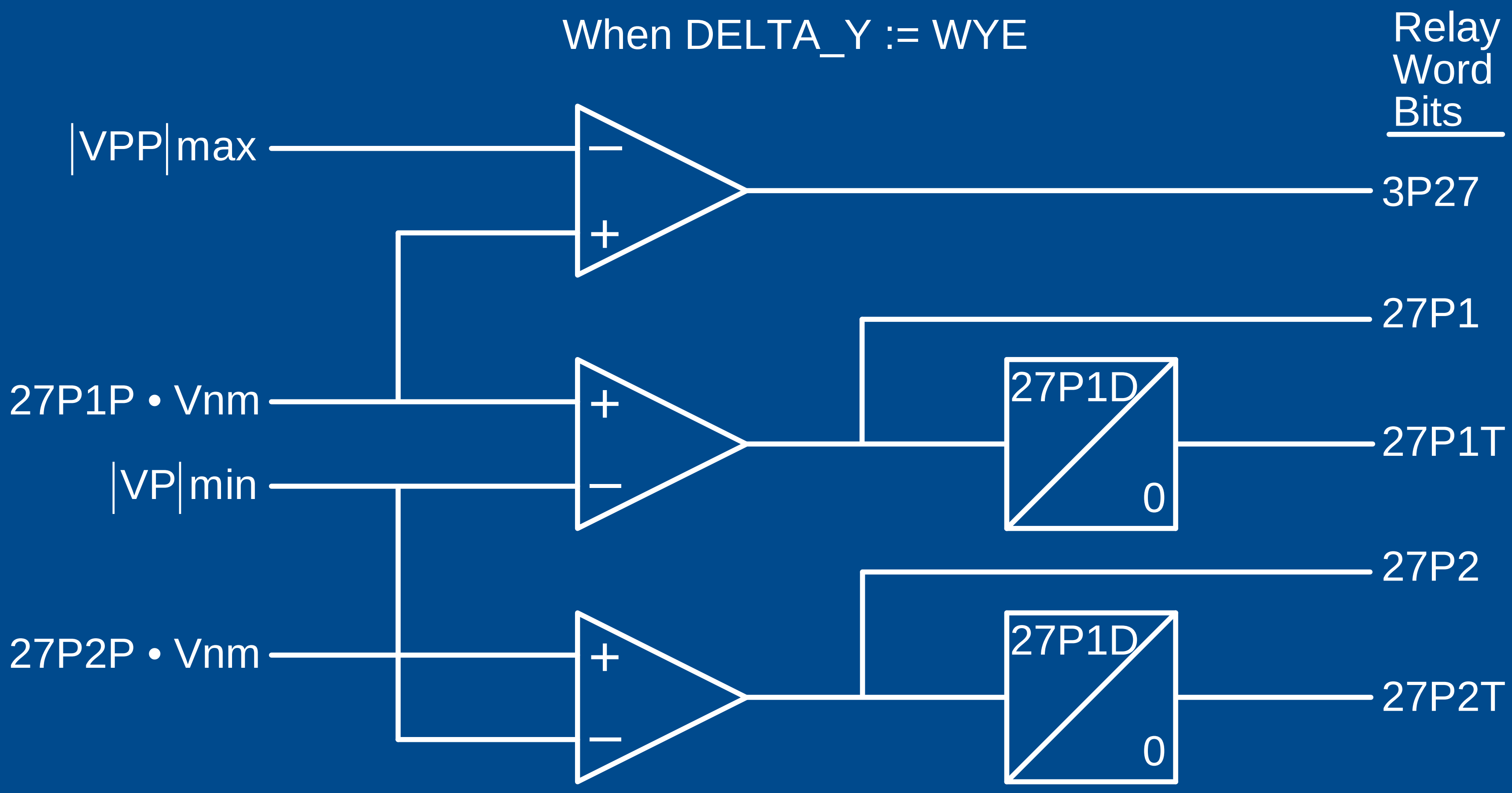
IEEE C37.112-1996

Curve Type	Operating Time	Reset Time
U1 (Moderately Inverse)	$t_p = TD \cdot \left(0.0226 + \frac{0.0104}{M^{0.02} - 1}\right)$	$t_r = TD \cdot \left(\frac{1.08}{1 - M^2}\right)$
U2 (Inverse)	$t_p = TD \cdot \left(0.180 + \frac{5.95}{M^2 - 1}\right)$	$t_r = TD \cdot \left(\frac{5.95}{1 - M^2}\right)$
U3 (Very Inverse)	$t_p = TD \cdot \left(0.0963 + \frac{3.88}{M^2 - 1}\right)$	$t_r = TD \cdot \left(\frac{3.88}{1 - M^2}\right)$
U4 (Extremely Inverse)	$t_p = TD \cdot \left(0.0352 + \frac{5.67}{M^2 - 1}\right)$	$t_r = TD \cdot \left(\frac{5.67}{1 - M^2}\right)$
U5 (Short-Time Inverse)	$t_p = TD \cdot \left(0.00262 + \frac{0.00342}{M^{0.02} - 1}\right)$	$t_r = TD \cdot \left(\frac{0.323}{1 - M^2}\right)$

SEL-751A Voltage Calculation



SEL-751A Single- and Three-Phase Voltage Elements



SEL-751A Relay Word Bit Tables

8 Relay Word Bits Per Numbered Row

Row	Relay Word Bits							
1	50A1P	50B1P	50C1P	50PAF	ORED50T	ORED51T	50NAF	52A
2	50P1P	50P2P	50P3P	50P4P	50Q1P	50Q2P	50Q3P	50Q4P
3	50P1T	50P2T	50P3T	50P4T	50Q1T	50Q2T	50Q3T	50Q4T
4	50N1P	50N2P	50N3P	50N4P	50G1P	50G2P	50G3P	50G4P
5	50N1T	50N2T	50N3T	50N4T	50G1T	50G2T	50G3T	50G4T

Logic

Boolean Logic

- Mathematics of logical variables (Relay Word bits)
- Operators: AND, OR, NOT, rising and falling edge, parentheses
- SELogic control equations Boolean operators
  - Defined symbols
  - Application rules

SELogic Control Equations Operators

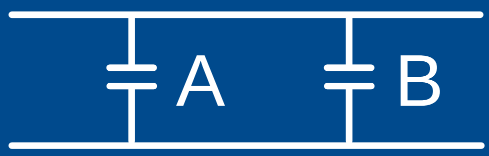
Operator	Symbol	Function
Parentheses	( )	Group terms
Negation	-	Changes sign of numerical value
NOT	NOT	Invert the logic
Rising edge	R_TRIG	Output asserts for one processing interval on inputs rising-edge transition
Falling edge	F_TRIG	Output asserts for one processing interval on inputs falling-edge transition
Multiply	*	Multiply numerical values

SELogic Control Equations Operators

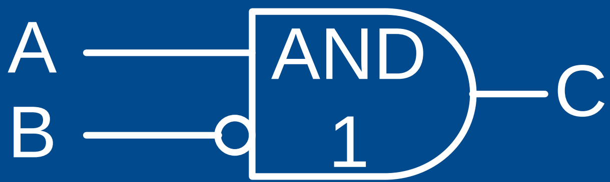
Operator	Symbol	Function
Divide	/	Divide numerical values
Add	+	Add numerical values
Subtract	–	Subtract numerical values
Comparison	<,>,<=,>= ,=, <>	Compare numerical values
AND	AND	Multiply Boolean values
OR	OR	Add Boolean values

SELogic Control Equation Examples

C = A OR B

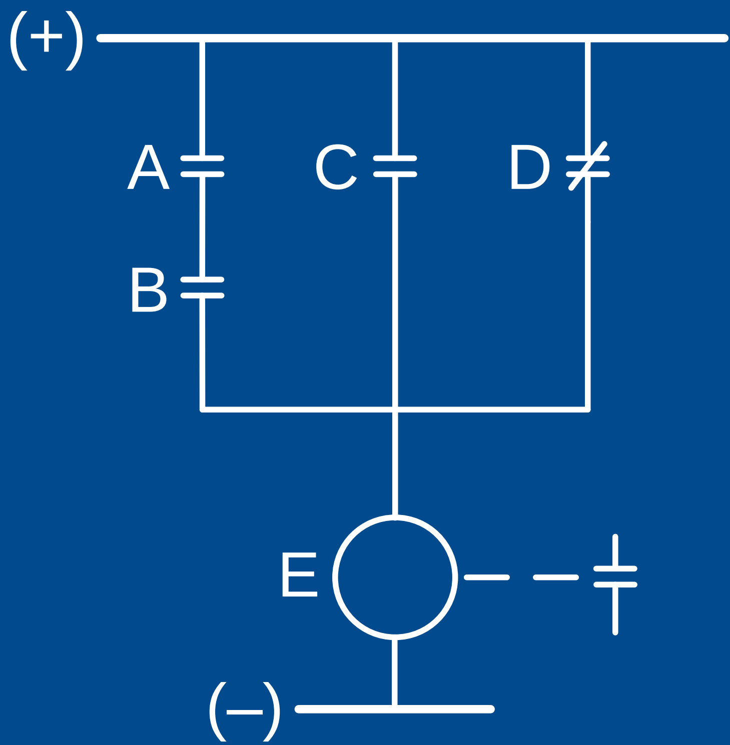


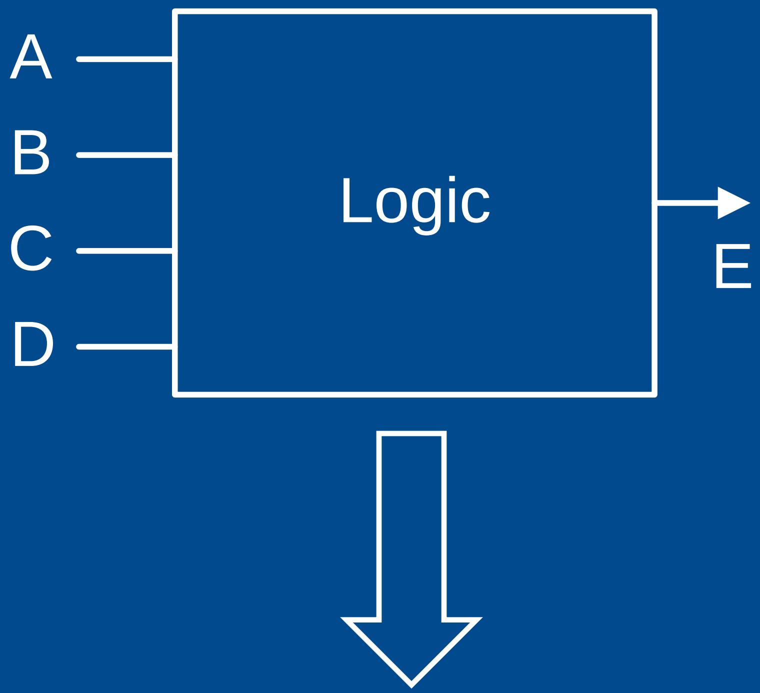
C = A AND B



C = A AND NOT B

Programmable Logic





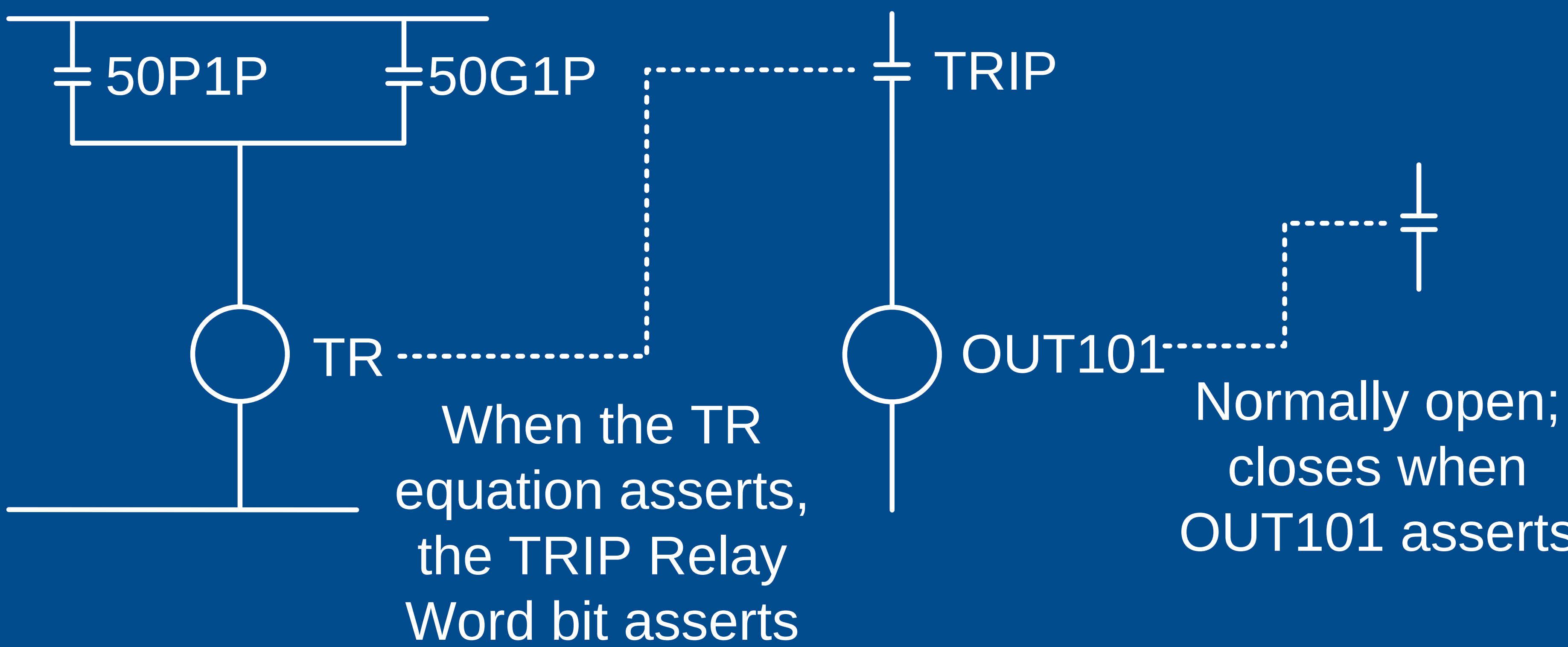
Equation implemented

E = A AND B OR C
OR NOT D

SELogic Control Equation Examples

TR = 50P1P AND 50G1

OUT101 = TRIP



Typical Logic Settings for Trip

TR Trip (SELogic)

ORED50T OR ORED51T OR 81D1T OR 81D2T OR 81D3T OR 81D4T OR 59P1T OR 59P

REMTRIP Remote Trip (SELogic)

0

OUT103FS OUT103 Fail-Safe

N

Select: Y, N

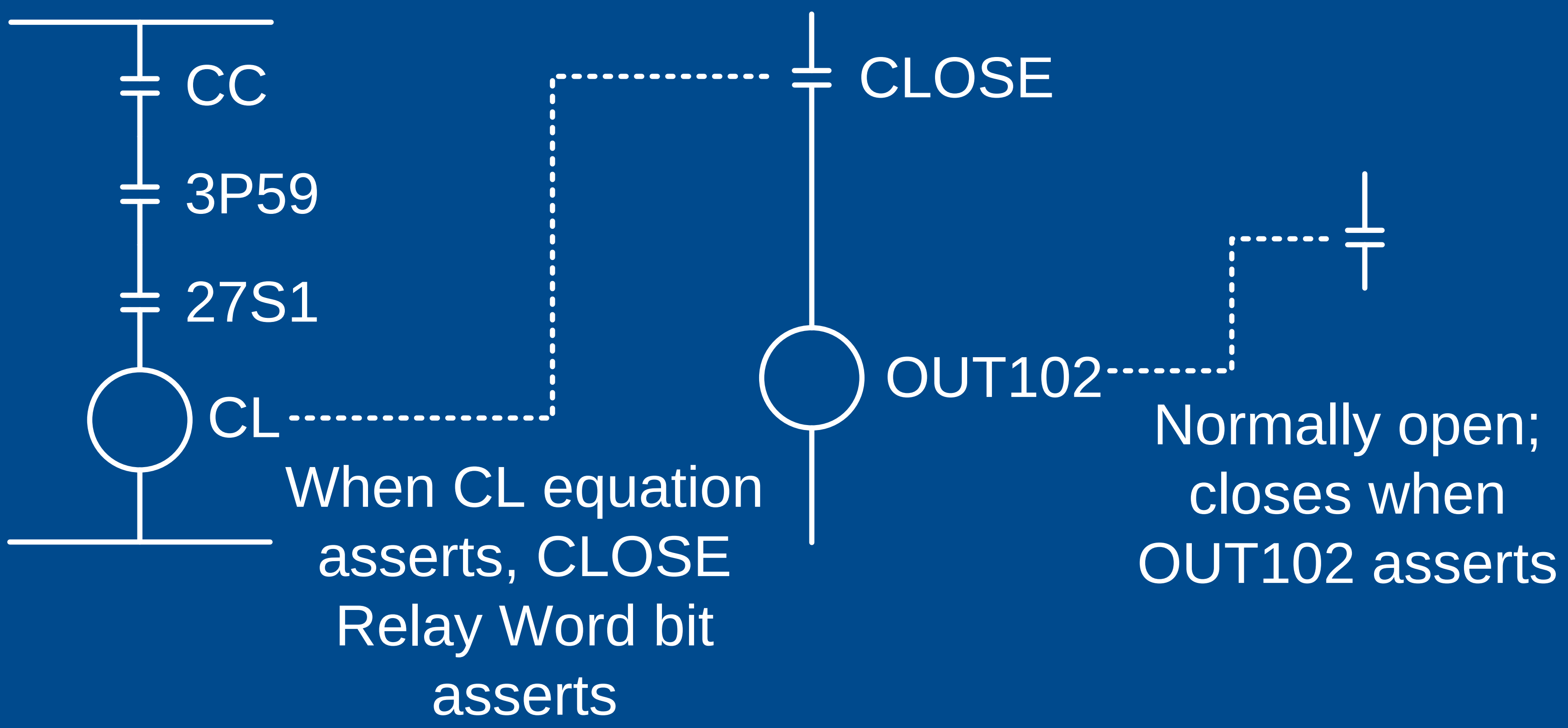
OUT103 (SELogic)

TRIP

SELOGIC Control Equation Examples

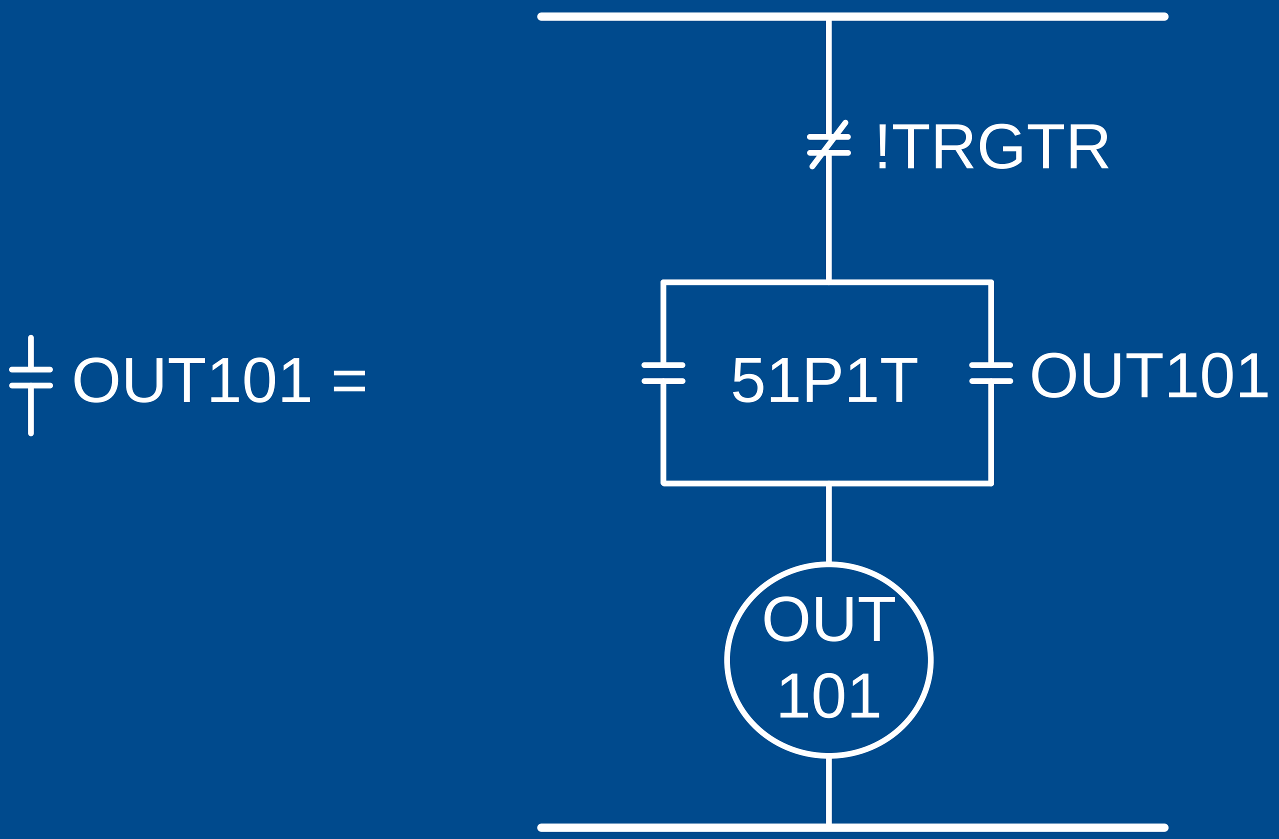
CL = CC AND 3P59 AND 27S1

OUT102 = CLOSE

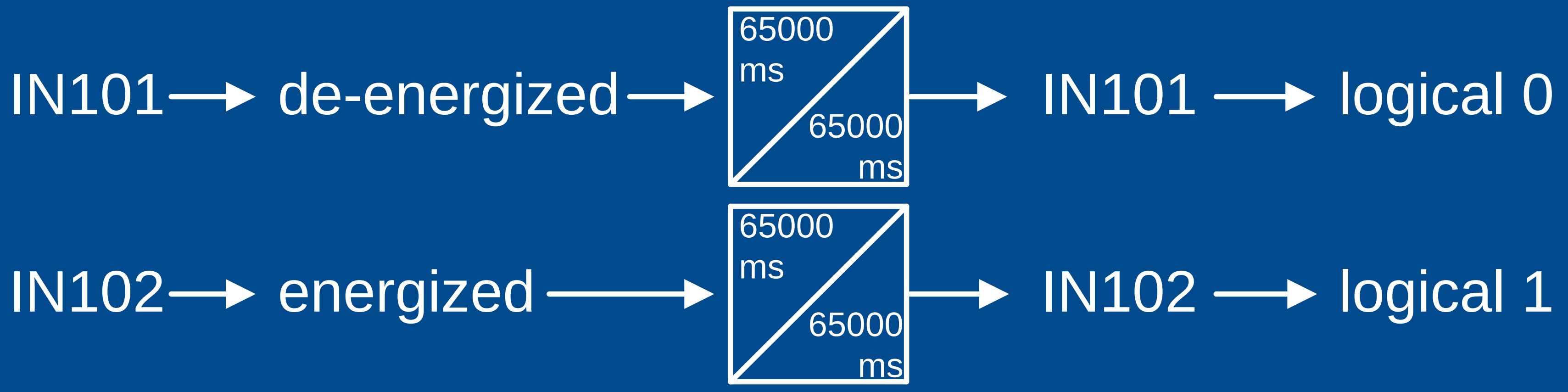


SELOGIC Example

OUT101 = (51P1T OR OUT101) AND NOT TRGTR

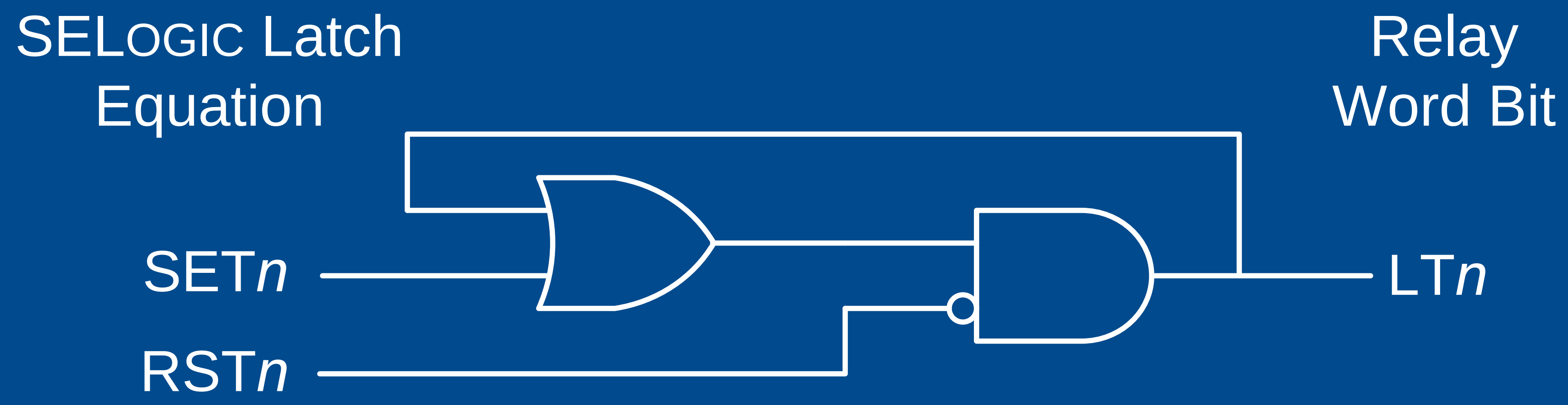


Optoisolated Inputs



- Relay Word bits IN101 and IN102 monitor physical state inputs
- Debounce timer is built in and settable

Latching Control Logic

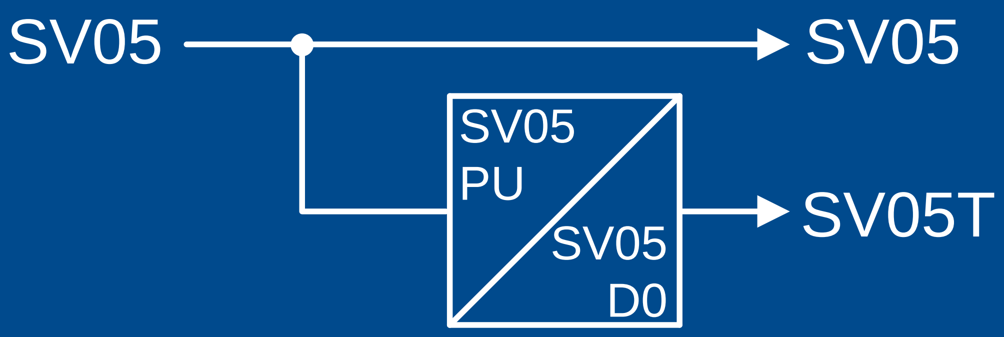


n = 1 – 32

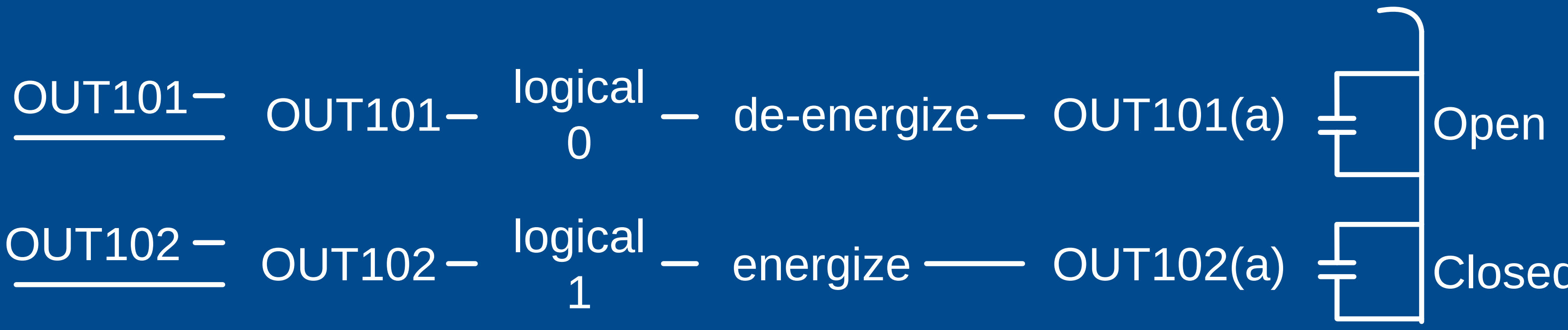
SET01 = CLOSE RST01 = TRIP 52A = LT01

SV Timer

- Set as logic placeholder and timer
- Example settings
  - SV05 = 50P1P
  - SV05PU = 0.17 seconds
- Operation
  - SV05 asserts when 50P1P asserts
  - SV05T asserts 0.17 seconds after 50P1P asserts



Outputs



- When OUT101 equation is true (logical 1), OUT101 closes
- Example setting: OUT301 = SV05T
- Operation: OUT301 closes after 50P1P has been asserted for 0.17 seconds

Track Relay Word Bit State Change With Sequential Events Report (SER)

Example: 50P1 = 4 A; CTR = 120;
Primary PU = 480 A

```
=>SER

SEL-751A                                    Date: 05/31/2011   Time: 20:24:04
FEEDER RELAY                                Time Source: Internal

Serial No = 2007254448      FID = SEL-751A-R301-V0-Z005003-D20090504
CID = 3148

#       DATE          TIME                    ELEMENT                  STATE
10   05/31/2011   20:09:47.808   50P1P                              Asserted
9    05/31/2011   20:09:47.808   TRIP                               Asserted
8    05/31/2011   20:09:47.808   SV05                               Asserted
7    05/31/2011   20:09:47.979   OUT301                             Asserted
6    05/31/2011   20:09:47.979   SV05T                              Asserted
5    05/31/2011   20:09:48.287   50P1P                              Deasserted
4    05/31/2011   20:09:48.287   SV05                               Deasserted
3    05/31/2011   20:09:48.316   TRIP                               Deasserted
2    05/31/2011   20:09:48.458   OUT301                             Deasserted
1    05/31/2011   20:09:48.458   SV05T                              Deasserted

=>
```

Event Reporting

- Helpful in fault analysis
- Relay collects 15-cycle event report when ER = R_TRIG 50P1P
- HIS command text

```
=>HIS

SEL-751A                                    Date: 05/31/2011   Time: 20:25:29
FEEDER RELAY                                Time Source: Internal

FID = SEL-751A-R301-V0-Z005003-D20090504

#     DATE         TIME            EVENT              CURRENT       FREQ  TARGETS
1  05/31/2011  20:09:47.808  Phase A1 50 Trip     501.5        60.0  11100000
2  05/31/2011  20:09:21.153  Trigger                6.1        60.0  10000000
3  05/31/2011  20:08:24.056  Phase A1 50 Trip     500.2        60.0  11100000
4  05/31/2011  20:05:45.806  Phase A1 50 Trip     501.2        60.4  11100000
5  05/31/2011  20:04:48.178  Phase A1 50 Trip     502.2        59.8  11100000
6  05/31/2011  20:04:15.681  Phase A1 50 Trip     503.3        60.4  11100000
7  05/31/2011  19:56:03.175  Phase A1 50 Trip     500.4        60.0  11100000

=>
```

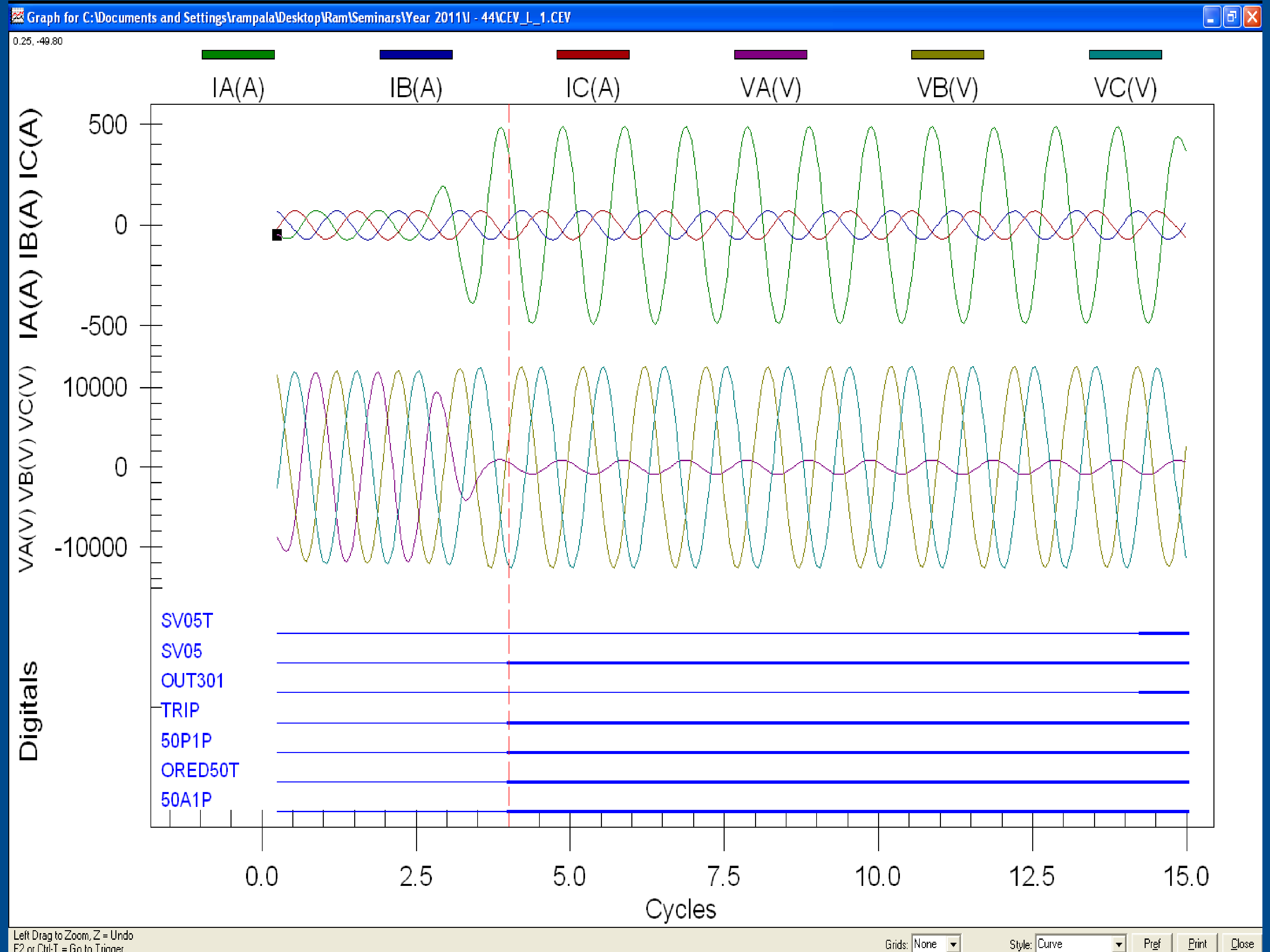
```
=>EVE

SEL-751A                                 Date: 05/31/2011   Time: 20:09:47.808
FEEDER RELAY


Serial Number=2007254448
FID=SEL-751A-R301-V0-Z005003-D20090504   CID=3148

                                                    55555 55 8   O
                                                    11111 00 1 I u
                                                    A      N   n t
      Currents (A Pri)            Voltages (V Pri)  B      Q   1 13
    IA    IB    IC    IN    IG     VA     VB     VC CPNGQ PG   2 2
[1]
 -49.8  68.4 -17.4   0.6   1.2  -8795  11563  -2646 ..... .. . . ..
 -56.4 -17.4  68.4   0.0  -5.4  -8305  -3589  11819 ..... .. . . ..
  48.0 -71.4  16.8  -1.2  -6.6   8800 -11565   2626 ..... .. . . ..
  54.6  18.0 -67.8   0.0   4.8   8296   3598 -11826 ..... .. . . ..
[2]
 -49.8  69.6 -20.4  -1.2  -0.6  -8824  11558  -2621 ..... .. . . ..
 -56.4 -20.4  67.2  -1.2  -9.6  -8291  -3616  11831 ..... .. . . ..
  48.0 -71.4  18.0   0.0  -5.4   8825 -11552   2599 ..... .. . . ..
  54.6  18.6 -71.4   0.6   1.8   8278   3622 -11840 ..... .. . . ..
[3]
 -51.0  67.2 -18.0  -2.4  -1.8  -8842  11547  -2587 ..... .. . . ..
 -55.2 -19.2  69.6  -2.4  -4.8  -8276  -3645  11828 ..... .. . . ..
  81.6 -71.4  16.8   0.0  27.0   7882 -11646   2615 ..... .. . . ..
   167  18.6 -69.0   0.0   117   5276   3640 -11959 ..... .. . . ..
[4]
  -232  69.6 -19.2   0.6  -182  -3794  11891  -2664 ..... .. . . ..
  -321 -20.4  67.2  -2.4  -274  -1449  -3746  12229 ..... .. . . ..
   347 -70.2  18.0  -2.4   295    653 -12064   2659 ..... .. . . ..
   354  16.8 -70.2   0.6   301    608   3859 -12377>..... 1. . . ..
[5]
  -349  69.6 -19.2   0.6  -299   -662  12051  -2650 ..... 1. . . .3
  -355 -20.4  67.2  -2.4  -308   -617  -3868  12371 ..... 1. . . .3
   347 -71.4  18.0  -1.2   294    664 -12049   2623 ..... 1. . . .3
   354  21.0 -71.4   0.0   304    612   3872 -12377 ..... 1. . . .3
[6]
  -351  69.6 -18.0   0.0  -299   -673  12044  -2615 ..... 1. . . .3
  -358 -21.6  69.6   0.0  -310   -617  -3899  12375*..... 1. . . .3
   351 -71.4  18.0  -1.2   298    671 -12042   2596 ..... 1. . . .3
   355  18.6 -70.2  -2.4   304    612   3911 -12388 ..... 1. . . .3
```

```
[7]
  -352  67.2 -19.2   0.6  -304   -677  12031  -2587 ..... 1. . . .3
  -356 -20.4  67.2   0.6  -309   -614  -3929  12386 ..... 1. . . .3
   350 -67.8  18.0  -3.6   300    671 -12033   2567 ..... 1. . . .3
   352  19.8 -71.4   0.0   300    608   3942 -12388 ..... 1. . . .3
[8]
  -349  67.2 -17.4   0.0  -299   -680  12020  -2556 ..... 1. . . .3
  -353 -20.4  69.6  -1.2  -304   -610  -3958  12389 ..... 1. . . .3
   349 -70.2  15.6   0.6   294    675 -12019   2533 ..... 1. . . .3
   352  19.8 -70.2   0.0   301    605   3967 -12400 ..... 1. . . .3
[9]
  -355  68.4 -18.0  -1.2  -304   -677  12006  -2516 ..... 1. . . .3
  -350 -21.6  68.4  -2.4  -304   -610  -3982  12397 ..... 1. . . .3
   353 -69.0  15.6  -2.4   299    668 -12011   2506 ..... 1. . . .3
   351  19.8 -70.2   1.8   301    612   3994 -12407 ..... 1. . . .3
[10]
  -353  66.0 -16.2   0.0  -304   -680  12006  -2493 ..... 1. . . .3
  -353 -22.8  68.4  -2.4  -308   -617  -4014  12402 ..... 1. . . .3
   353 -69.0  14.4  -1.2   298    675 -12008   2470 ..... 1. . . .3
   349  19.8 -71.4   0.6   297    605   4023 -12404 ..... 1. . . .3
[11]
  -353  68.4 -16.2   0.6  -301   -673  11999  -2464 ..... 1. . . .3
  -350 -21.6  67.2   0.6  -305   -610  -4048  12398 ..... 1. . . .3
   354 -70.2  14.4  -2.4   298    671 -11990   2450 ..... 1. . . .3
   349  19.8 -70.2  -2.4   298    605   4054 -12407 ..... 1. . . .3
[12]
  -356  68.4 -16.2   0.0  -304   -689  11979  -2441 ..... 1. . . .3
  -349 -21.6  68.4  -2.4  -302   -614  -4066  12413 ..... 1. . . .3
   351 -70.2  15.6   0.0   296    688 -11990   2414 ..... 1. . . .3
   347  22.2 -70.2   0.6   299    601   4084 -12418 ..... 1. . . .3
[13]
  -352  66.0 -16.2   0.0  -302   -682  11979  -2408 ..... 1. . . .3
  -350 -21.6  68.4  -1.2  -304   -603  -4104  12413 ..... 1. . . .3
   354 -69.0  15.6  -2.4   301    675 -11974   2390 ..... 1. . . .3
   349  16.8 -70.2   0.0   295    605   4106 -12422 ..... 1. . . .3
[14]
  -358  69.6 -18.0   0.6  -307   -677  11961  -2378 ..... 1. . . .3
  -348 -20.4  69.6   0.0  -299   -614  -4133  12424 ..... 1. . . .3
   358 -70.2  13.2  -2.4   301    675 -11963   2358 ..... 1. . . .3
   346  19.8 -71.4  -2.4   295    605   4136 -12436 ..... 1. . . .3
[15]
  -357  67.2 -16.2   0.6  -306   -693  11954  -2351 ..... 1. . . .3
  -349 -20.4  68.4   0.6  -301   -607  -4156  12438 ..... 1. . . .3
   356 -69.0  16.8  -1.2   304    684 -11952   2327 ..... 1. . . .3
   347  19.8 -72.0  -1.2   295    598   4165 -12443 ..... 1. . . .3
```


Graph for C:\Documents and Settings\rampala\Desktop\Ram\Seminars\Year 2011\I - 44\CEV_L_1.CEV
0.25, -49.80
IA(A)
IB(A)
IC(A)
VA(V)
VB(V)
VC(V)
IA(A) IB(A) IC(A)
500
0
-500
VA(V) VB(V) VC(V)
10000
0
-10000
Digitals
SV05T
SV05
OUT301
TRIP
50P1P
ORED50T
50A1P
0.0
2.5
5.0
7.5
10.0
12.5
15.0
Cycles
Left Drag to Zoom, Z = Undo
F2 or Ctrl-T = Go to Trigger
Grids: None
Style: Curve
Pref
Print
Close

Summary

- Microprocessor-based relays create phasors from sinusoid (waveform) input
- Relay Word bits control relay I/O
- Microprocessor-based relays offer many troubleshooting and fault analysis tools
- SELogic control equations provide programming flexibility to create virtual control circuits

Questions?

Protection Basics: Overcurrent Protection

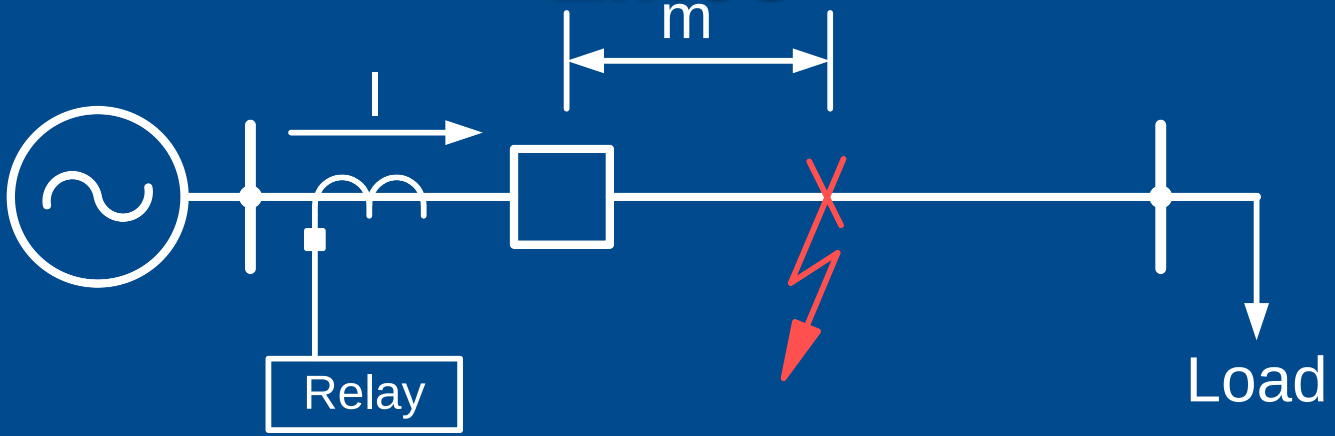
Fast Protection Minimizes

- Temperature rise
- Mechanical damage from magnetic forces
- Voltage sag
- Transient stability issues
- Shock and arc-flash hazards

Understand Basic Protection Principles

- Overcurrent (50, 51, 50N, 51N)
- Directional overcurrent (67, 67N)
- Distance (21, 21N)
- Differential (87)

Overcurrent Relays Protect Radial Lines

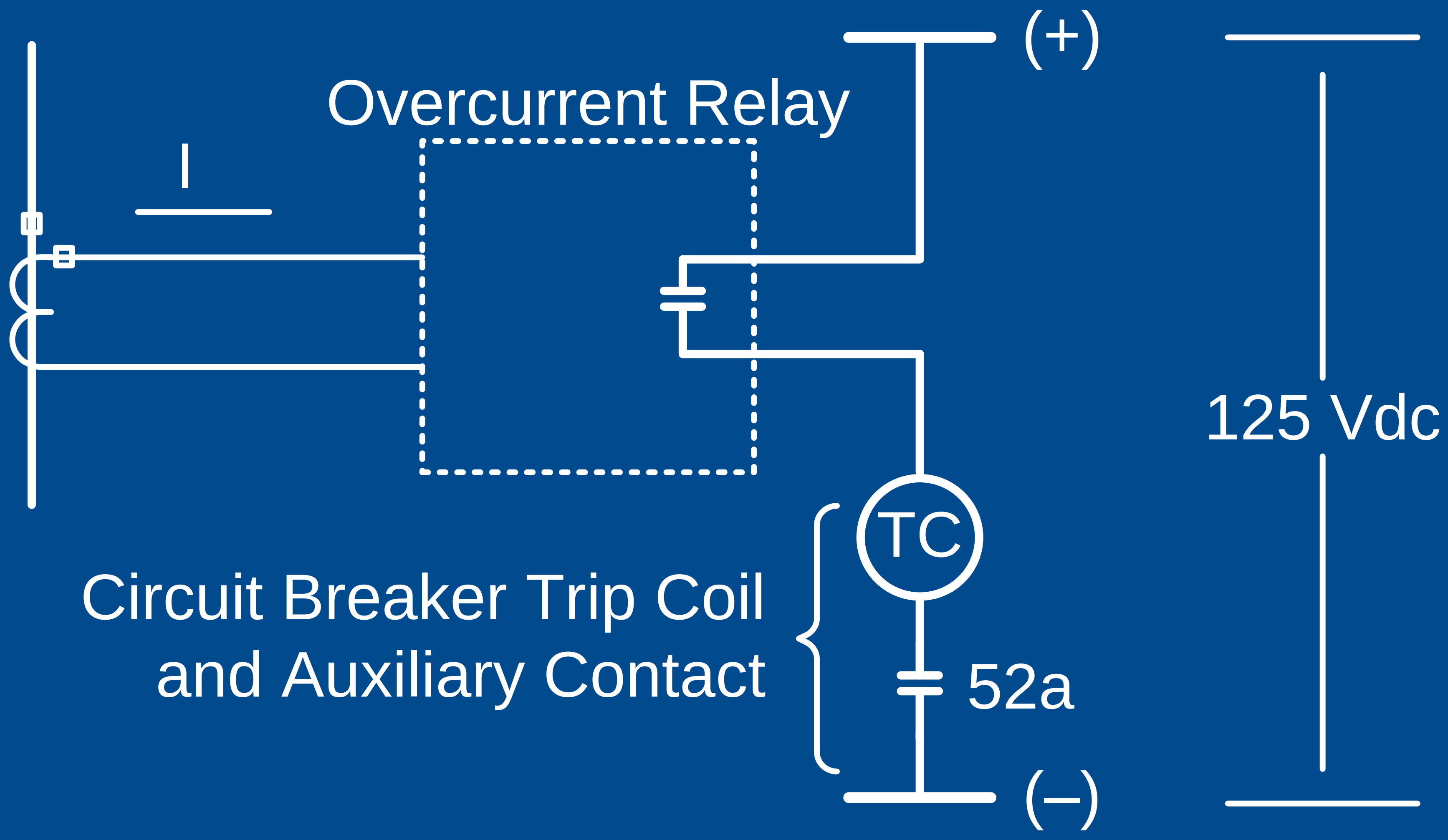


$$I_{LOAD} = \frac{E}{\overline{Z}_{Source} + \overline{Z}_{Line} + \overline{Z}_{LOAD}}$$

$$I_{FAULT} = \frac{E}{\overline{Z}_{Source} + m \bullet \overline{Z}_{Line}}$$

$$I_{FAULT} >> I_{LOAD}$$

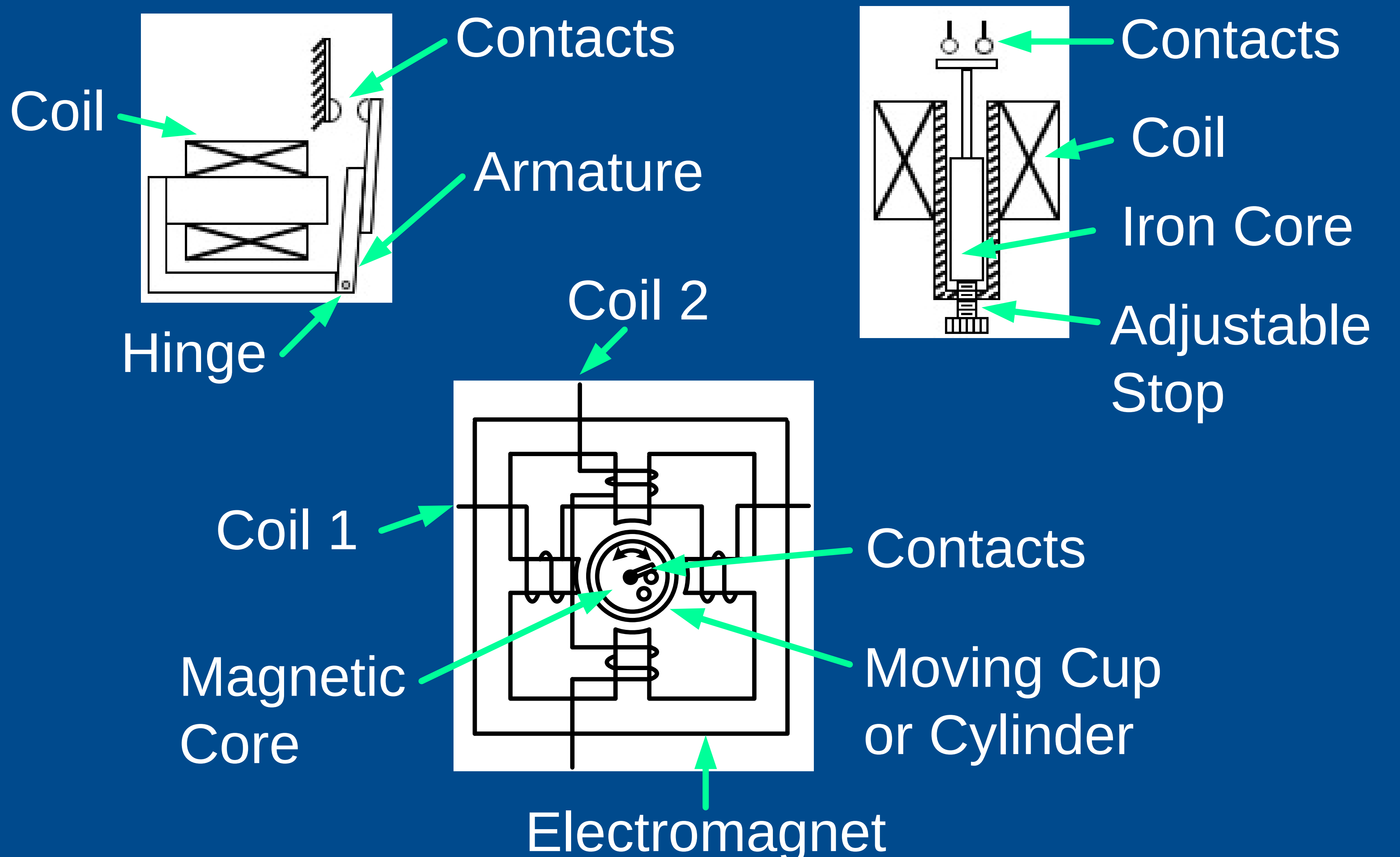
Relay Operates When Current Magnitude Rises Above Threshold



Evolving Protective Relay Designs

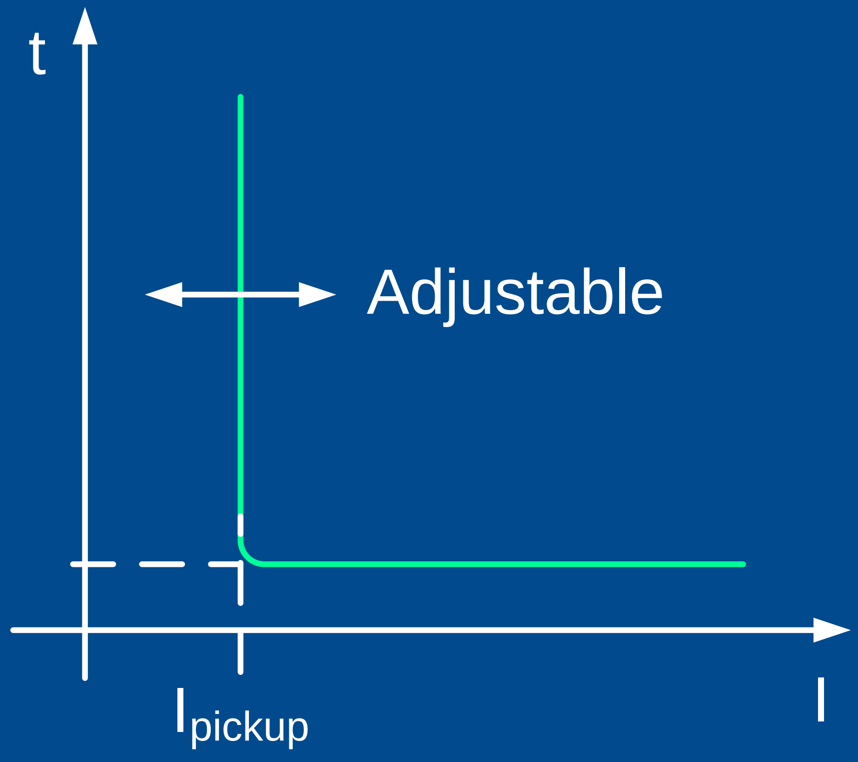
- Electromechanical relays
- Electronic analog relays – solid state (transistors, integrated circuits)
- Microprocessor-based relays – digital or numeric

How Do Instantaneous Relays Work?



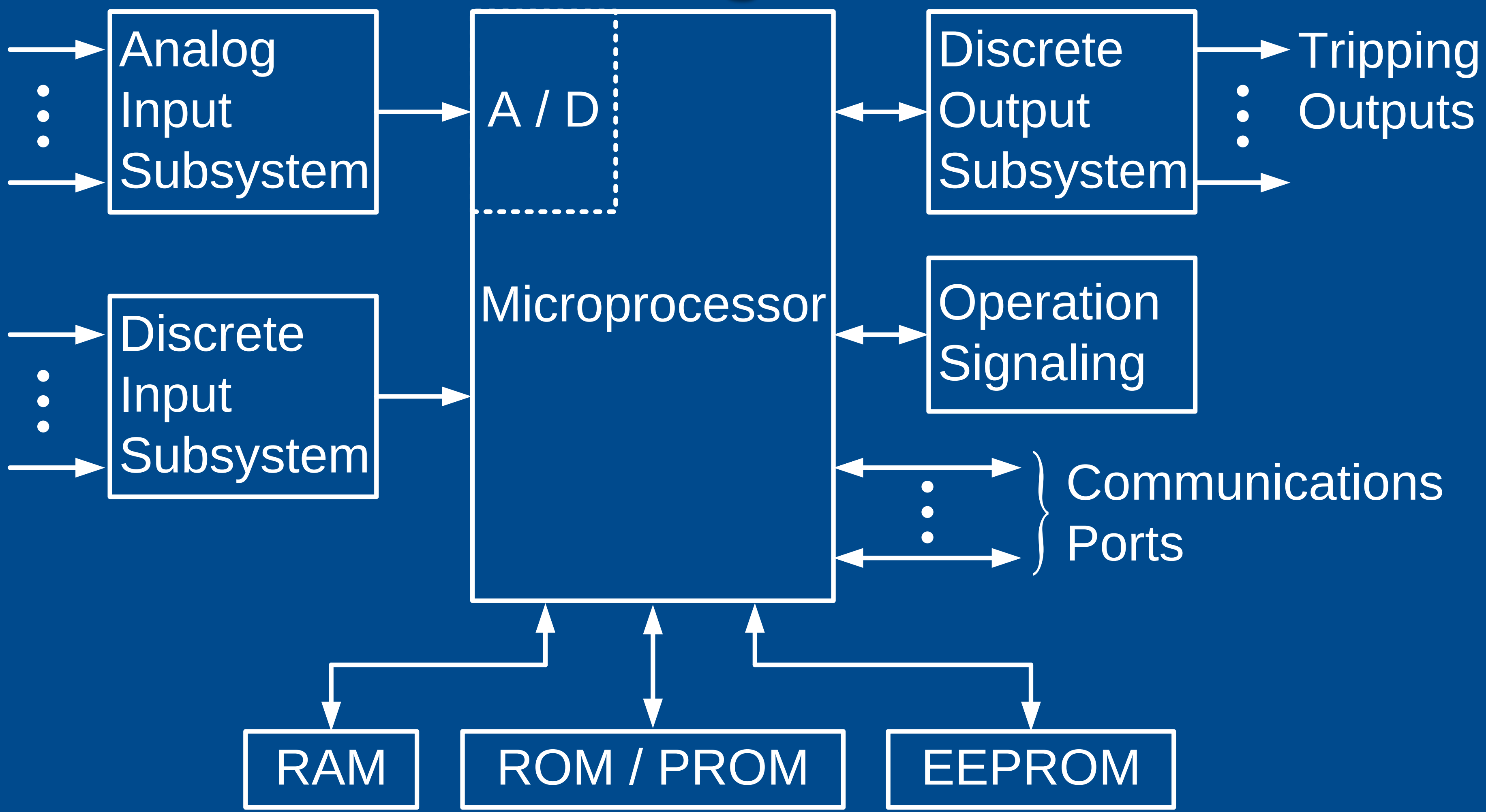
Plotting Electromechanical 50 Elements

Time vs. Current Curve

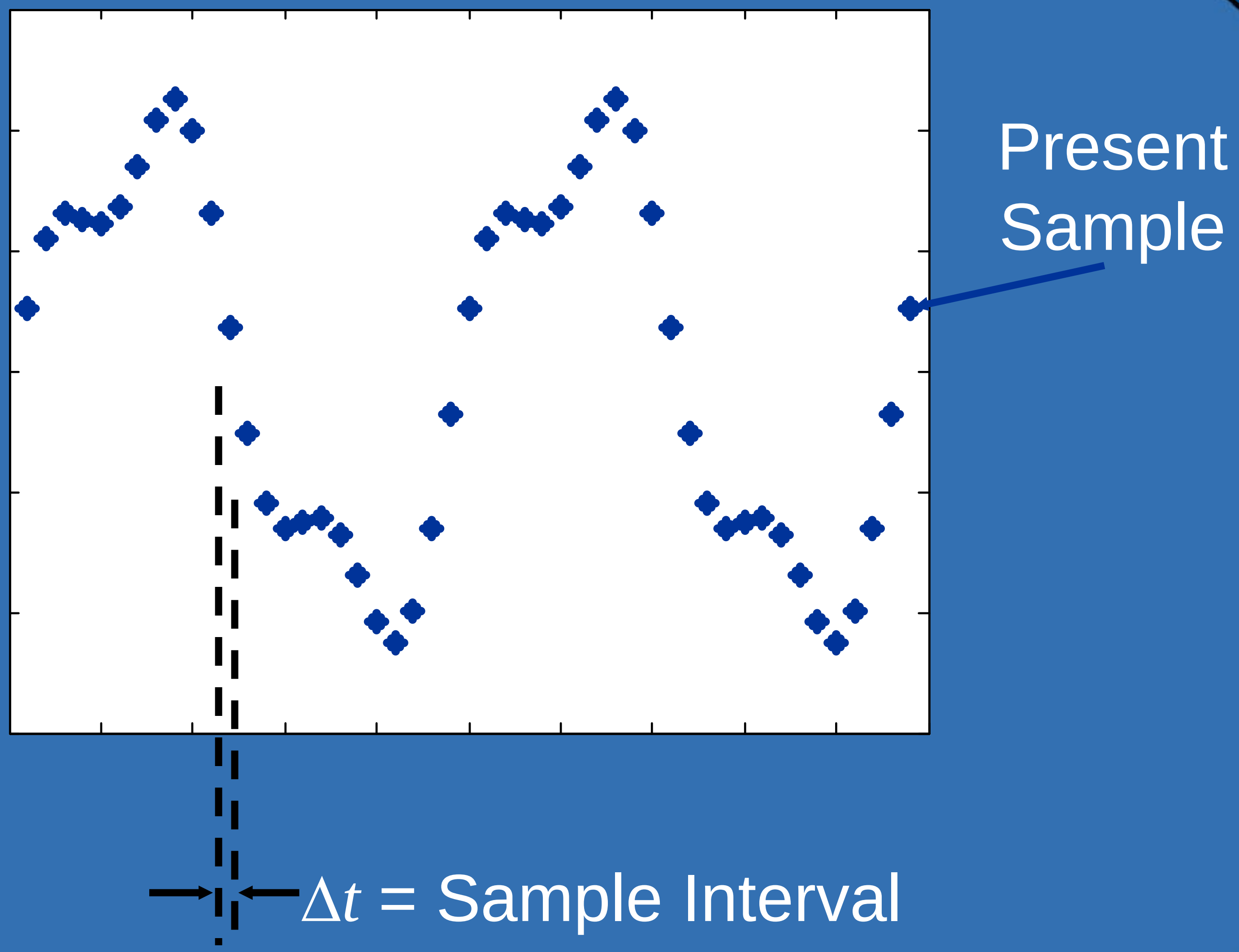


$t_{operate}$ < 1.5 Cycles

Digital Overcurrent Relay Block Diagram



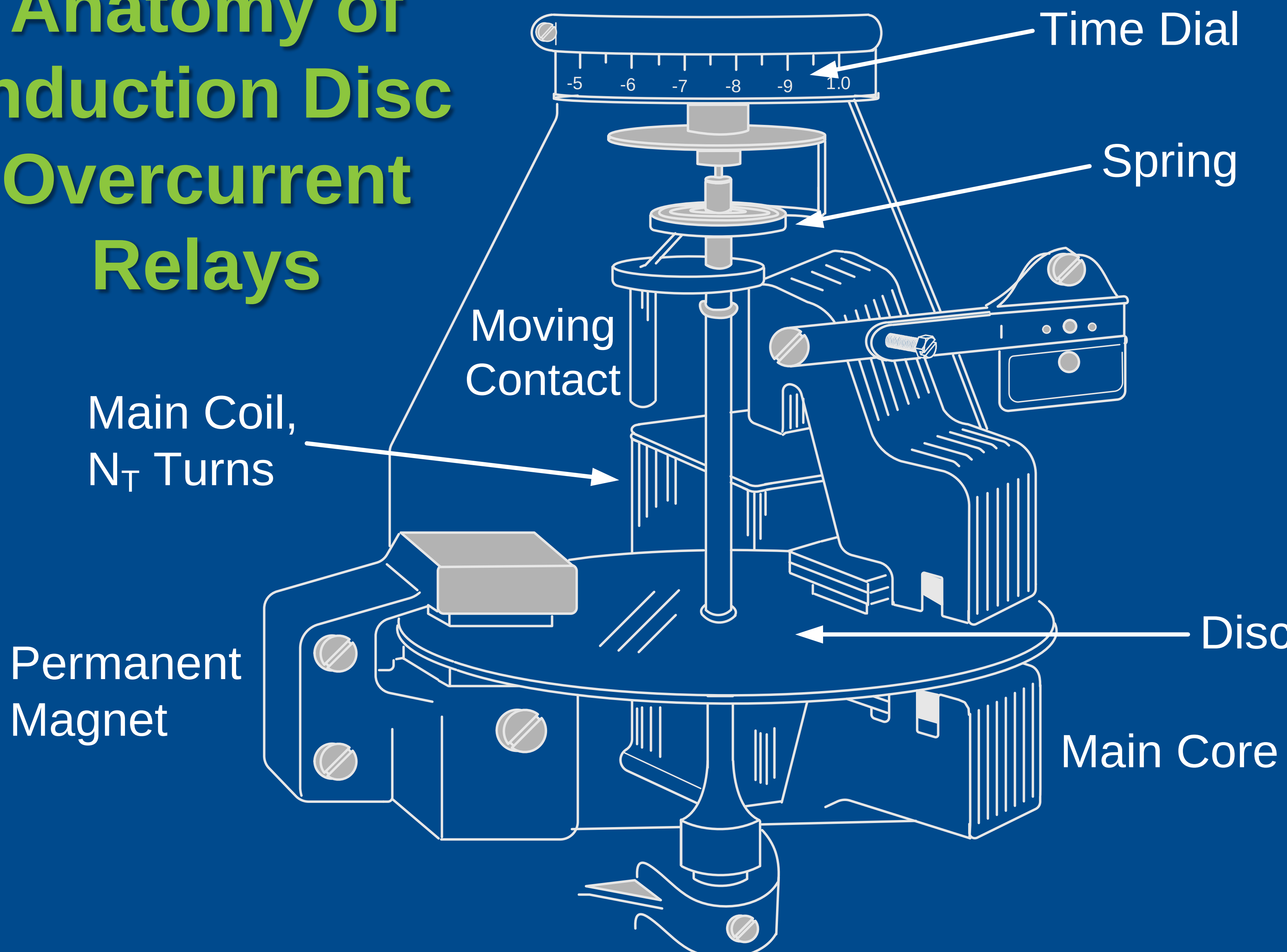
Digital Relays Use Sampled Signals



Advantages of Digital 50 Elements

- No contact chatter with alternating currents
- Not affected by dc offset
- Reset-to-pickup ratio close to one
- Resistant to misoperation due to mechanical shock

Anatomy of Induction Disc Overcurrent Relays



Induction Disc Operation Condition

Operating torque > spring torque

$$K_e I^2 \geq T_s$$

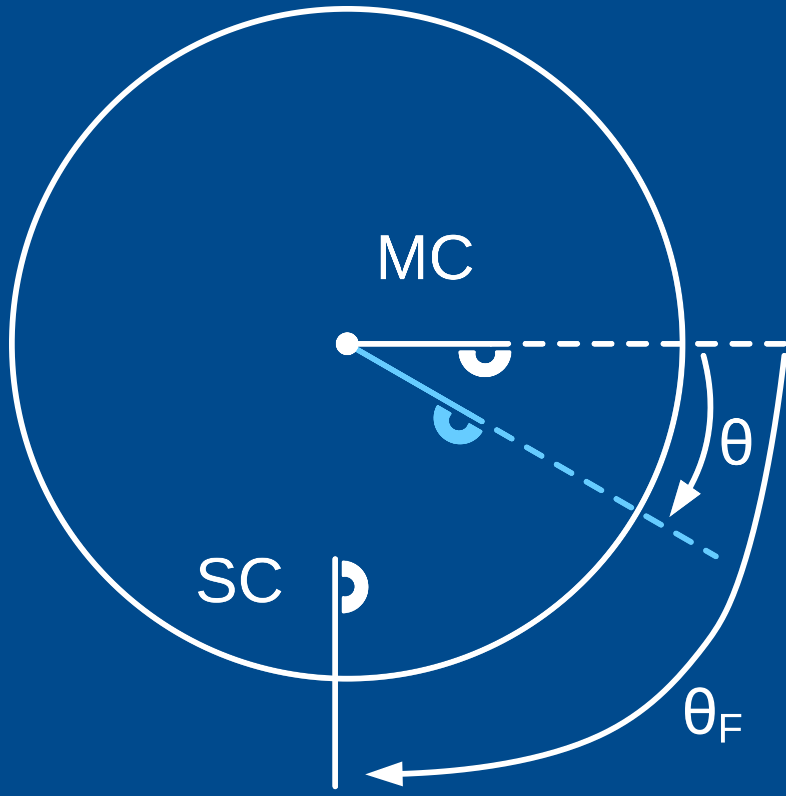
Pickup condition

$$K_e I_{pu}^2 \geq T_s$$

Pickup set by changing number of turns (TAP)

$$I_{pu} = \sqrt{T_s / K_e} = \sqrt{T_s / K'} / N_T$$

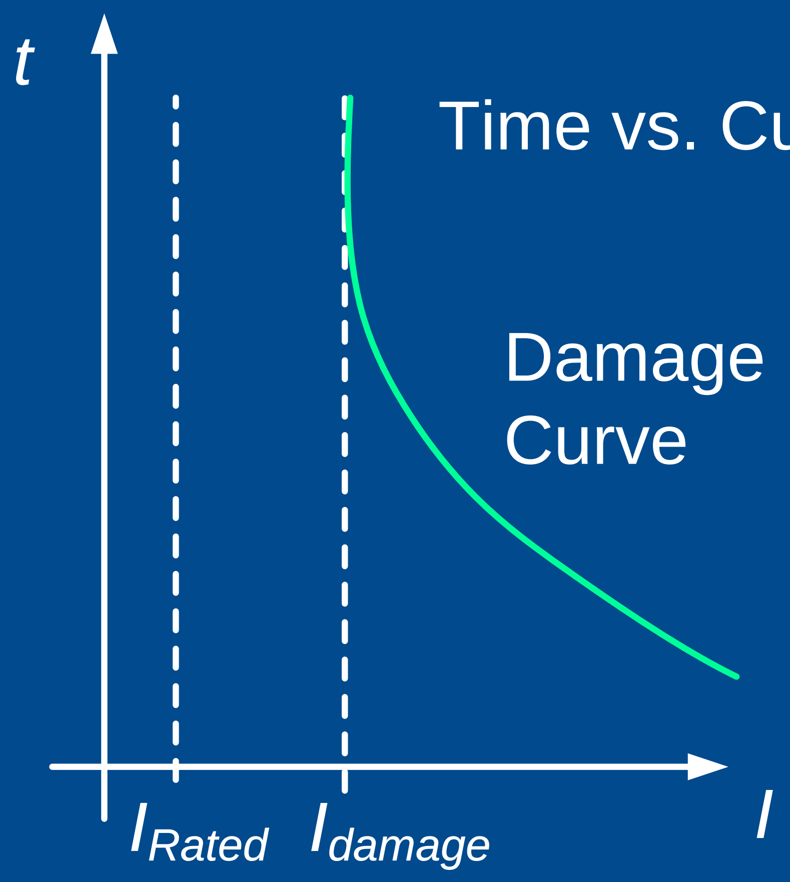
Induction Disc Relay Dynamics



Acceleration Torque

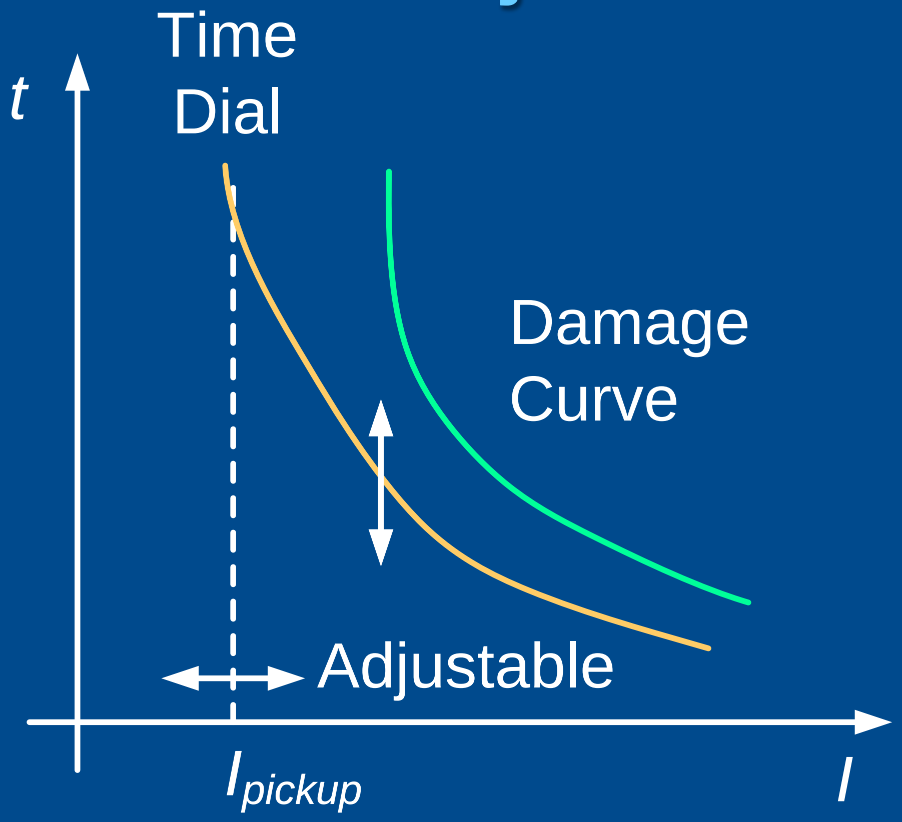
$$T_a = T_{op} - T_{pm} - T_s - T_f$$

High Current Can Damage Equipment
Thermal Damage Curve



Changing Induction Disc Operation Time

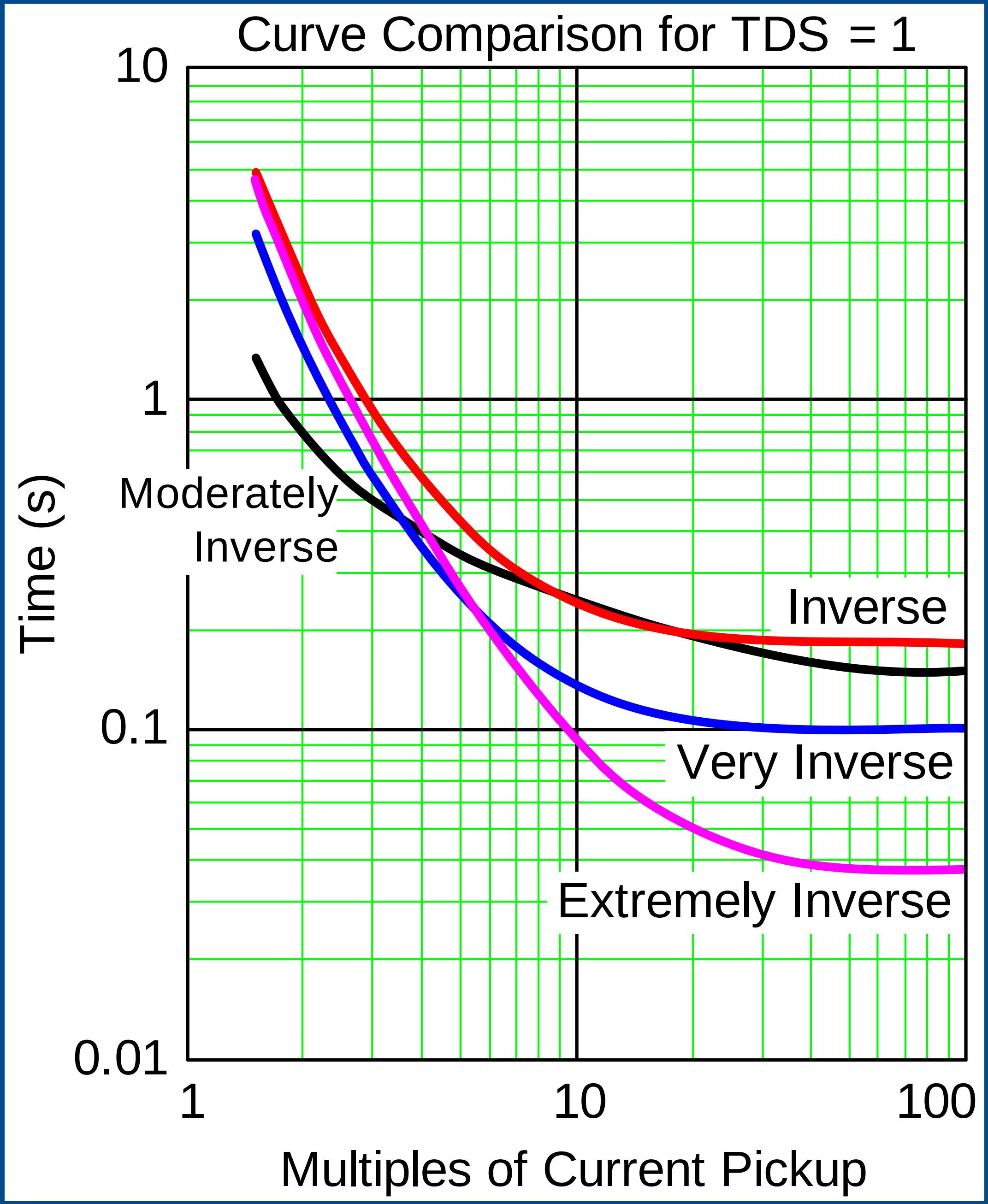
Adjustment of Time Curve



- Displacement of moving contact is adjustable
- Time dial sets total movement required to close contact

Select Overcurrent Relay Curve

Curve shape not adjustable for induction disc relays



Time-Current Characteristics Become Standard

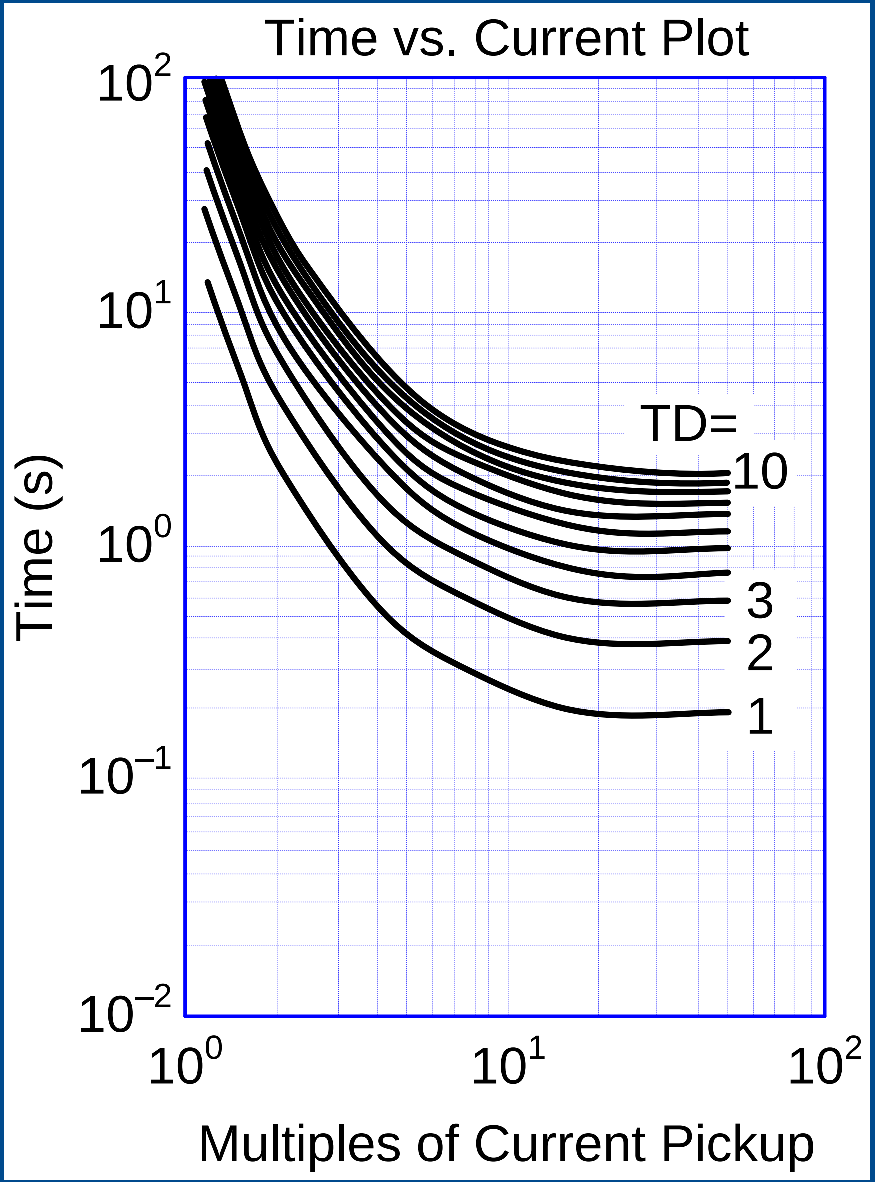
- IEEE C37.112-1996

$$t = TD \bullet \left(\frac{A}{M^P - 1} + B \right)$$

- IEC 225-4

$$t = TD \bullet \frac{A}{M^P - 1}$$

Family of IEEE Inverse Characteristics



U.S. inverse curve

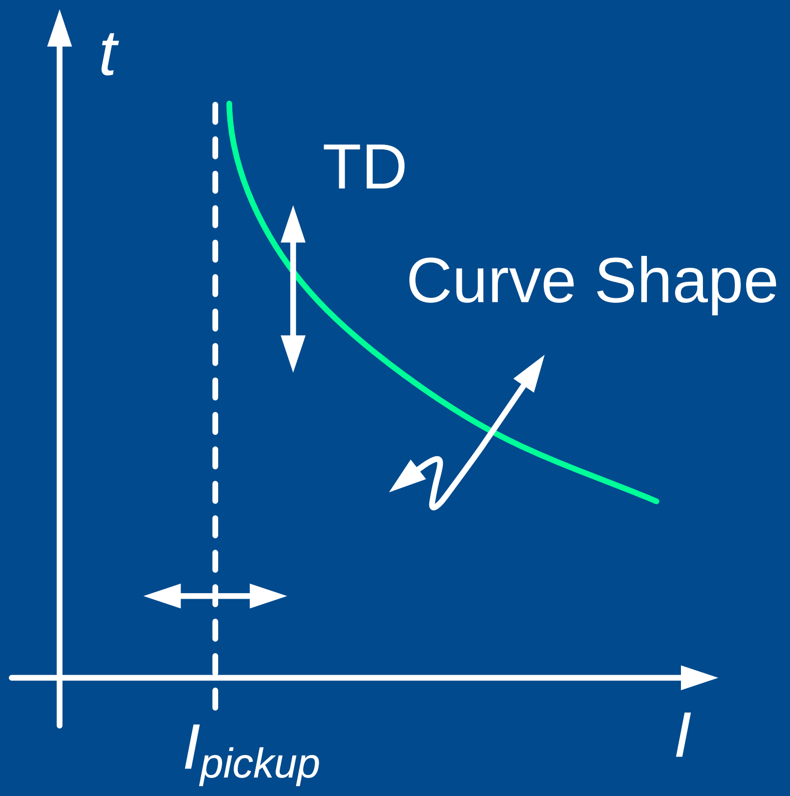
A = 5.95, P = 2, B = 0.18

$$t_{OP} = TD \bullet \left[\frac{5.95}{M^2 - 1} + 0.18 \right]$$

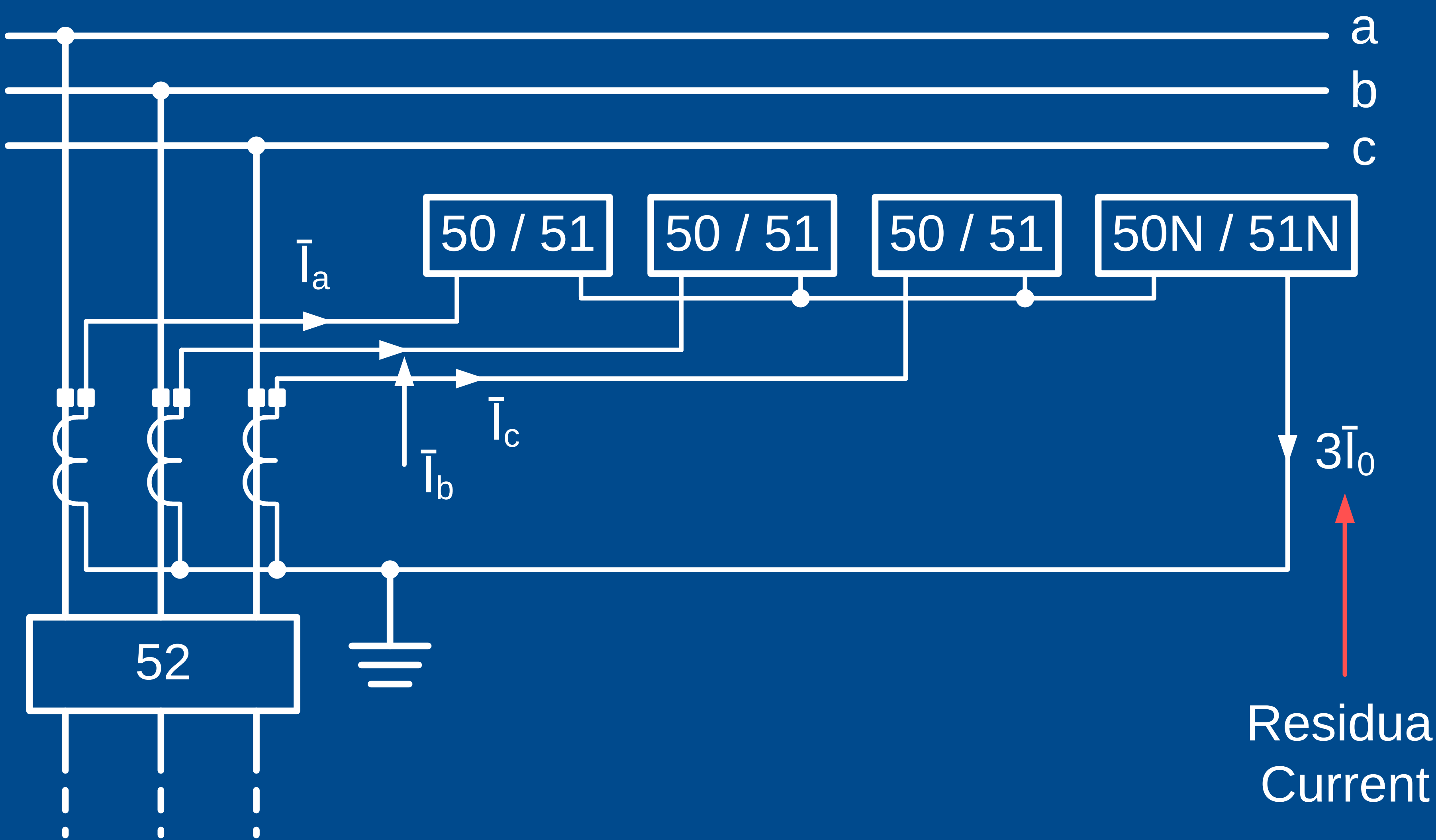
Increase Flexibility With Digital 51 Relays

Settings

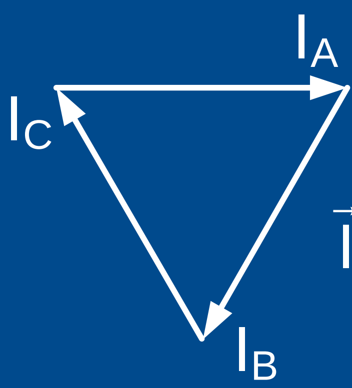
- Pickup current (or tap)
- Time-dial setting (TD)
- Curve shape – inverse, very inverse, etc.



Connecting Electromechanical Overcurrent Relays



Digital Relays Calculate Residual Current

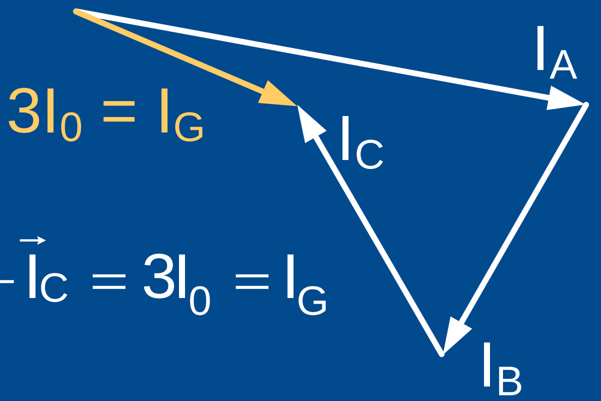


$$\vec{I}_A + \vec{I}_B + \vec{I}_C = 3I_0 = I_G = 0$$

Residual current for balanced load or three-phase faults

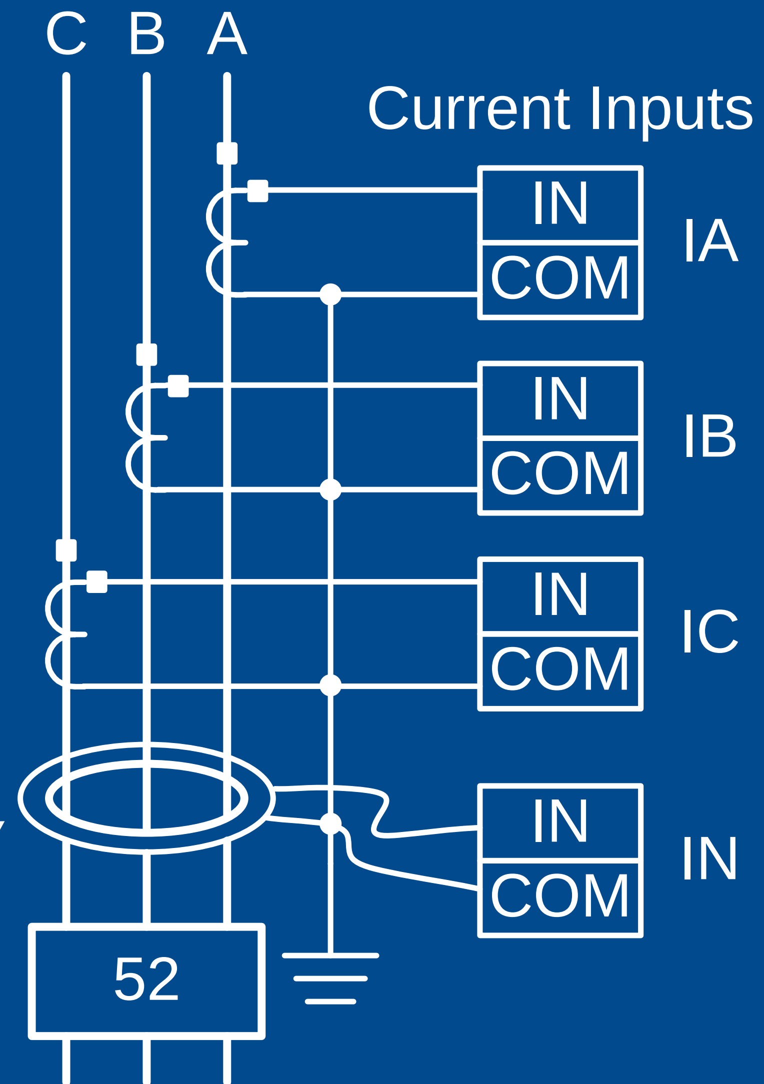
Residual current for ground fault

$$\vec{I}_A + \vec{I}_B + \vec{I}_C = 3I_0 = I_G$$



Using Zero-Sequence CT for Ground Fault Protection


Photo courtesy of NEI Electric Power Engineering

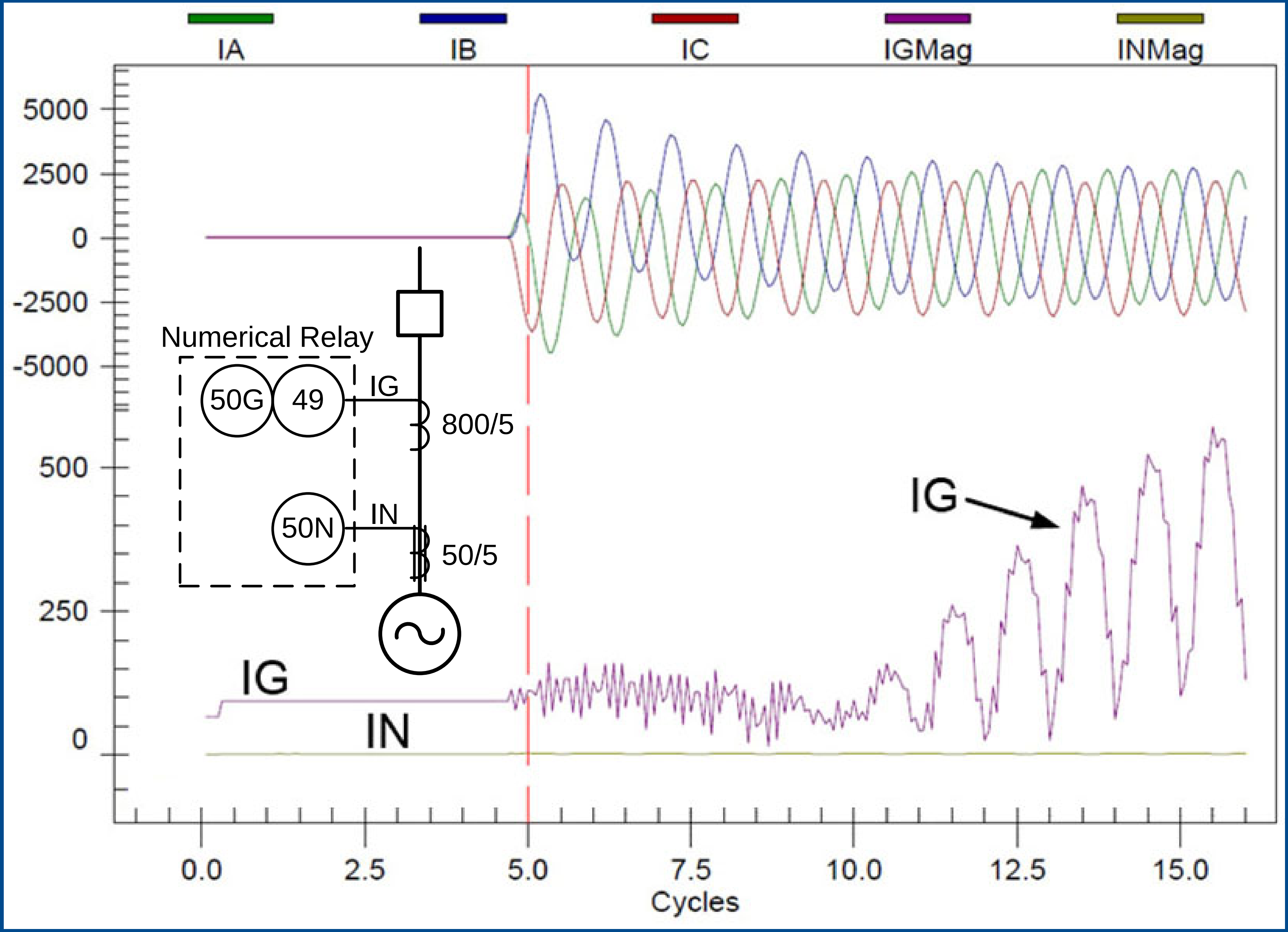


Zero-sequence or core-balance CT

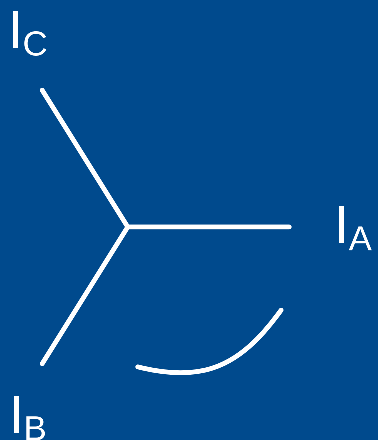
High Residual Current Due to CT Saturation

- Residual settings must be higher than elements operating from zero-sequence CTs
- Residual elements may not be appropriate for motors
- Zero-sequence CTs not subject to this problem

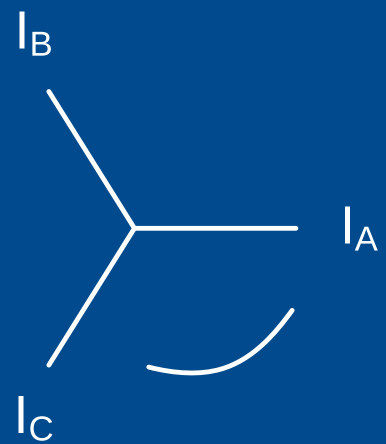
15,000 HP Motor Trips on Start



What Are Negative-Sequence Quantities?



Positive Sequence



Negative Sequence

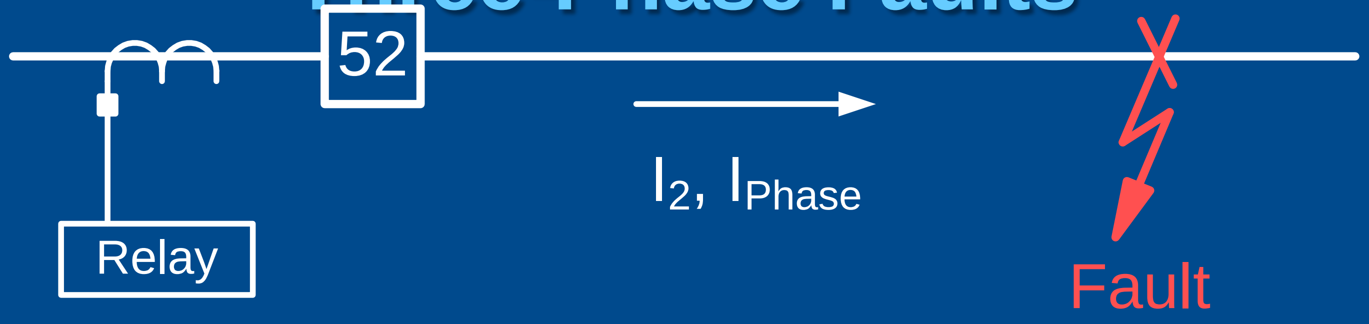
- Unbalanced load
- Rolled phases
- Open phases
- Unbalanced faults

$$3I_2 = I_A + a^2 I_B + a I_C$$

$$\text{where } a = 1\angle 120°$$

Negative-Sequence Element Response

Three-Phase Faults



$$I_A = 1\angle 0^\circ \qquad I_B = 1\angle -120^\circ \qquad I_C = 1\angle 120^\circ$$

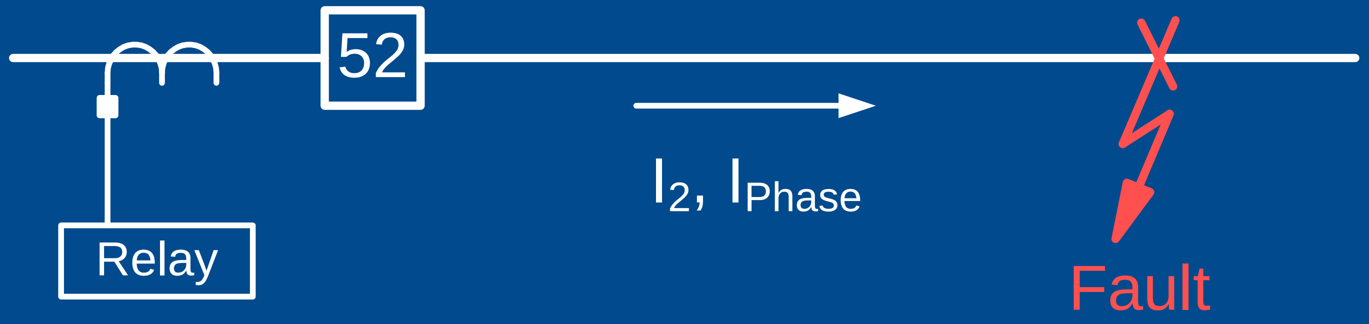
$$3I_2 = I_A \quad + \quad a^2 I_B \quad + \quad aI_C$$

$$= 1\angle 0^\circ \; + 1\angle 240^\circ \bullet 1\angle -120^\circ \; + \; 1\angle 120^\circ \bullet 1\angle 120^\circ$$

$$= 0$$

Negative-Sequence Element Response

Phase-to-Phase Faults



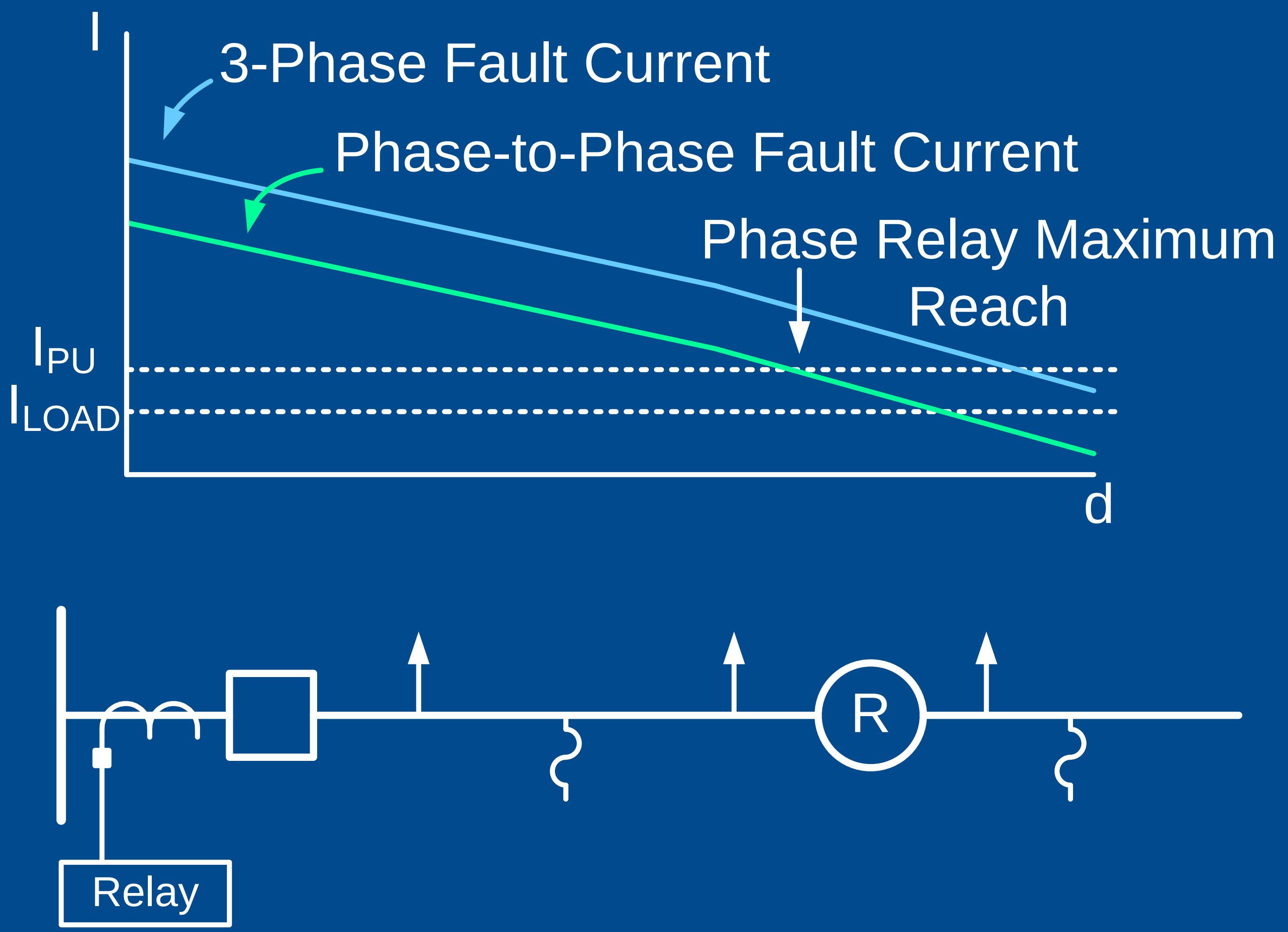
$$I_A = 0 \qquad I_B = 1\angle 0° \qquad I_C = 1\angle 180°$$

$$3I_2 = I_A + a^2 I_B + aI_C$$

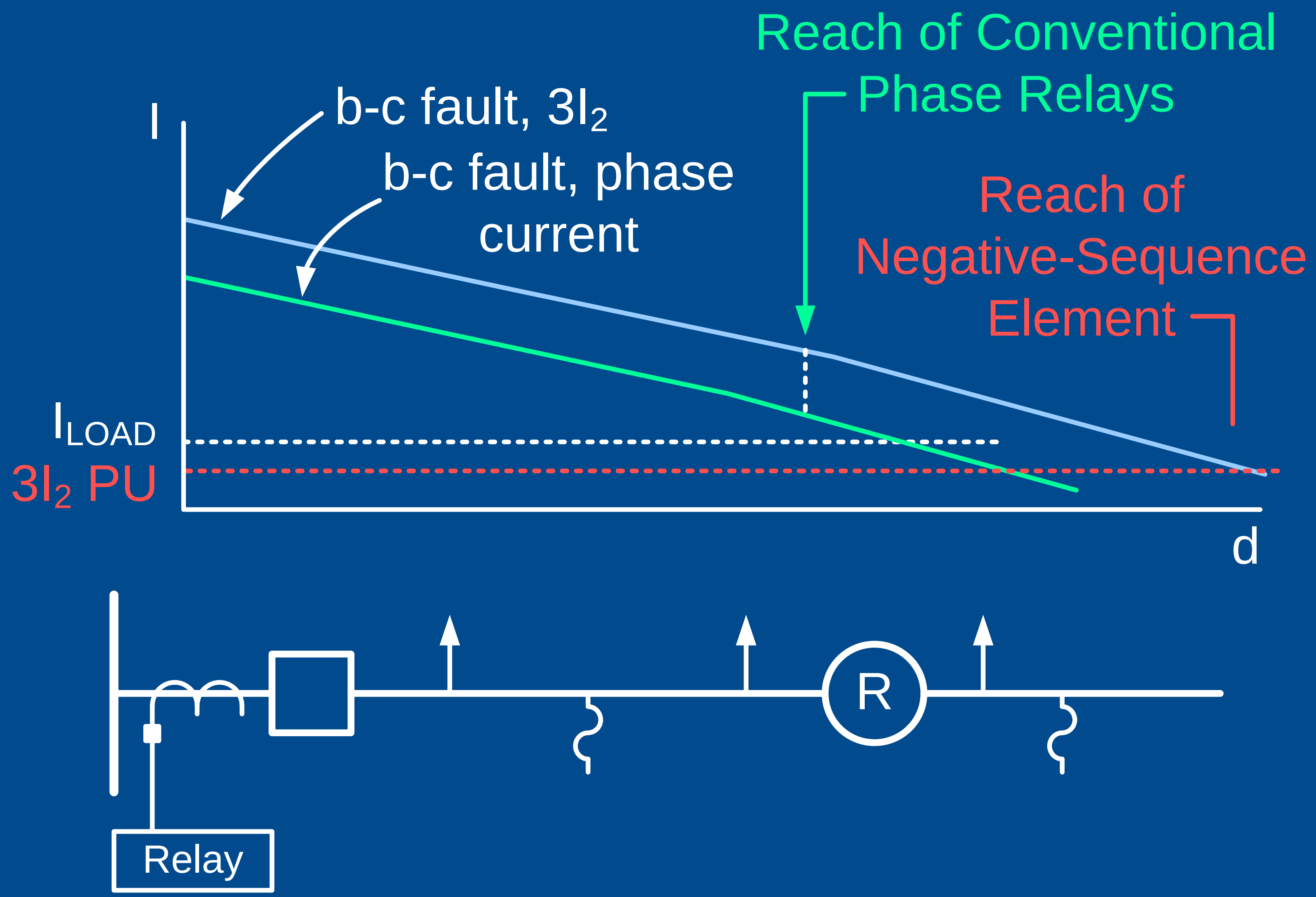
$$= 0 + 1\angle 240° \cdot 1\angle 0° + 1\angle 120° \cdot 1\angle 180°$$

$$= 1.73\angle -90°$$

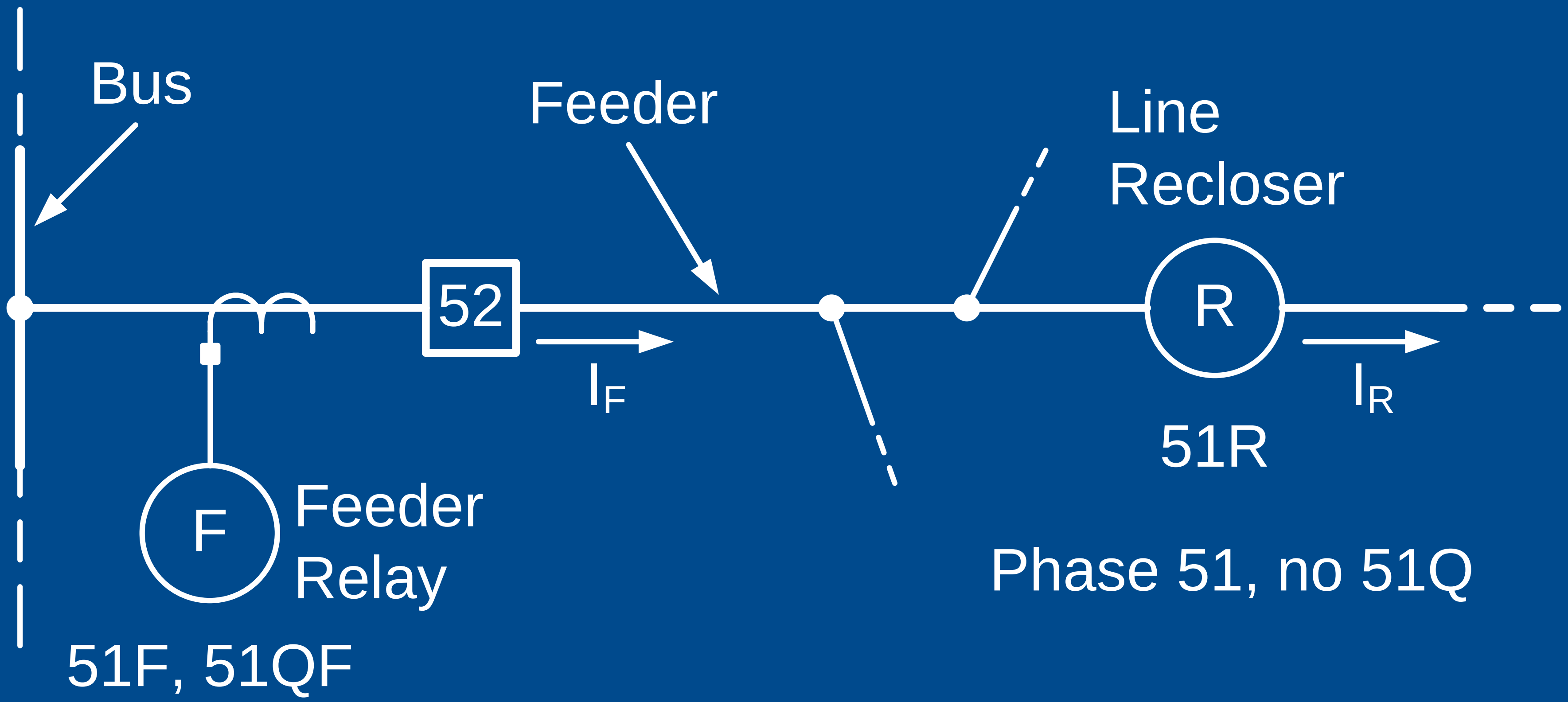
Maximum Load vs. Minimum Short Circuit



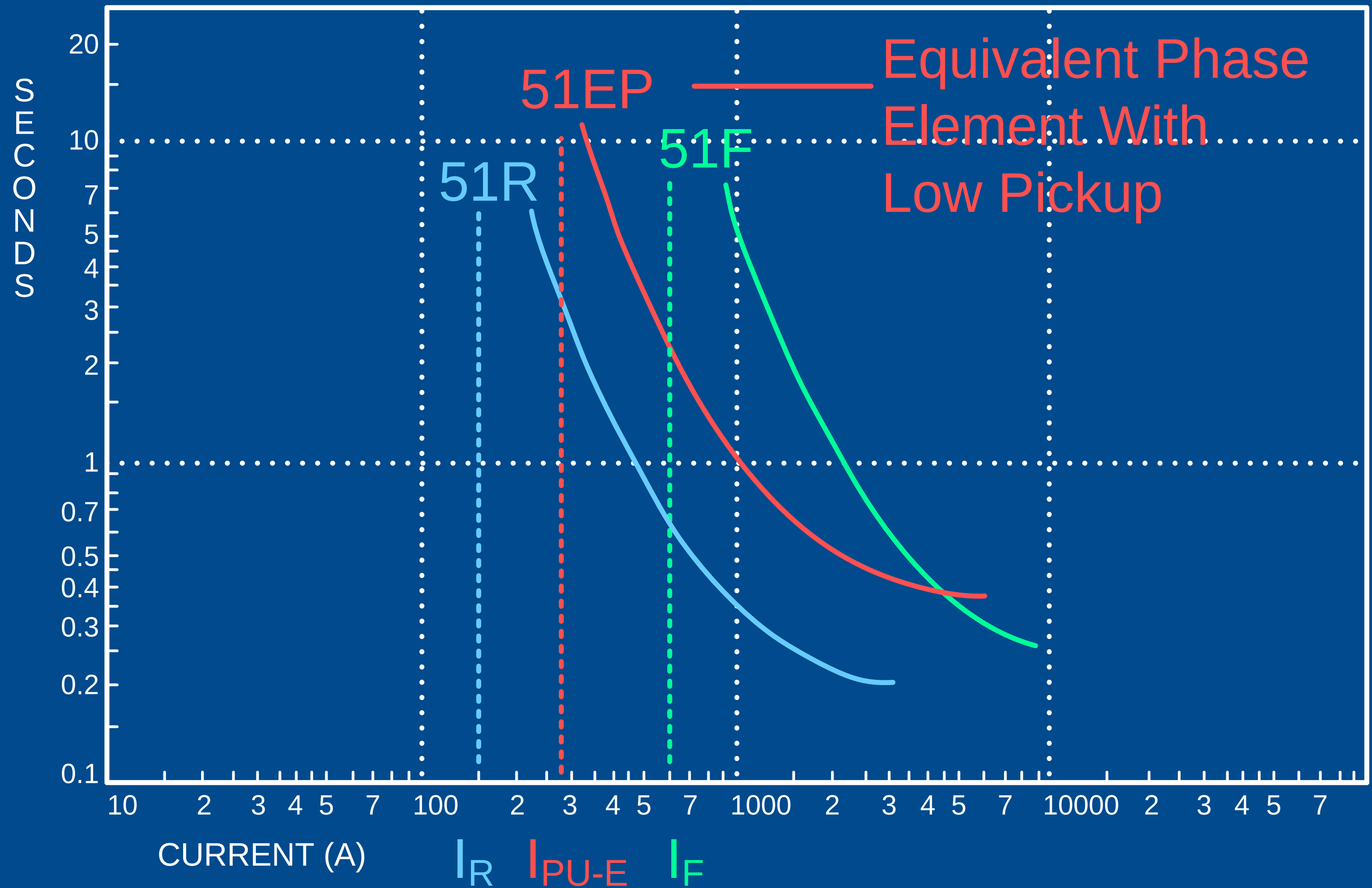
Sensitive Protection With Negative-Sequence Elements



Coordinating Negative-Sequence Elements



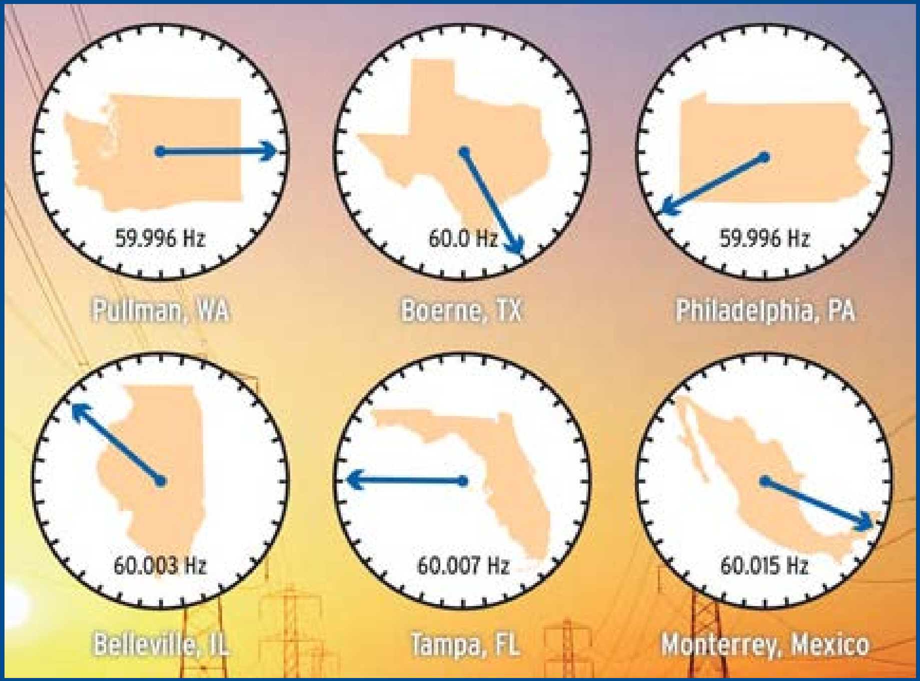
Traditional Phase Coordination Plus Negative Sequence



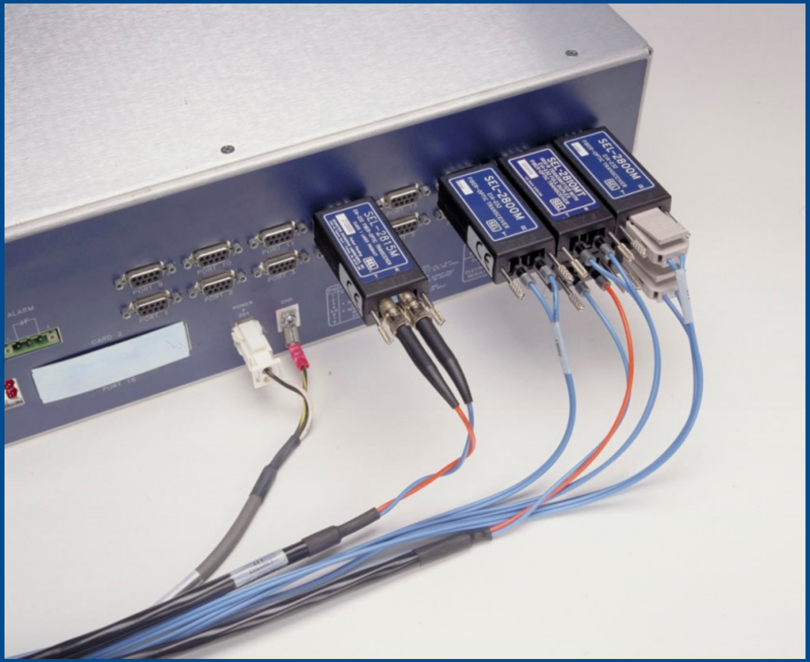
Set Negative-Sequence Element Pickup

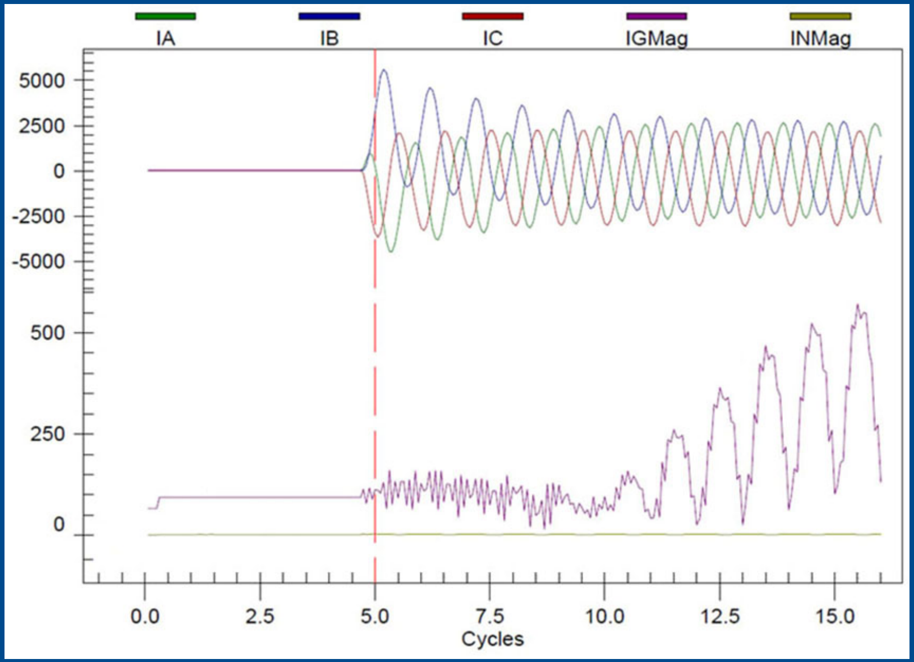
$$51Q\ \text{pickup} = \sqrt{3} \bullet (51EP\ \text{pickup})$$

Negative-sequence element is faster and more sensitive than phase overcurrent element for phase-to-phase faults



Protection Plus …



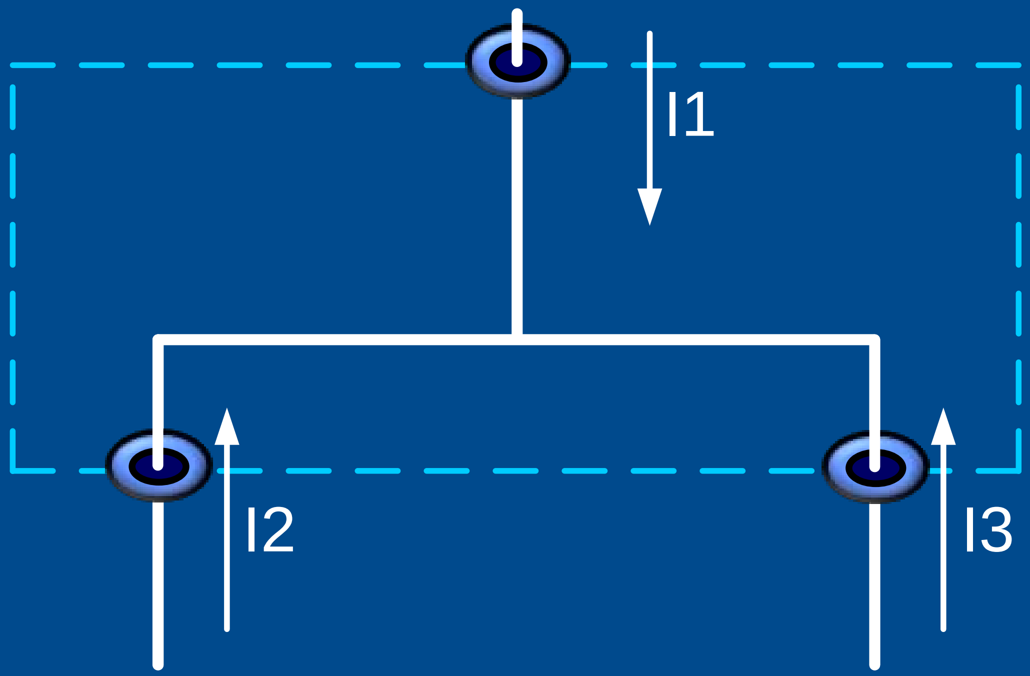


Questions?

Transformer Protection Basics

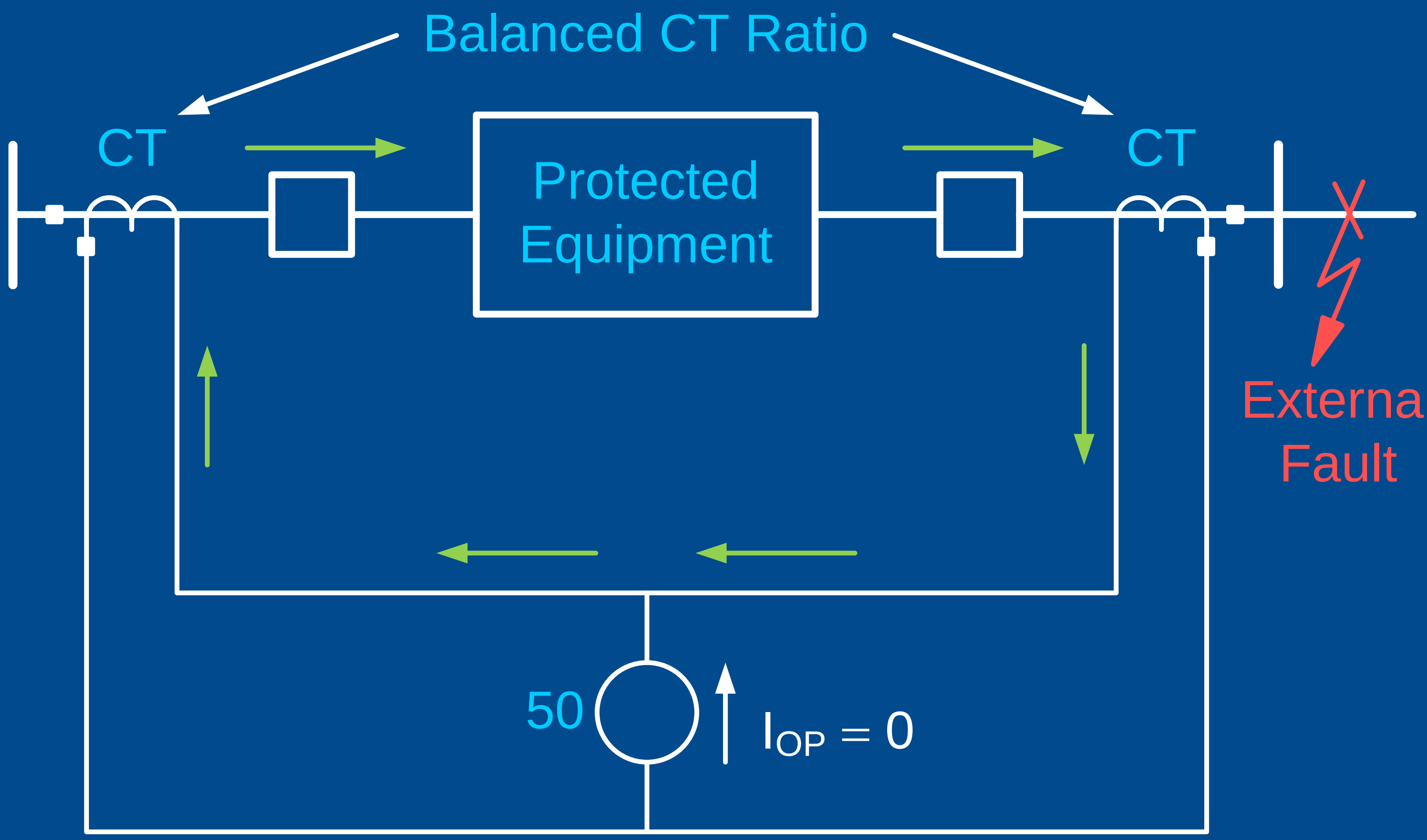
TECHNOLOGY EXCHANGE
Learn. Connect. Solve.

Differential Protection Is Easy in Theory



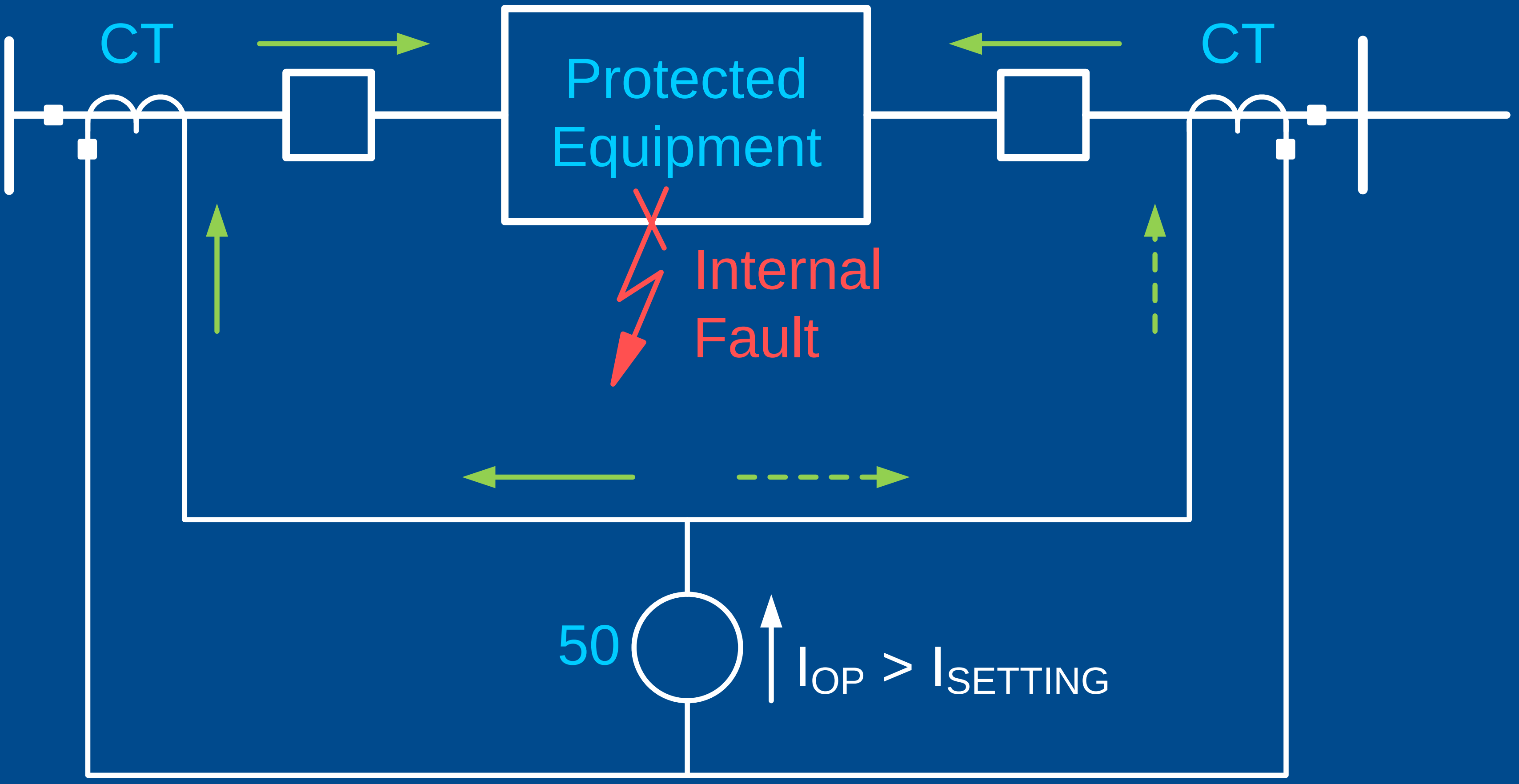
Kirchhoff's Current Law (KCL): $\sum_{k=1}^{n} I_k = 0$

Current In = Current Out



No Relay Operation if CTs Are Considered Ideal

Operate Current Flows

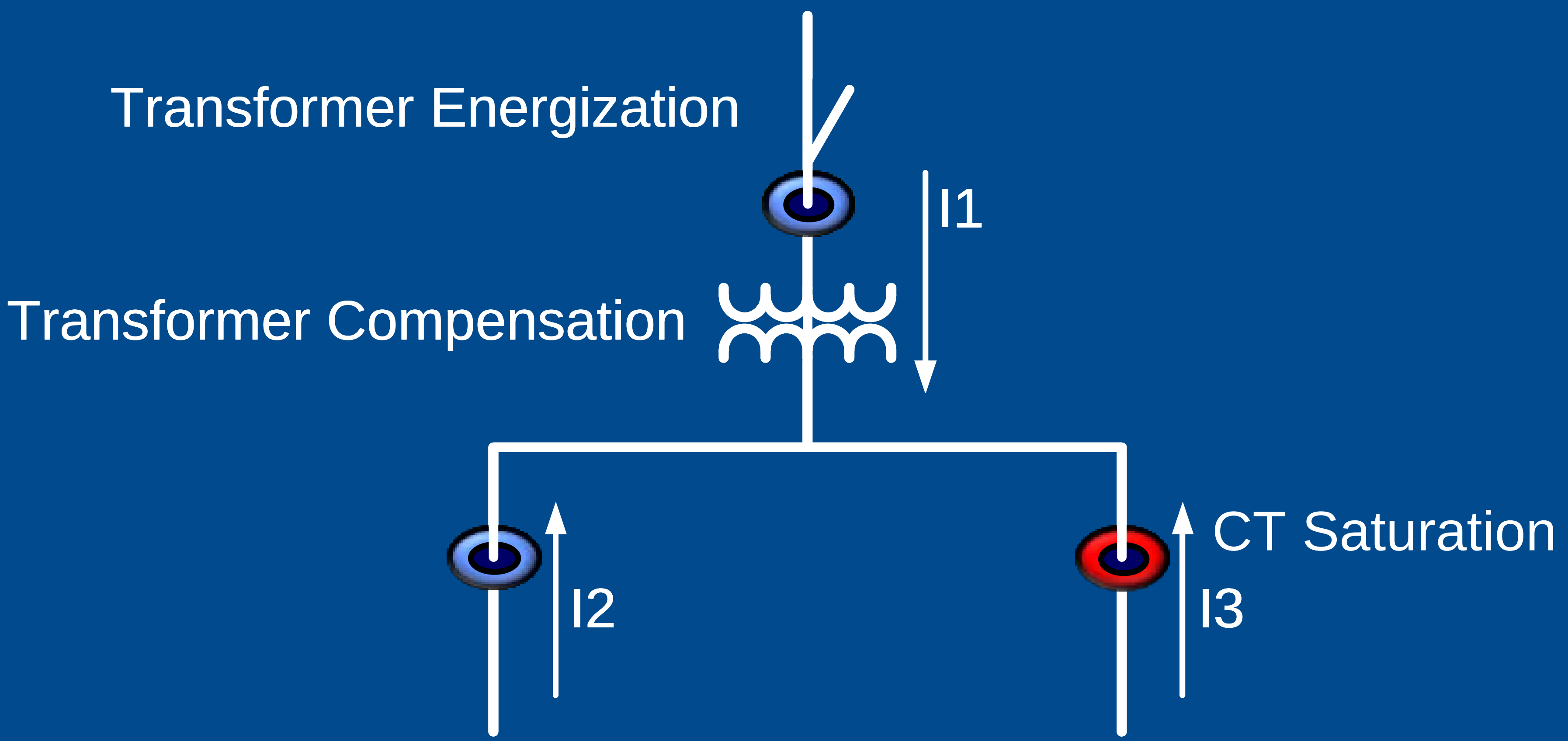


Relay Operates

Differential Scheme Objective

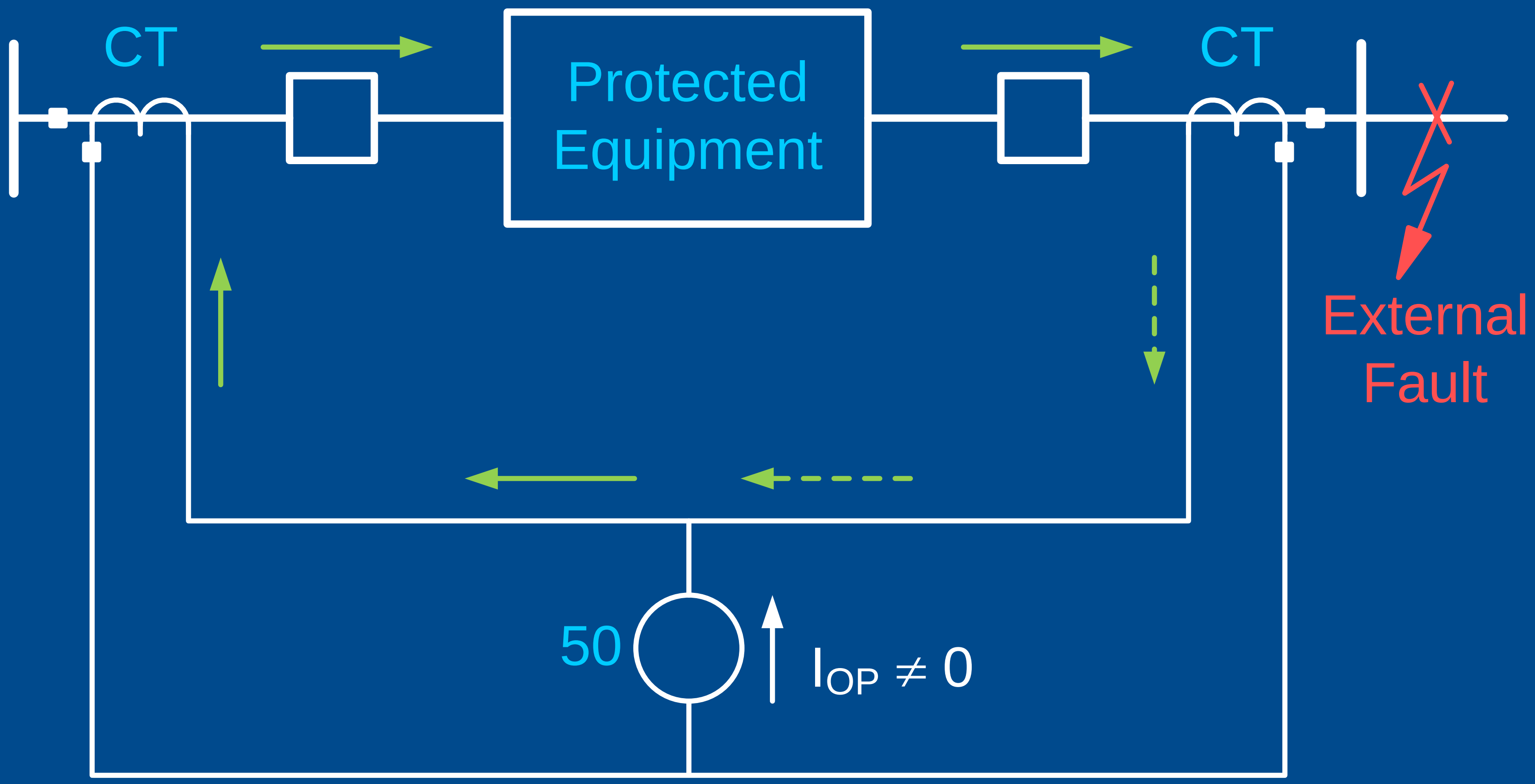
- Provide security during through faults
- Operate fast for internal faults

What Makes Differential Protection Challenging?

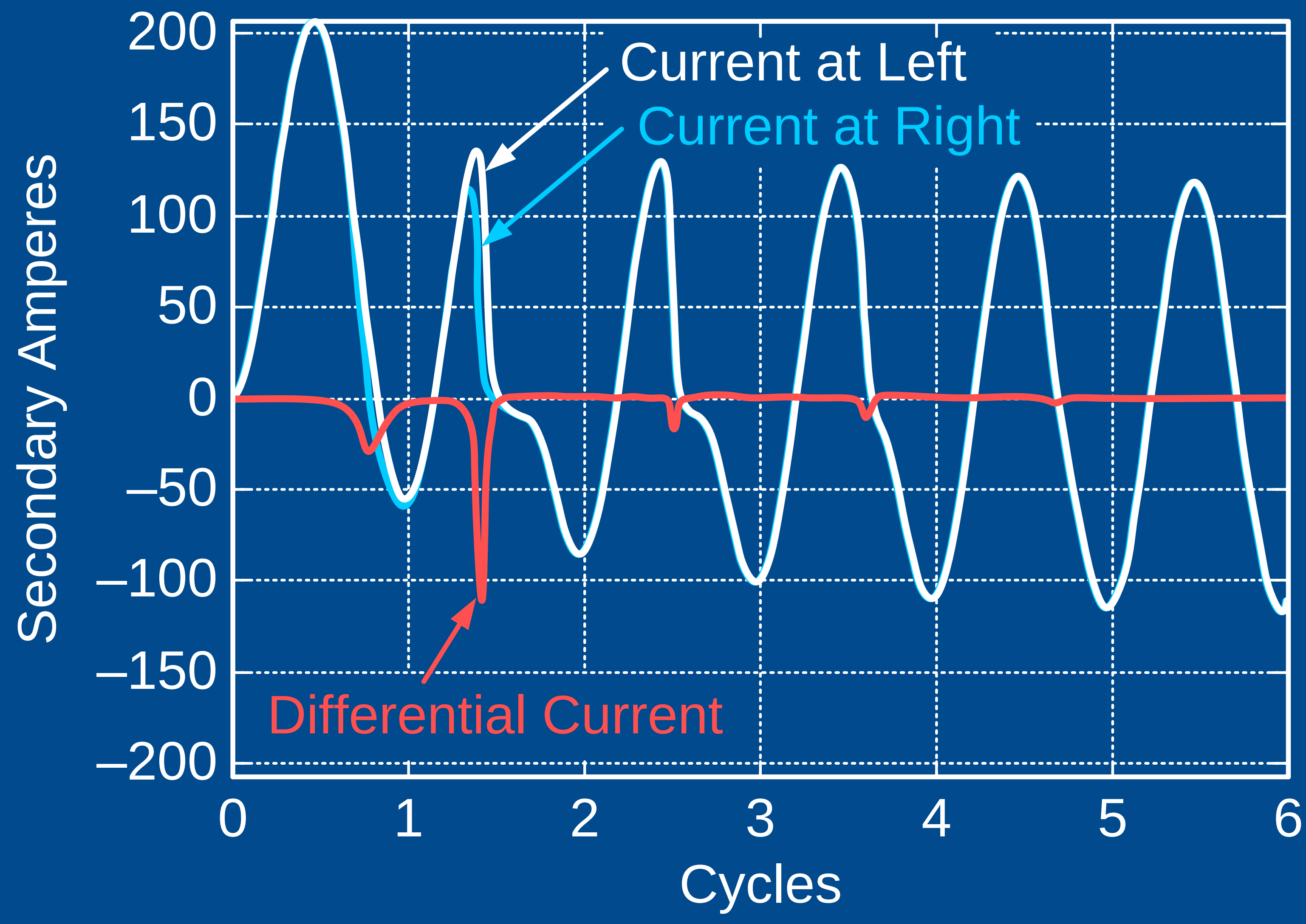


Examine CT Saturation Challenges

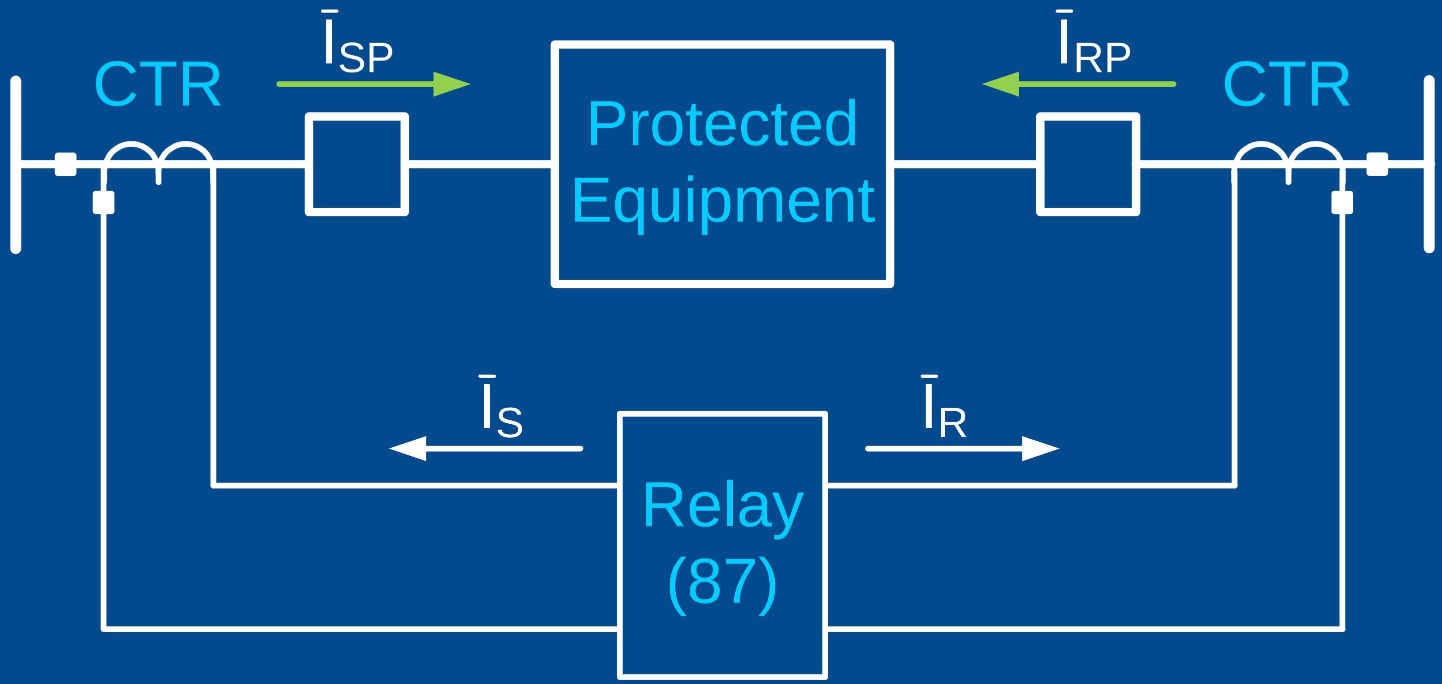
Unequal CT Performance Problems



Unequal CT Saturation



Possible Scheme – Percentage Differential Protection Principle

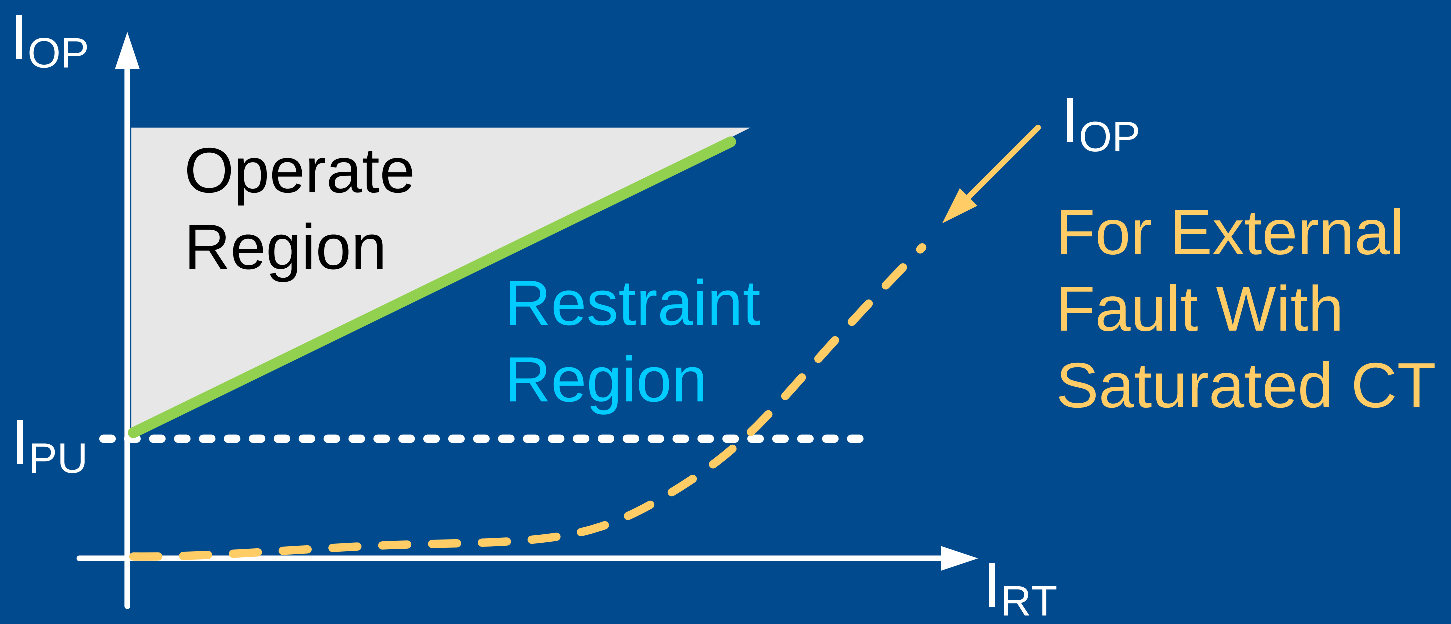


Compares:

$$\begin{cases} I_{OP} = \left|\bar{I}_S + \bar{I}_R\right| \\ k \bullet I_{RT} = k \bullet \dfrac{\left|\bar{I}_S\right| + \left|\bar{I}_R\right|}{2} \end{cases}$$

Differential Element

Differential Characteristic Basics

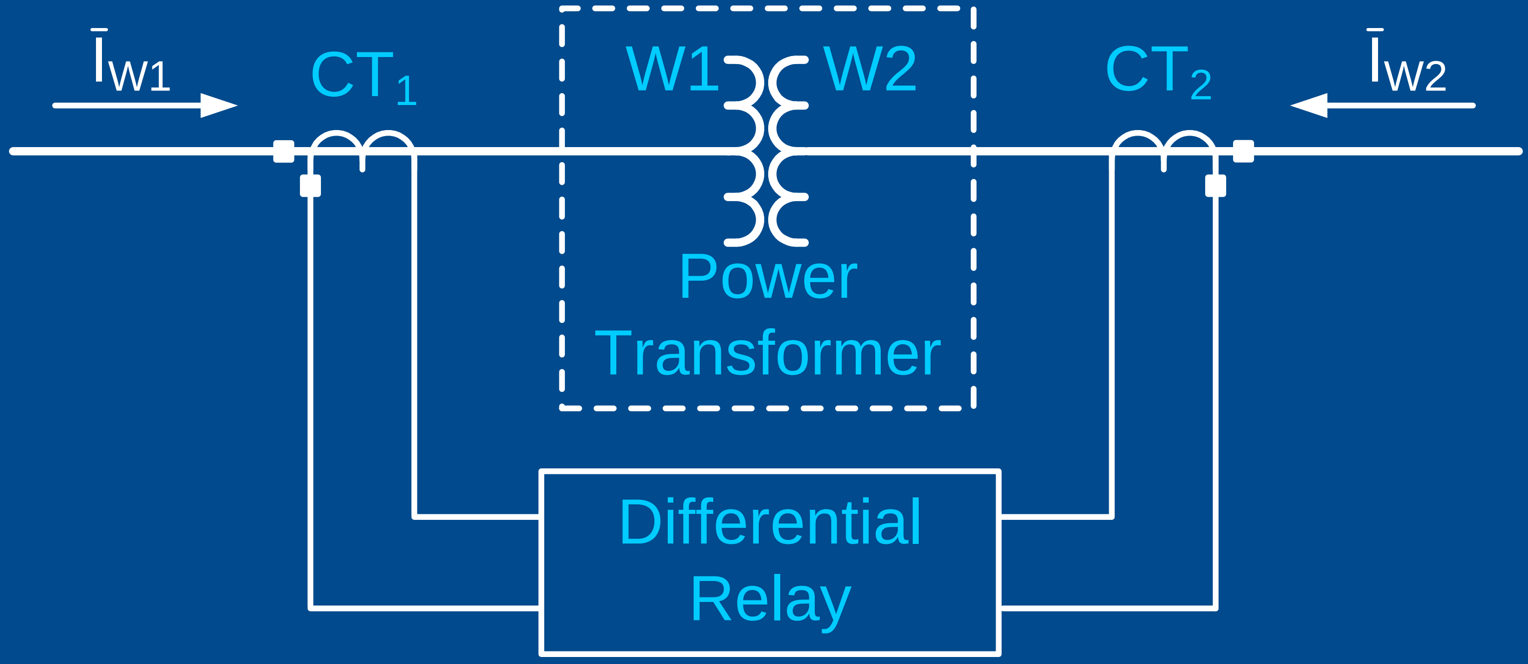


Relay Operates When:

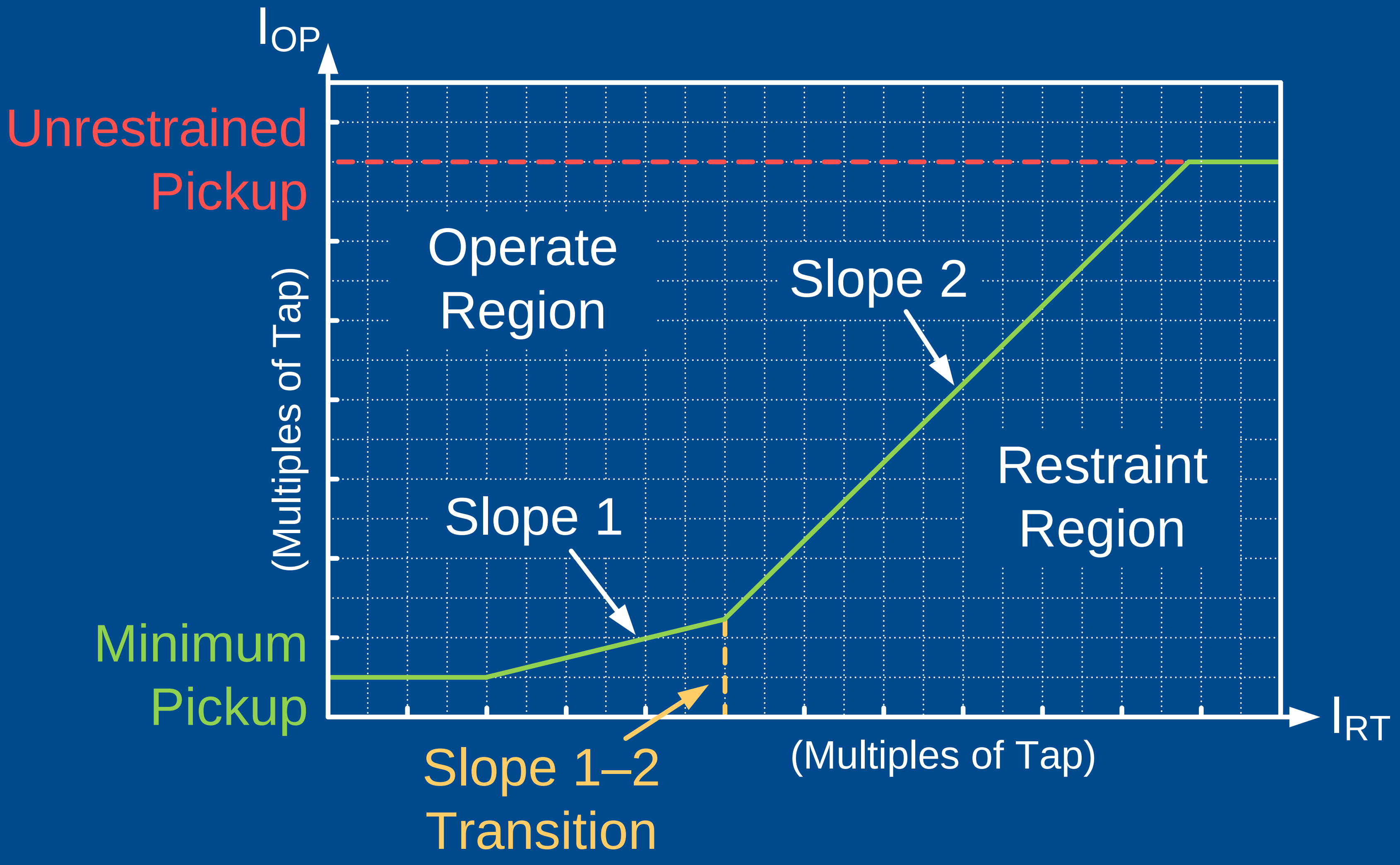
$$\left| I_{OP} \right| \geq k \bullet I_{RT} + I_{PU}$$

Percentage Differential Relays

I_{OP} Versus I_{RT}



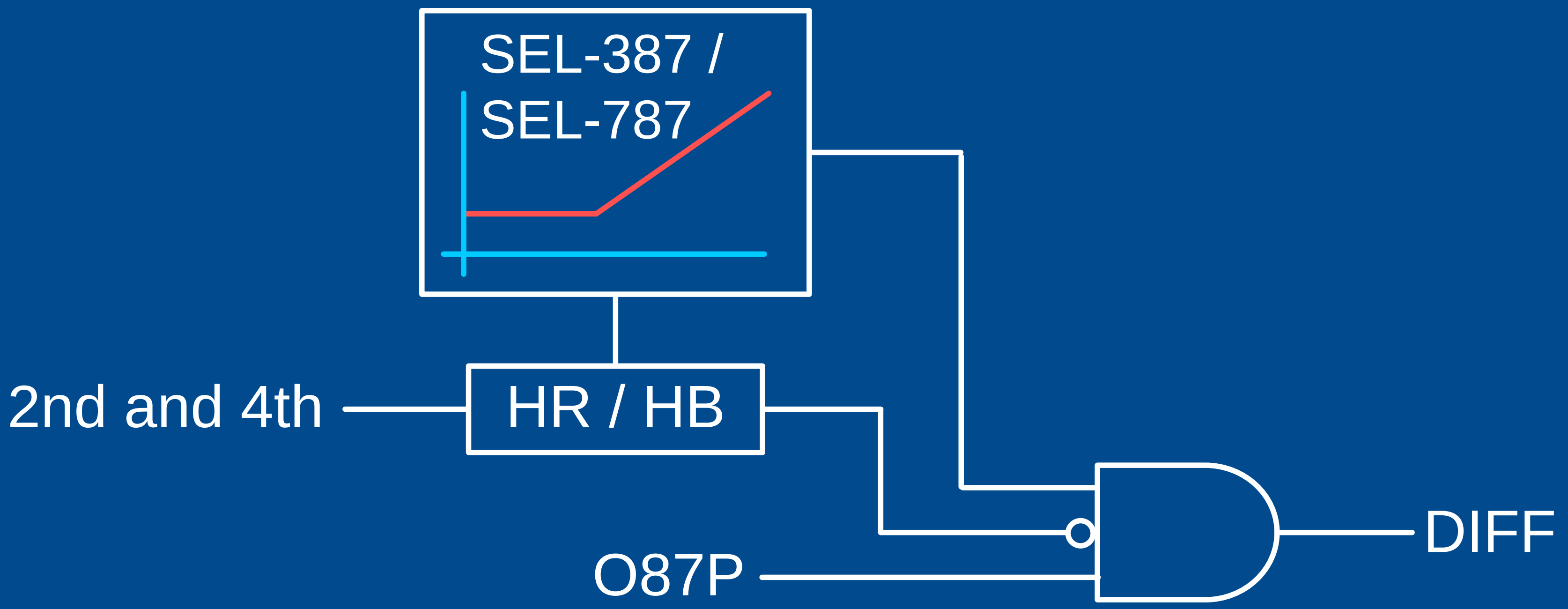
Dual-Slope Characteristic



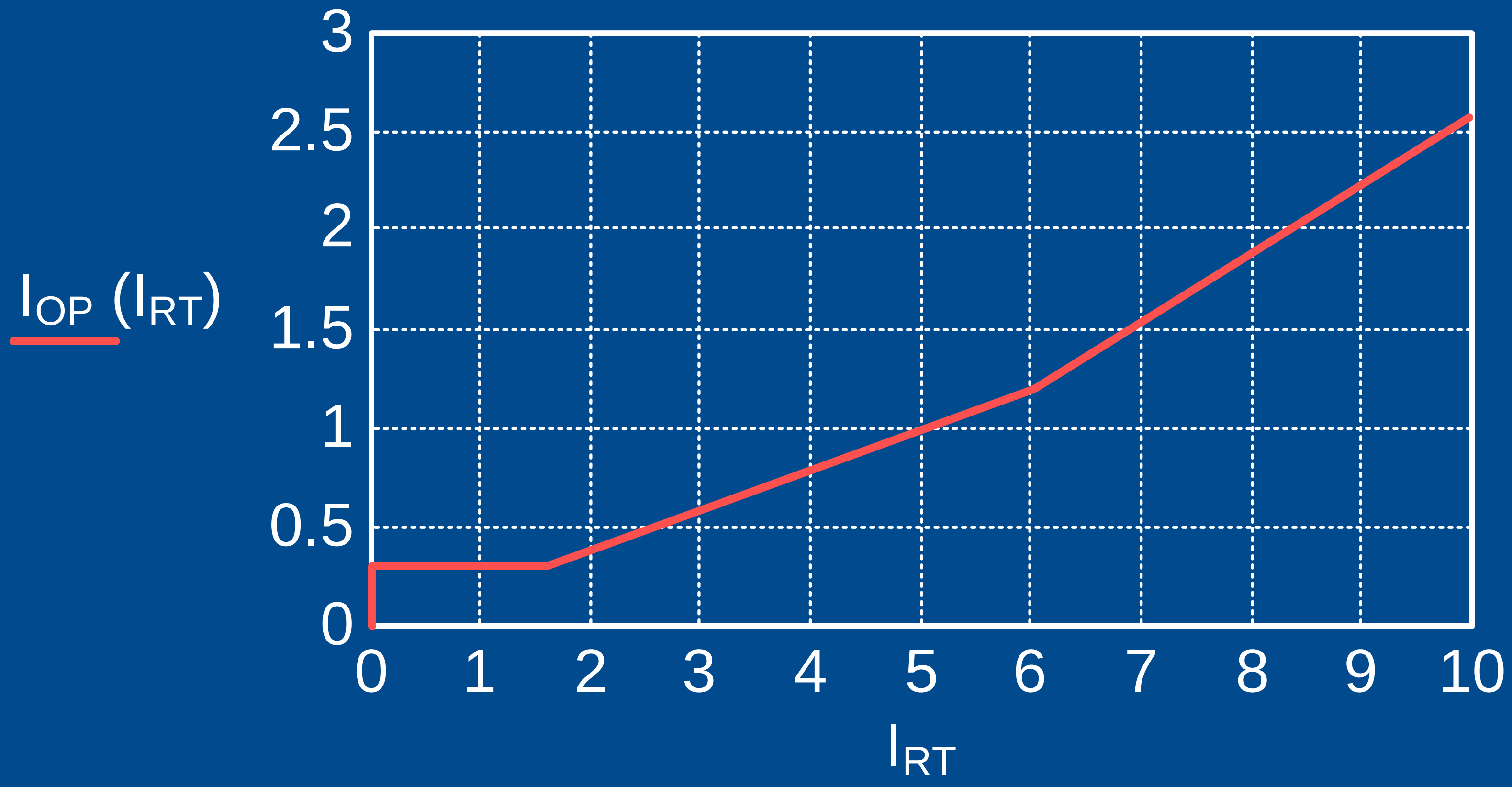
How to Set Slope Characteristic Settings

- Load tap changer (10%)
- No-load tap changer (5%)
- Measuring relay error (< 5%)
- CT errors (1 to 10%)
- Transformer excitation (3 to 4%)

SEL-387 / SEL-787 Logic



SEL-387 / SEL-787 Slope

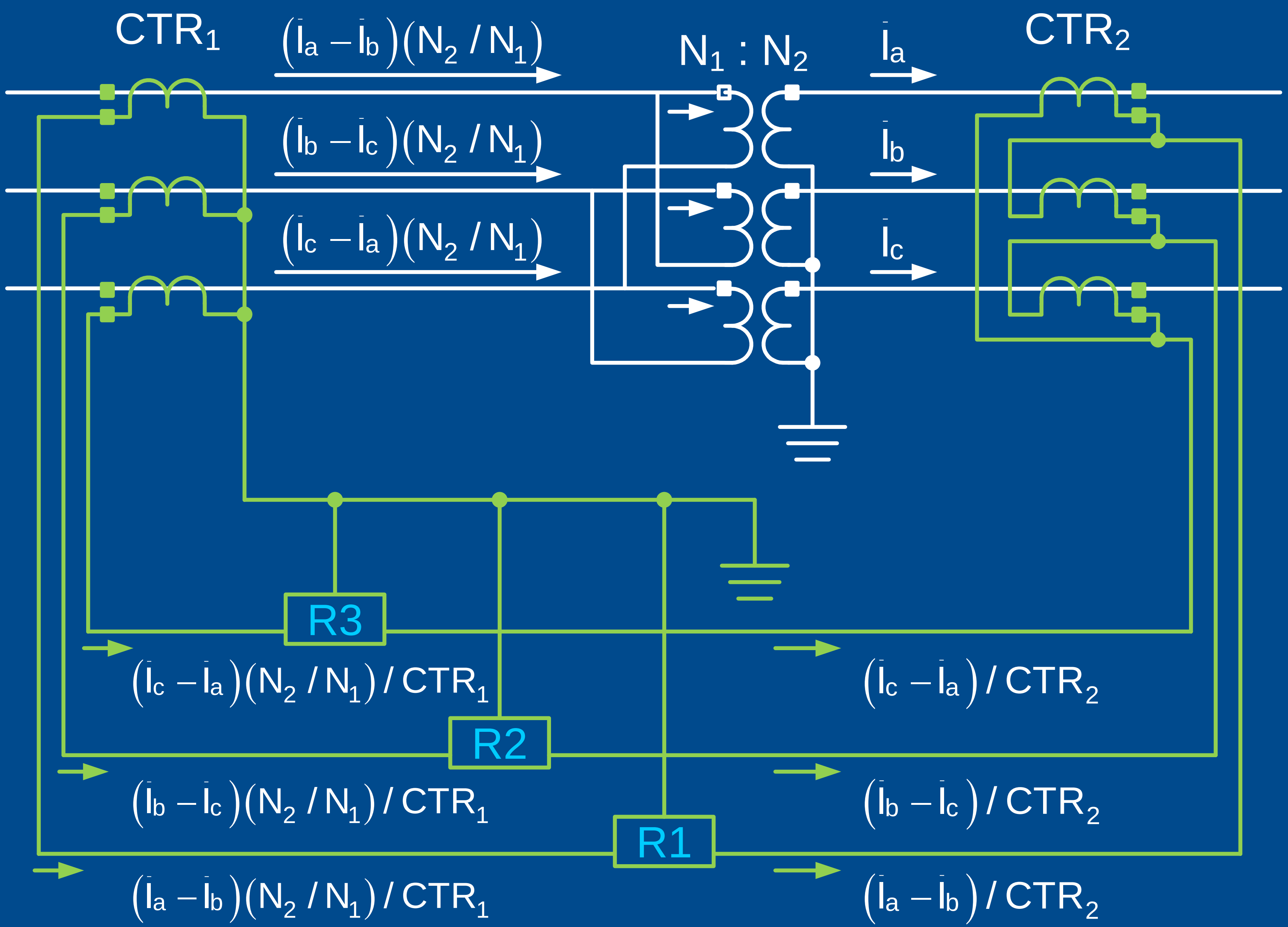


Examine Transformer Compensation Challenges

Transformer Connection Compensation

Phase Shift (Degrees)	Connections		
0	Yy0	Dd0	Dz0
30 lag	Yd1	Dy1	Yz1
60 lag	Dd2	Dz2	
120 lag	Dd4	Dz4	
150 lag	Yd5	Dy5	Yz5
180 lag	Yy6	Dd6	Dz6
150 lead	Yd7	Dy7	Yz7
120 lead	Dd8	Dz8	
60 lead	Dd10	Dz10	
30 lead	Yd11	Dy11	Yz11

Traditional Compensation Method



Compensation With Digital Relays

- Current magnitude and phase shift compensation
- Set relay according to transformer characteristics
- Consider all possible connections

Tap Compensation

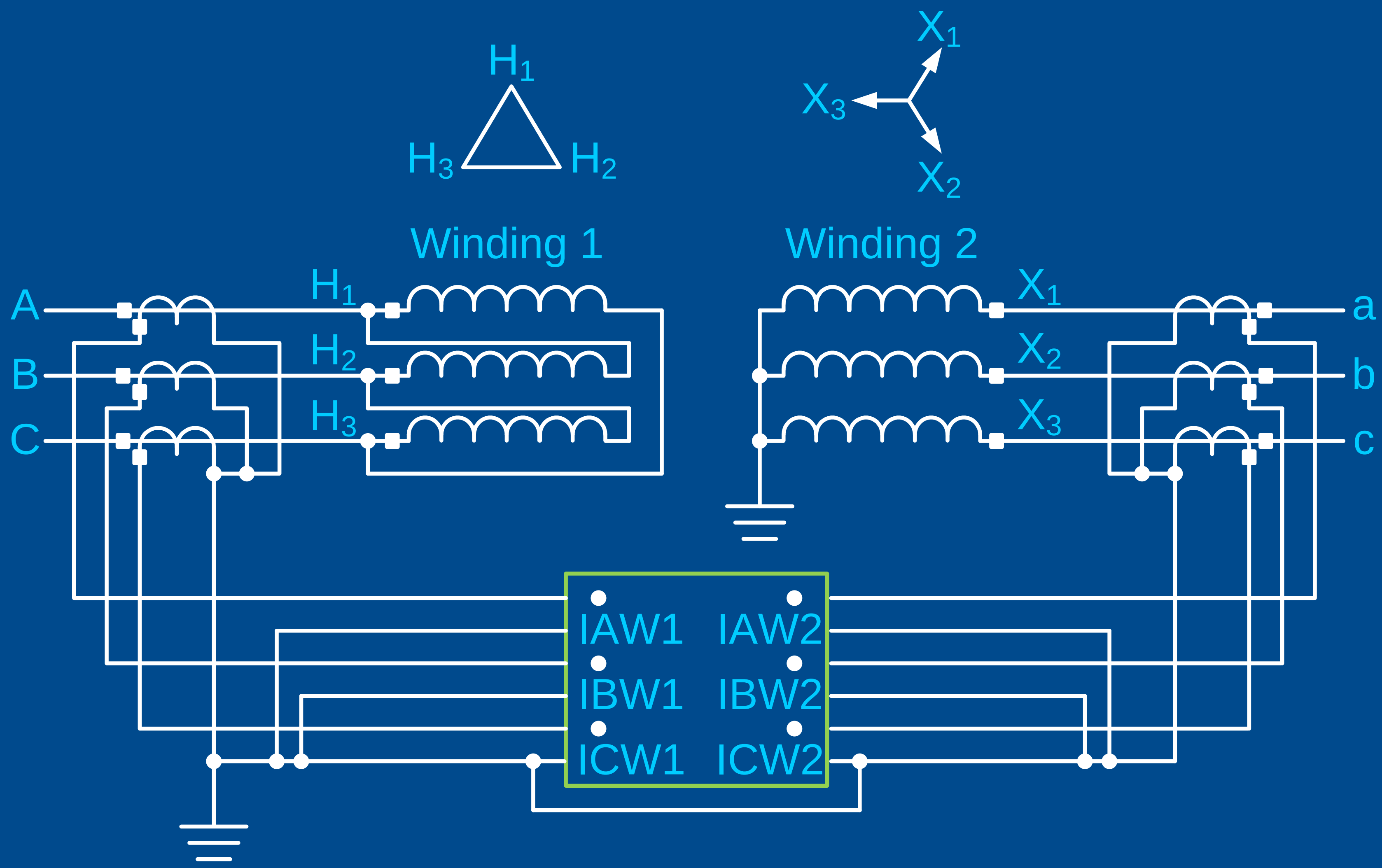
$$TAP = \frac{MVA \bullet 1000 \bullet C}{\sqrt{3} \bullet KV_{LL} \bullet CTR}$$

where:

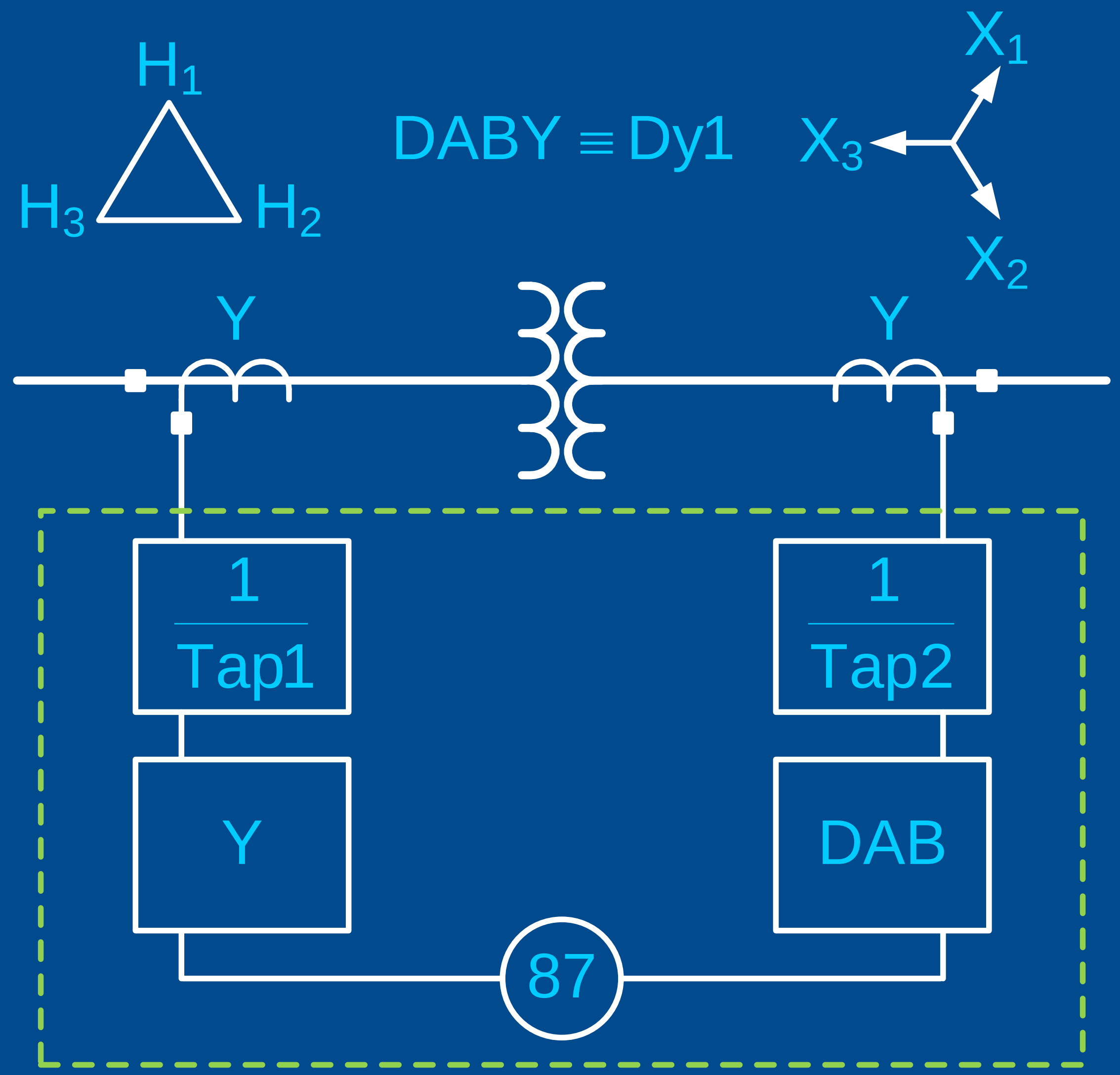
C = 1 for wye-connected CTs

$C = \sqrt{3}$ for delta-connected CTs

Simpler and Better Connections

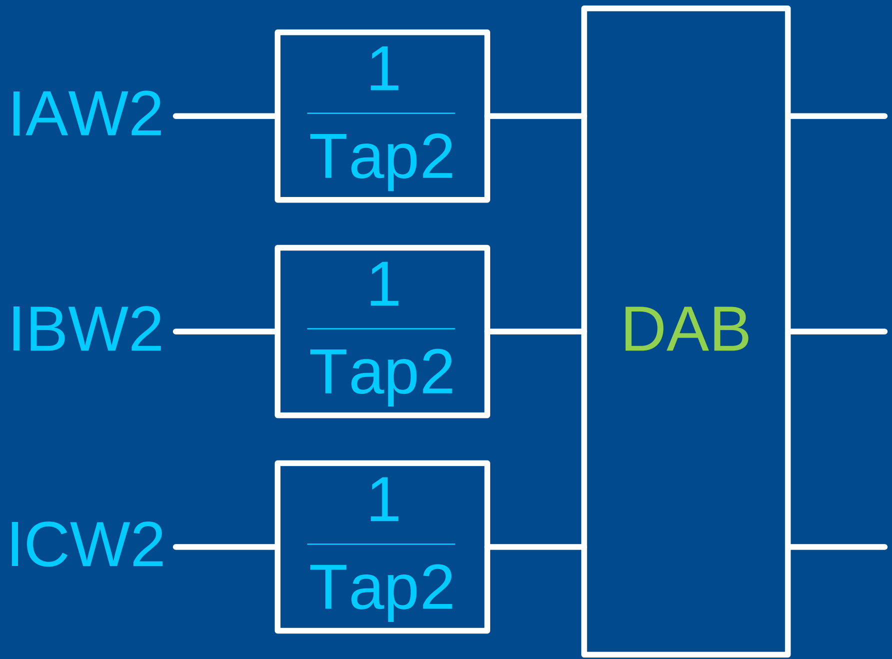


DABY Transformer and CT Connection Compensation



Wye Connection Compensation

DAB Connection Compensation

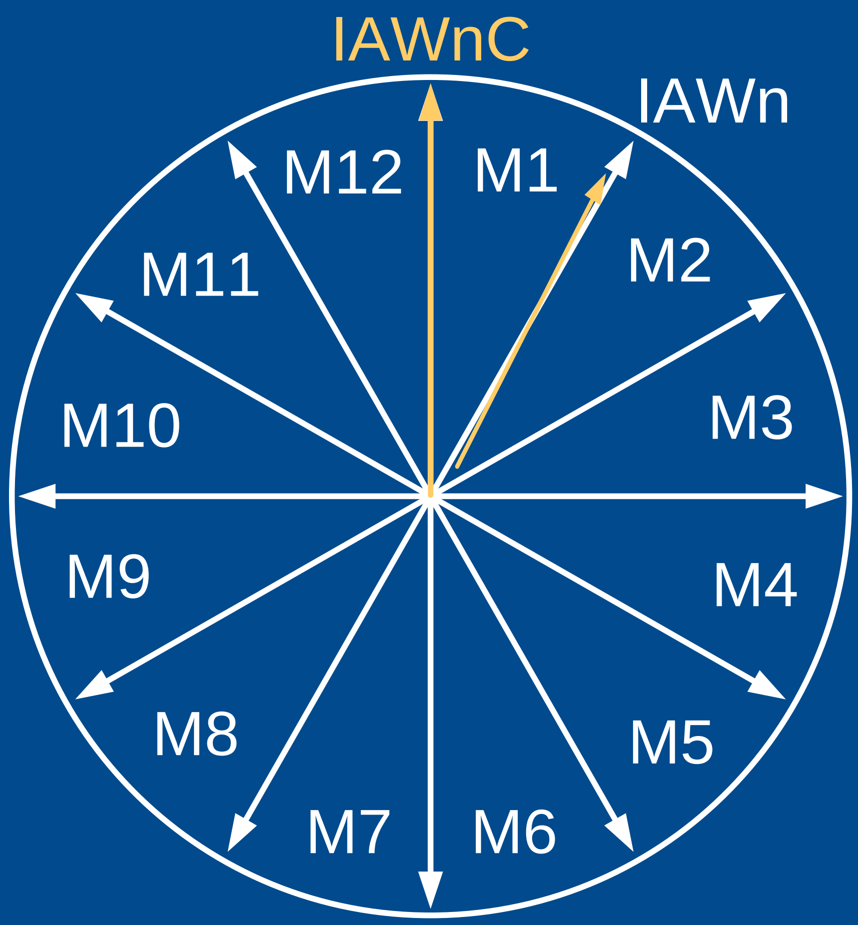


$$I1W2C = \frac{1}{Tap2} \bullet \frac{(IAW2 - IBW2)}{\sqrt{3}}$$

$$I2W2C = \frac{1}{Tap2} \bullet \frac{(IBW2 - ICW2)}{\sqrt{3}}$$

$$I3W2C = \frac{1}{Tap2} \bullet \frac{(ICW2 - IAW2)}{\sqrt{3}}$$

Compensation Matrices

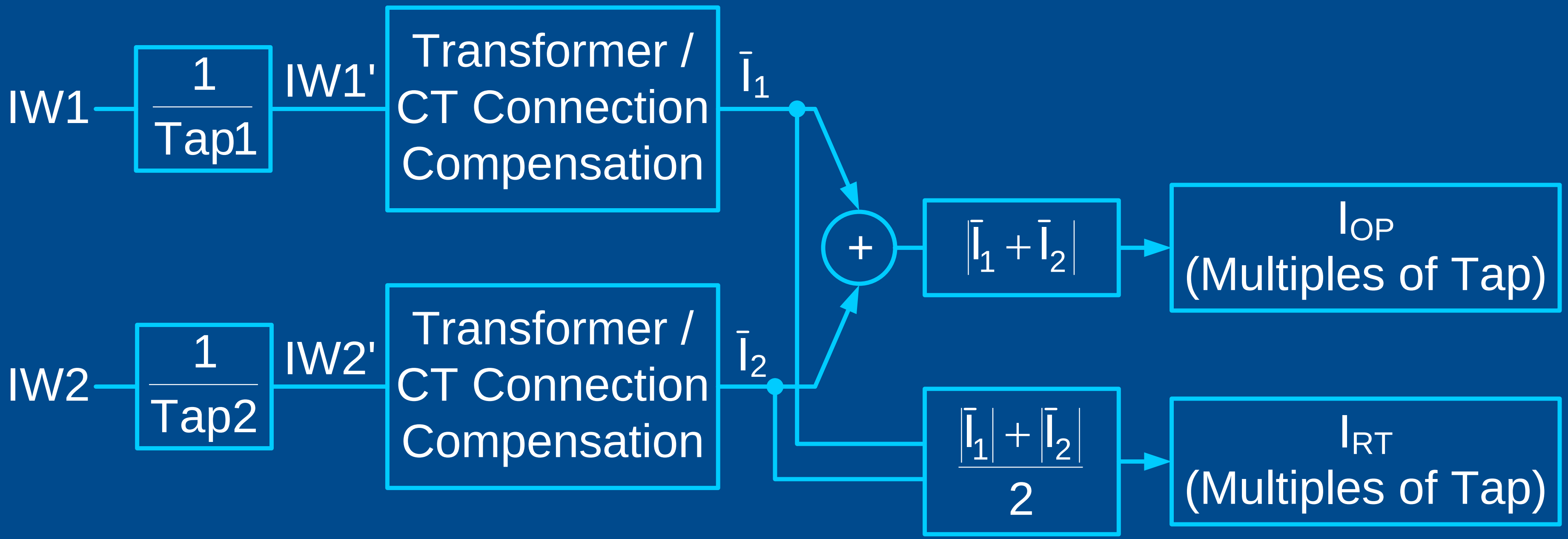


SEL-387 Compensation Method

$$\begin{bmatrix} IAWnC \\ IBWnC \\ ICWnC \end{bmatrix} = [CTC(m)] \cdot \begin{bmatrix} IAWn \\ IBWn \\ ICWn \end{bmatrix}$$

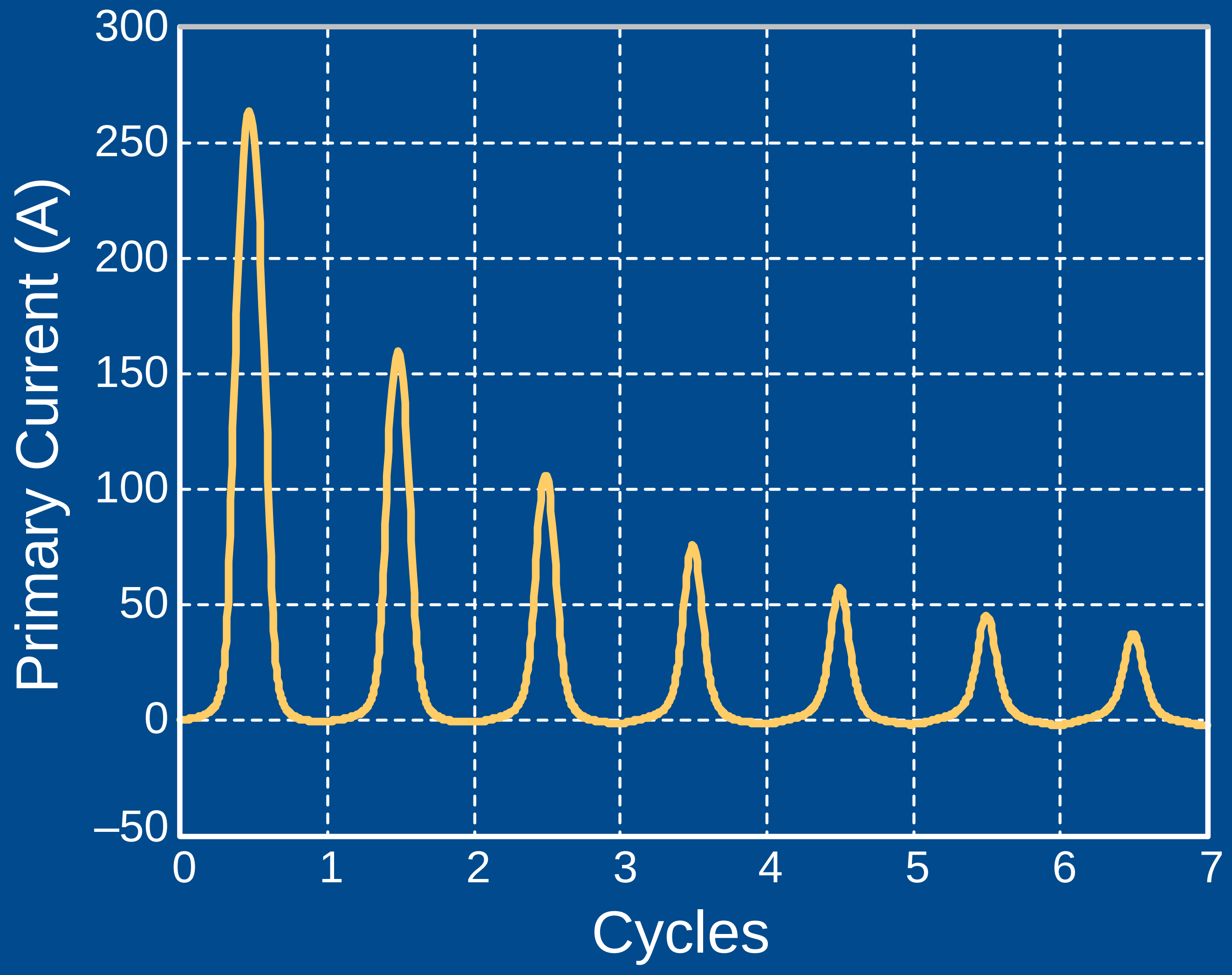
- [CTC(m)]: 3 x 3 matrix
- m = 0, 1,…12
  - m = 0: identity matrix (no changes)
  - m ≠ 0: remove I0; compensate angles
  - m = 12: remove I0; no angle compensation

Differential Element Operate and Restraint Quantities

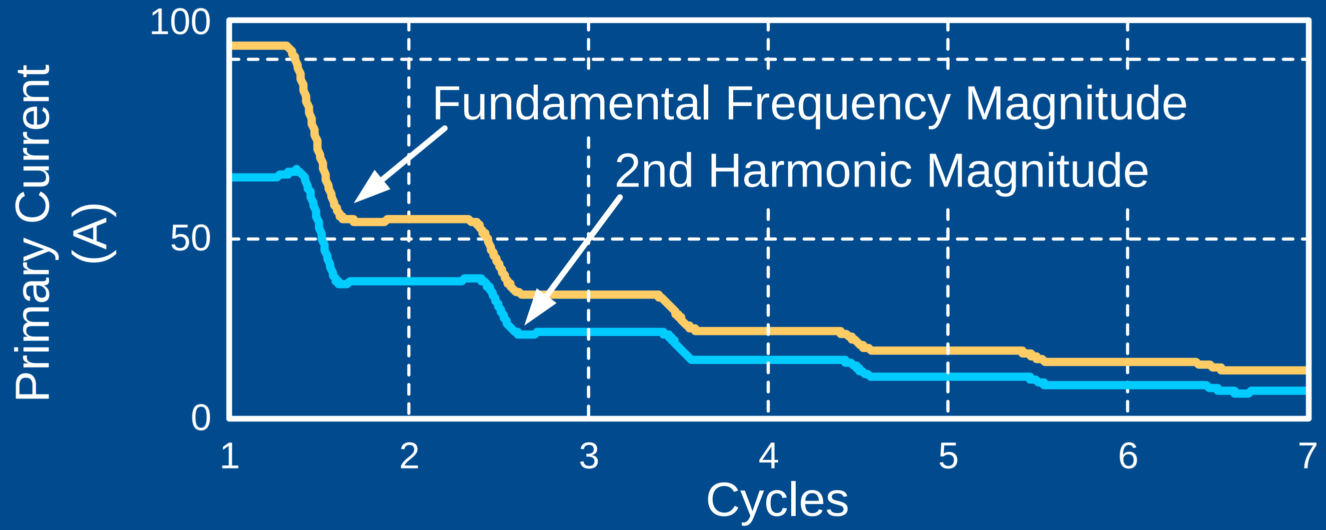


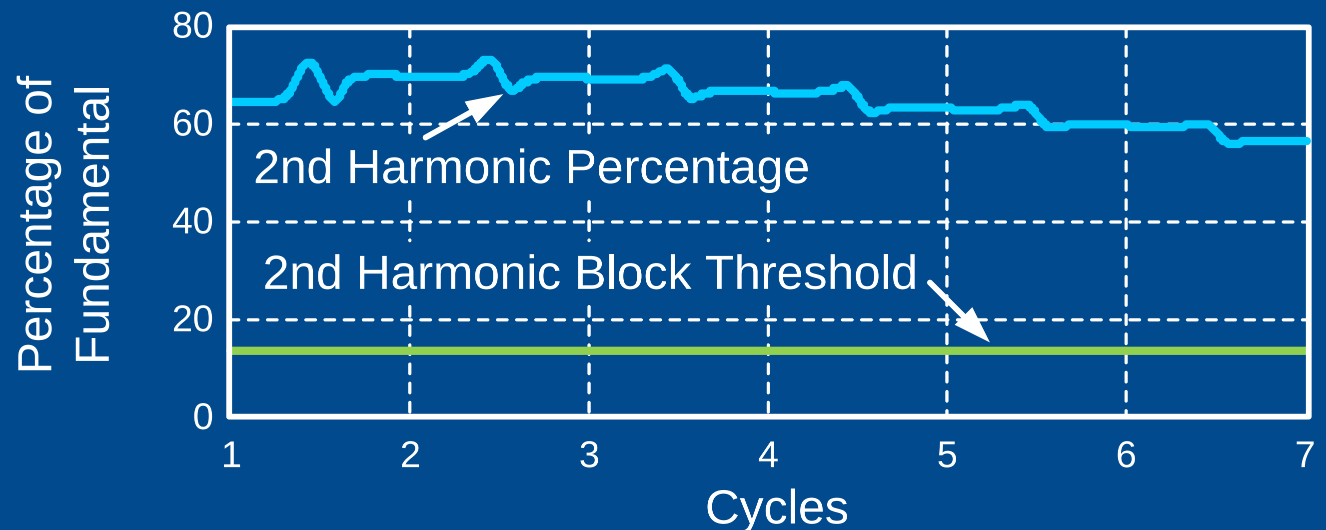
Examine Transformer Inrush Challenges

Phase C Inrush Current Obtained From Transformer Testing



Inrush Current Has High Second Harmonic



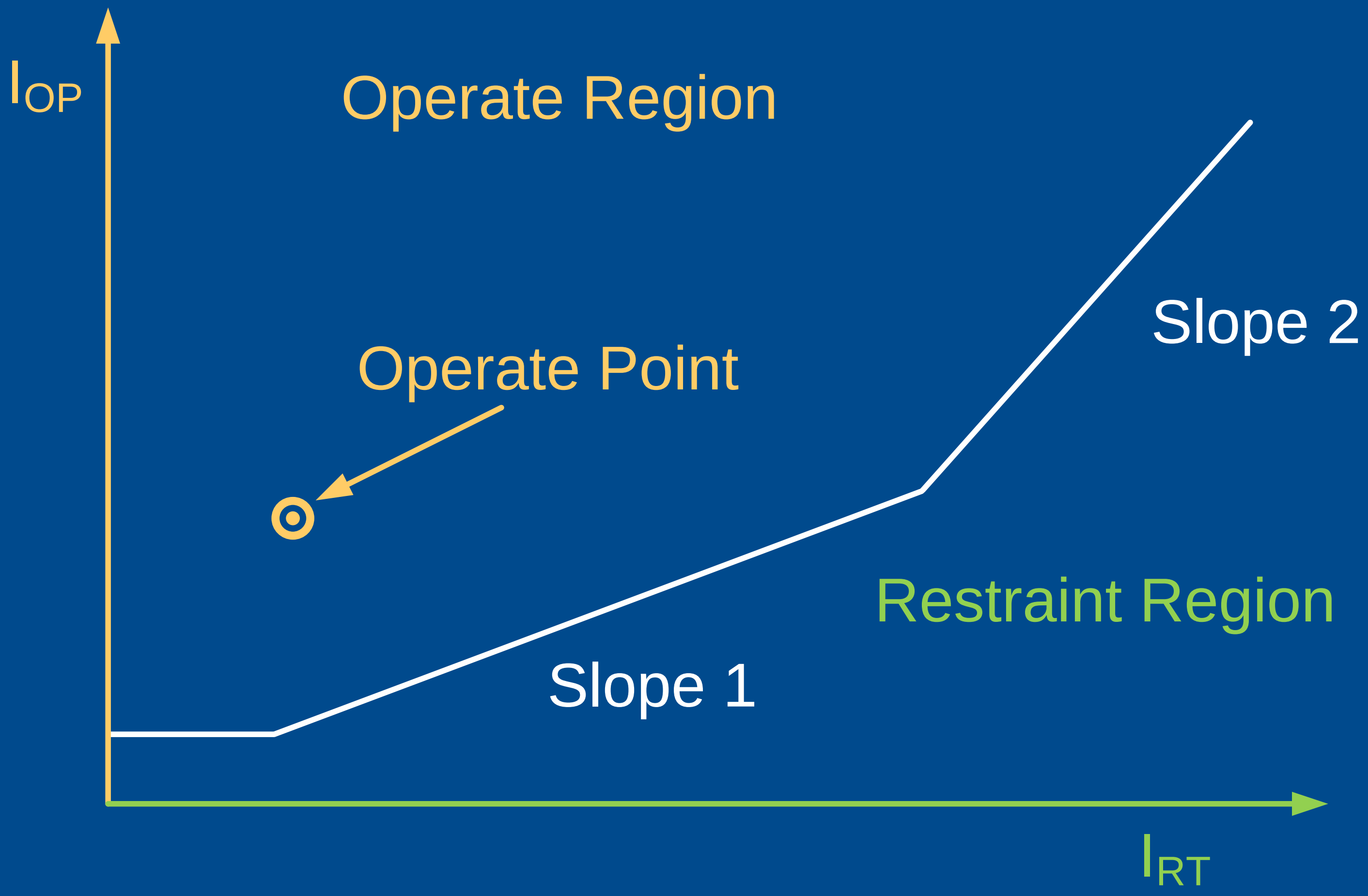


Internal Faults Versus Inrush

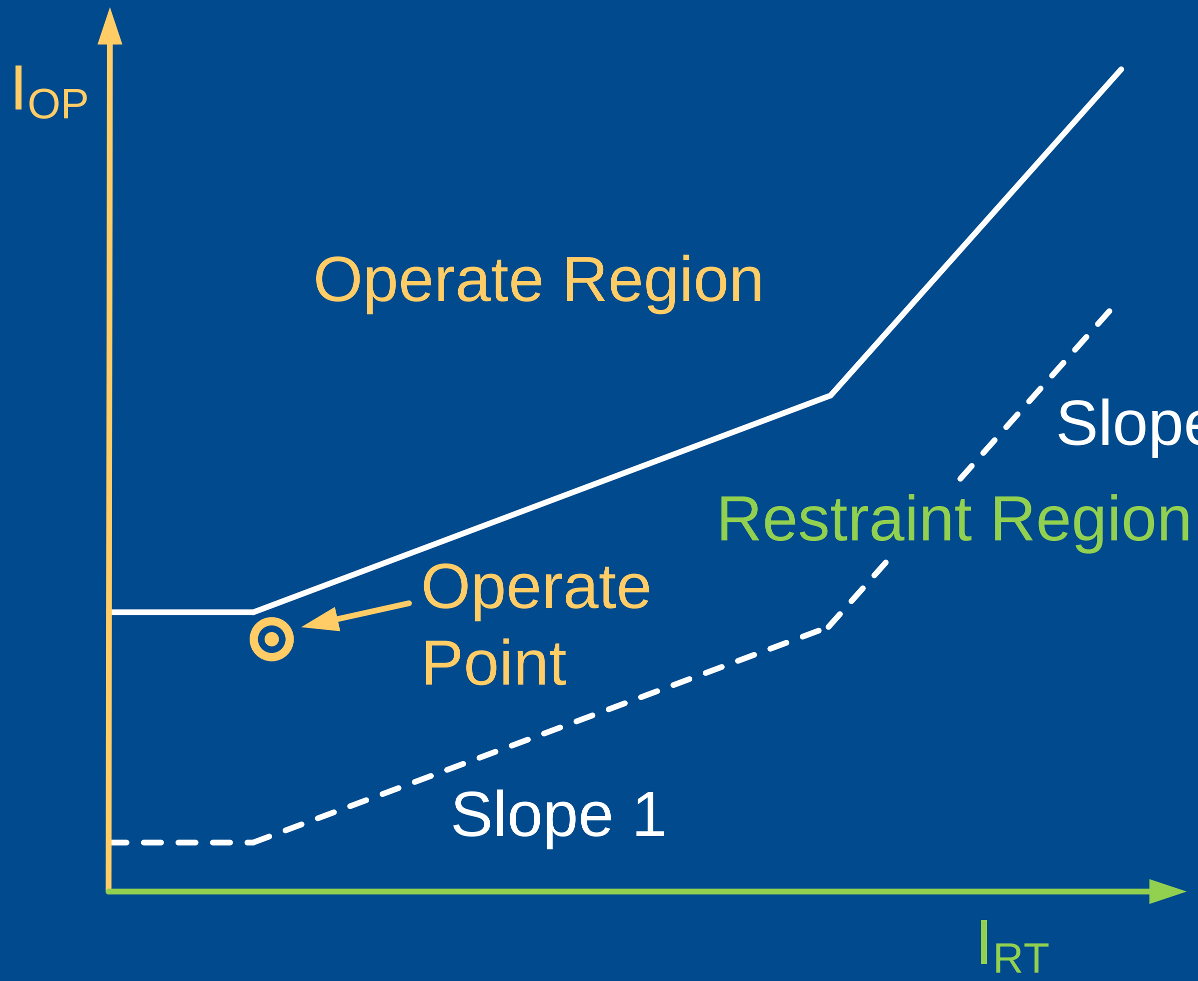
Harmonic-Based Methods

- Harmonic blocking
- Harmonic restraint

Inrush Conditions – Blocking



Inrush Conditions – Restraint



Conclusions

- Apply differential element Slope 2 to compensate for CT saturation
- Set current compensation for phase and magnitude differences across transformers
- Use harmonic blocking and restraint to prevent differential element assertion during inrush

Questions?

Induction and Synchronous Motor Protection Recommendations

TECHNOLOGY EXCHANGE
Learn. Connect. Solve.

Induction Motor Protection

- Phase overcurrent (50 / 51)
- Ground overcurrent (50G / 50N / 51G / 51N)
- Voltage (27 / 59)
- Current unbalance (46)
- Differential (87)

Induction Motor Protection

- Phase sequence (47)
- Resistance temperature device (RTD) thermal (49R)
- Thermal overload (49)
- Load-loss / load-jam (37)
- Starts per hour, time between starts (66)
- Antibackspin

Synchronous Motor Protection

- Induction motor protection elements
- Loss-of-excitation (40)
- Loss-of-synchronism (78)
- Field ground fault (64F)

Phase Overcurrent Protection (50 / 51)

Ground Overcurrent Protection (50G / 50N / 51G / 51N)

Phase Overcurrent Protection

- Phase overcurrent devices detect phase-to-phase and three-phase faults within motor windings and on feeder cables
- Failure to clear fault quickly causes
  - Increased motor conductor or feeder cable damage
  - Stator iron damage
  - Prolonged system voltage dips

Settings Considerations

- Do not use relay phase fault protection with fused motor contactors
- Avoid tripping on motor inrush
  - Symmetrical locked rotor current
  - Subtransient component
  - Asymmetrical (dc offset) component effectively removed from element by microprocessor-based relay
- Coordinate with upstream protection

Optimum Two-Level Phase Overcurrent Protection

- Level 1 settings
  - Phase overcurrent pickup at 1.2 to 1.5 • LRA
  - Overcurrent delay at 6 to 10 cycles to ride through subtransient inrush
- Level 2 settings
  - Phase overcurrent pickup at 1.65 to 2.0 • LRA
  - Phase overcurrent delay at 0

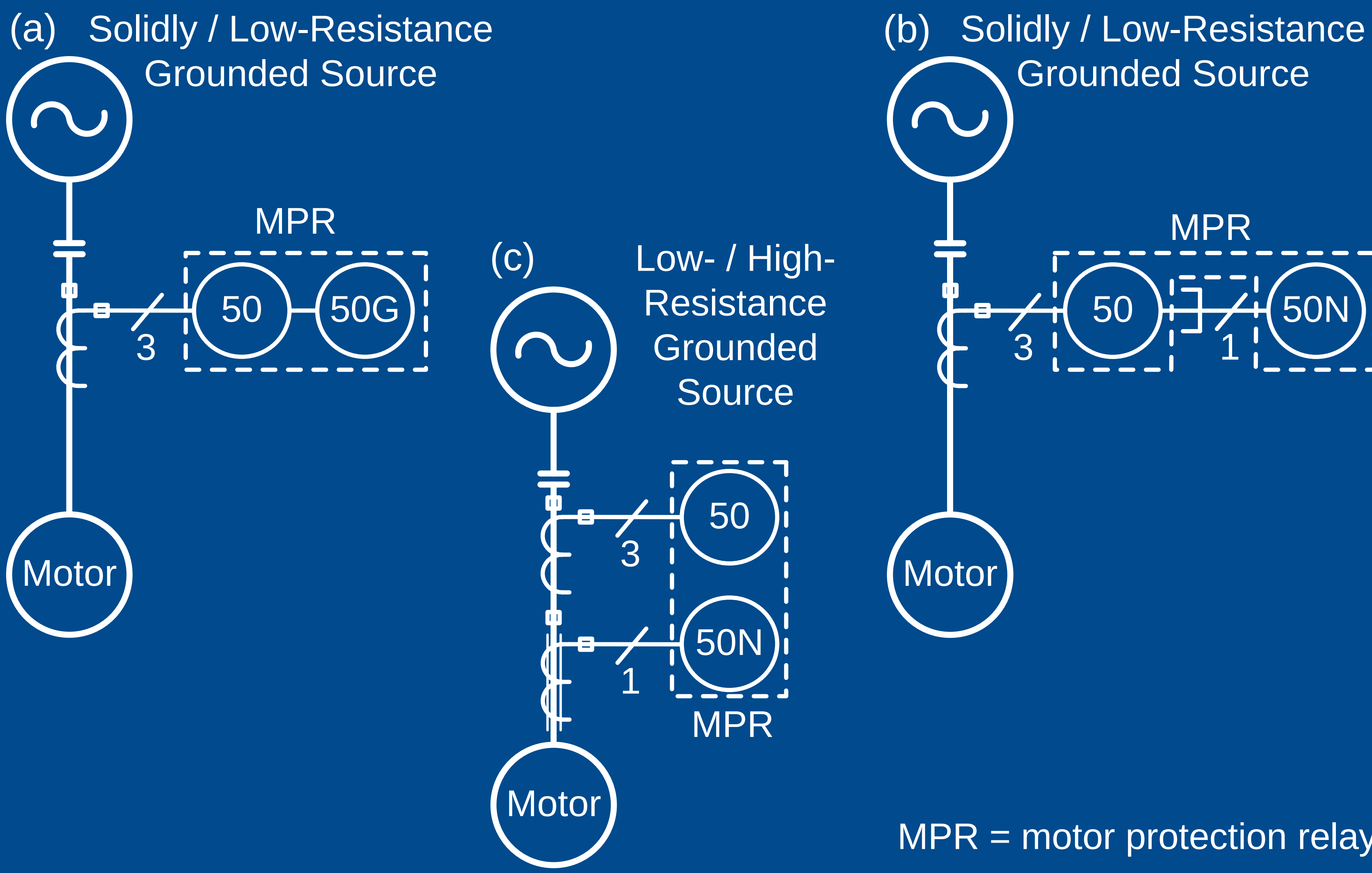
Ground Overcurrent Protection

- Ground overcurrent devices detect faults involving ground within motor windings and on feeder cables
- Failure to clear these faults quickly causes
  - Increased motor conductor or feeder cable damage
  - Stator iron damage
  - Prolonged system voltage dips

Ground Fault Protection Depends on System Grounding Design

- Solidly grounded systems have high phase-to-ground fault currents
- Resistance-grounded systems limit phase-to-ground fault current
- Limiting current limits damage due to ground faults but requires increased relay sensitivity

CT Connections



MPR = motor protection relay

Solidly Grounded Systems

- Ground fault currents in solidly grounded systems can approach phase fault levels
- Ground fault protection for these systems is usually provided by residual protection, either calculated by relay or by external CT residual connection to IN input

Settings Considerations

- Residual protection set to coordinate with upstream devices
- False residual current can occur because of CT saturation
- Level 1 residual overcurrent pickup set at 0.4 to 0.6 • FLA
- Level 1 residual overcurrent delay set at 0.2 s to ride through false residuals

Low-Resistance Grounded Systems

- Ground fault currents limited to 100 to 1000 A
- Ground faults cleared in < 10 s
  - ♦ Minimize fault arc damage
  - ♦ Protect grounding resistors from thermal damage
- Ground fault protection for motors is usually instantaneous or definite-time

Settings Considerations

- Residual elements
  - ♦ Set Level 1 residual overcurrent pickup at 0.4 to 0.6 • FLA
  - ♦ Set Level 1 residual overcurrent delay at 0.2 s to ride through false residuals upon starting
- Ground elements with core-balance CT
  - ♦ Set Level 1 neutral overcurrent pickup at 5 to 20 A primary current
  - ♦ Set Level 1 neutral overcurrent delay at 0.1 s

High-Resistance Grounded Systems

- Typically found on low-voltage systems but sometimes used on medium-voltage systems
- Limit phase-to-ground fault currents to < 10 A

High-Resistance Grounded Systems

- Single-phase-to-ground fault produces an alarm only – ground can then be located and cleared in controlled manner
- This system requires core-balance CT for sensitivity

Settings Considerations

- Set Level 1 neutral overcurrent pickup at 25 to 50% of available ground fault current
- Set Level 1 neutral overcurrent delay at 2 to 5 s
- Program neutral overcurrent for alarm only

Ground Overcurrent Settings Considerations

Source Grounding	Available Ground Fault Current	CT Connections	Relay Function	Setting Considerations	Delay
Solidly grounded	Can approach phase fault levels	a	50G	40 to 60% • FLA	0.2 s
		b	50N		
Low-resistance grounded	100 to 1000 A	a	50G	40 to 60% • FLA	0.2 s
		b	50N		
		c	50N	5 to 20 A (primary)	0.1 s
High-resistance grounded	< 10 A	c	50N	25 to 50% of available ground fault current	2 to 5 s

Undervoltage Protection (27)

Overvoltage Protection (59)

Undervoltage

- Running motors for prolonged periods at less than rated voltage can cause overheating
- Undervoltage tripping can clear a bus after complete loss of voltage – prevents simultaneous restart of connected motors when voltage returns

Settings Considerations

- Motor standards require motors capable of continuous operation at 90% of motor-rated voltage per motor specification
- Undervoltage protection should not trip motors because of voltage dips caused by faults or motor starts
- Undervoltage protection is not usually set to trip motors during fast bus transfers

Settings Considerations – Trip

- Set undervoltage trip pickup slightly under minimum rated operating voltage
- Set undervoltage trip delay longer than
  - Maximum time required for fast bus transfers
  - Maximum fault-clearing time for faults that would cause voltage to drop below pickup
  - Starting time for any motor on bus if motor starts will cause bus voltage to drop below undervoltage trip pickup

Settings Considerations – Alarm

- Set undervoltage alarm level at or slightly above motor minimum rated operating voltage
- Set undervoltage alarm delay longer than
  - Maximum time required for normal bus transfers
  - Maximum fault-clearing time for faults that would cause voltage to drop below pickup

Overvoltage

Running motors for prolonged periods at greater than rated voltage can cause loss of insulation life or insulation failure

Settings Considerations

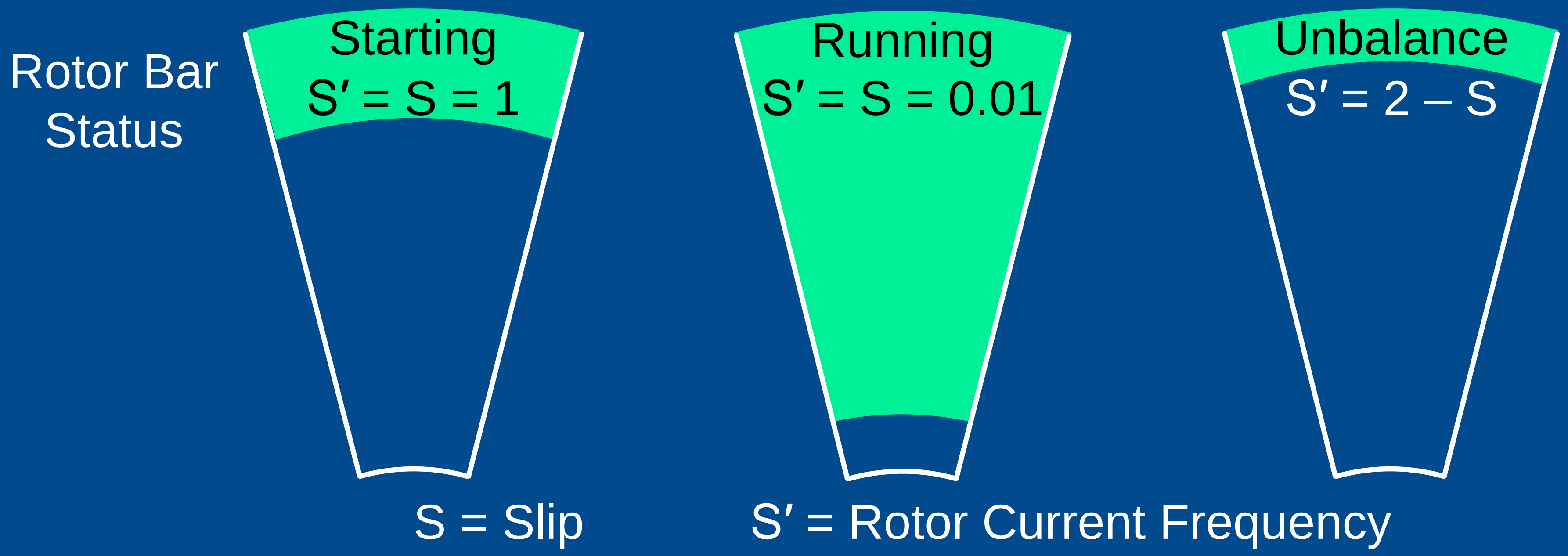
- Motor standards require that motors be capable of continuous operation at 110% of rated voltage
- Overvoltage alarming is generally used in favor of overvoltage tripping
- If overvoltage tripping is applied, consider using a time delay

Current Unbalance Protection (46)

Current Unbalance

- Caused by
  - Unbalanced voltages
  - Single phasing
- Creates negative-sequence current flow in rotor
  - Heating effect at full load is same as locked rotor condition
  - Rotor overheats

Negative-Sequence Heating



- Negative-sequence current causes double-frequency flux in rotor
- Rotor current occupies one-sixth of cross-section area of bars, causing overheating at periphery

Current Unbalance

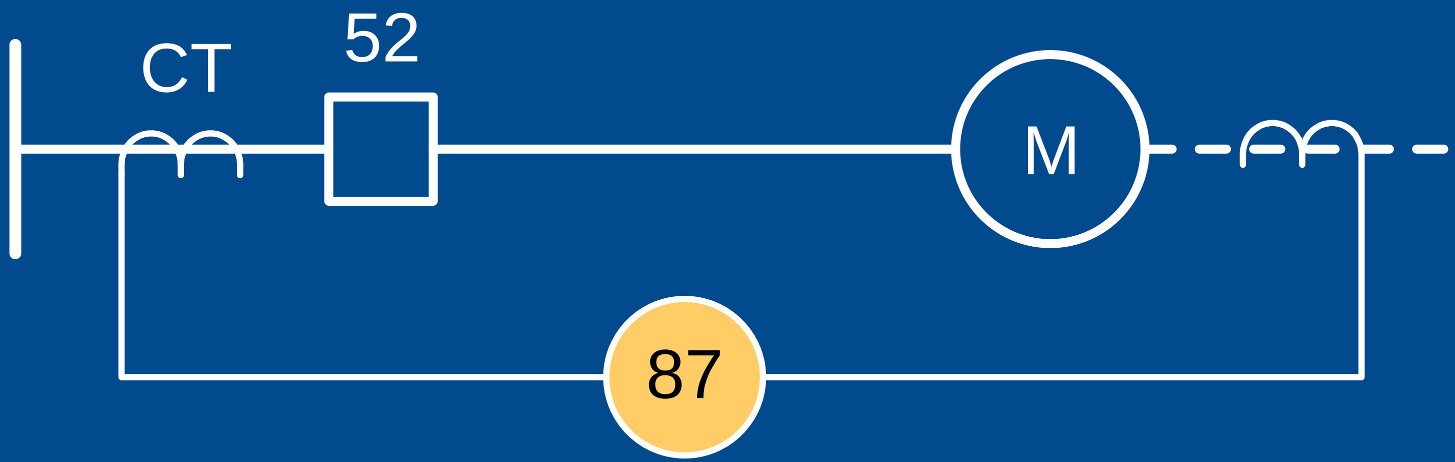
- Biases thermal overload element
- Is detected by
  - Thermal model under moderate conditions
  - Current unbalance elements under severe conditions

Settings Considerations

- Trip
  - Set current unbalance trip pickup to 15%
  - Set current unbalance trip delay to 5 s
- Alarm
  - Set current unbalance alarm pickup to 10%
  - Set current unbalance alarm delay to 10 s

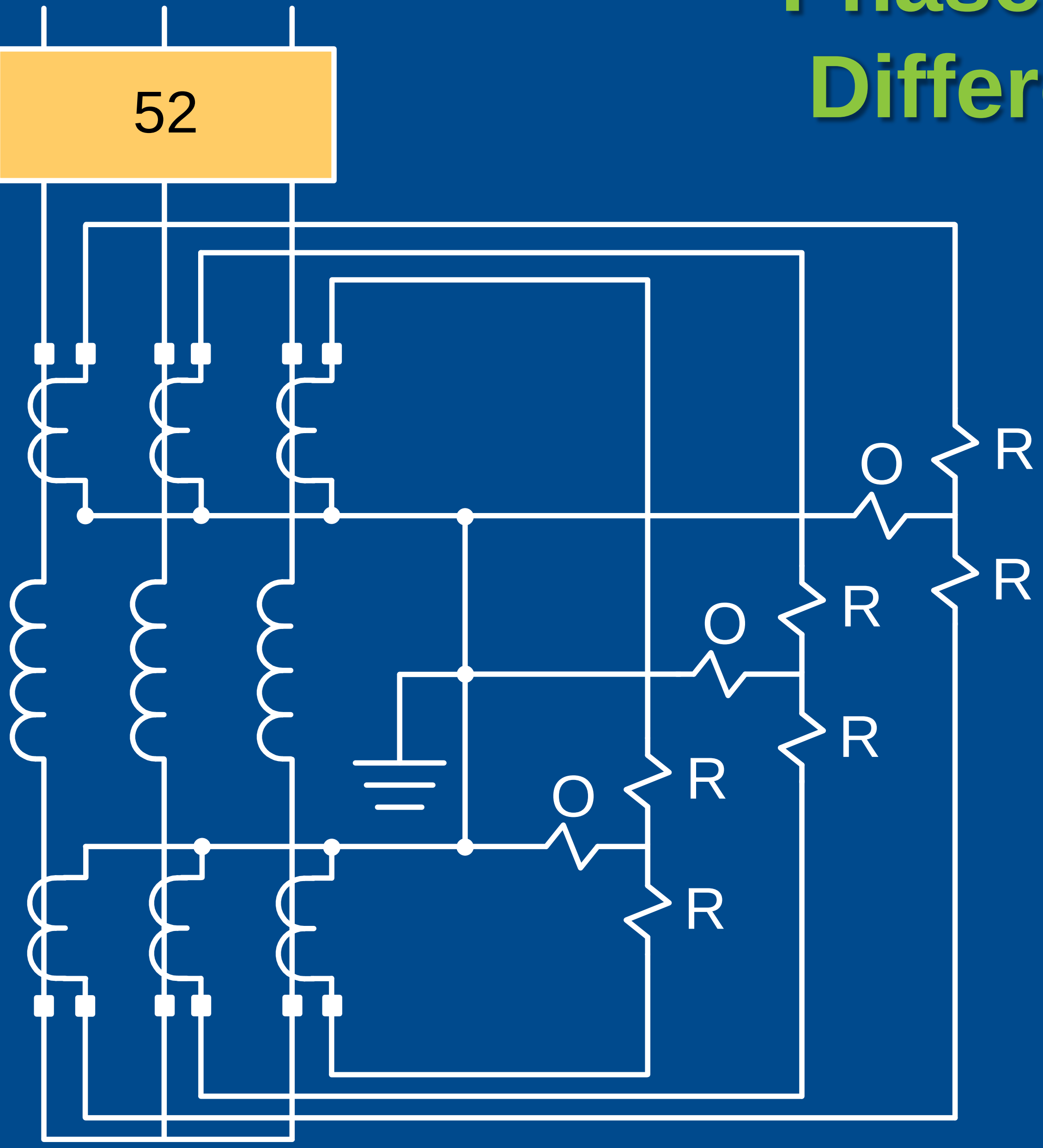
Differential Protection (87)

Differential Protection



- Phase differential (large machines)
- Self-balancing (87M) differential (machines rated 1000 hp and up)
- Detection of phase faults and possibly phase-to-ground faults depending on system grounding

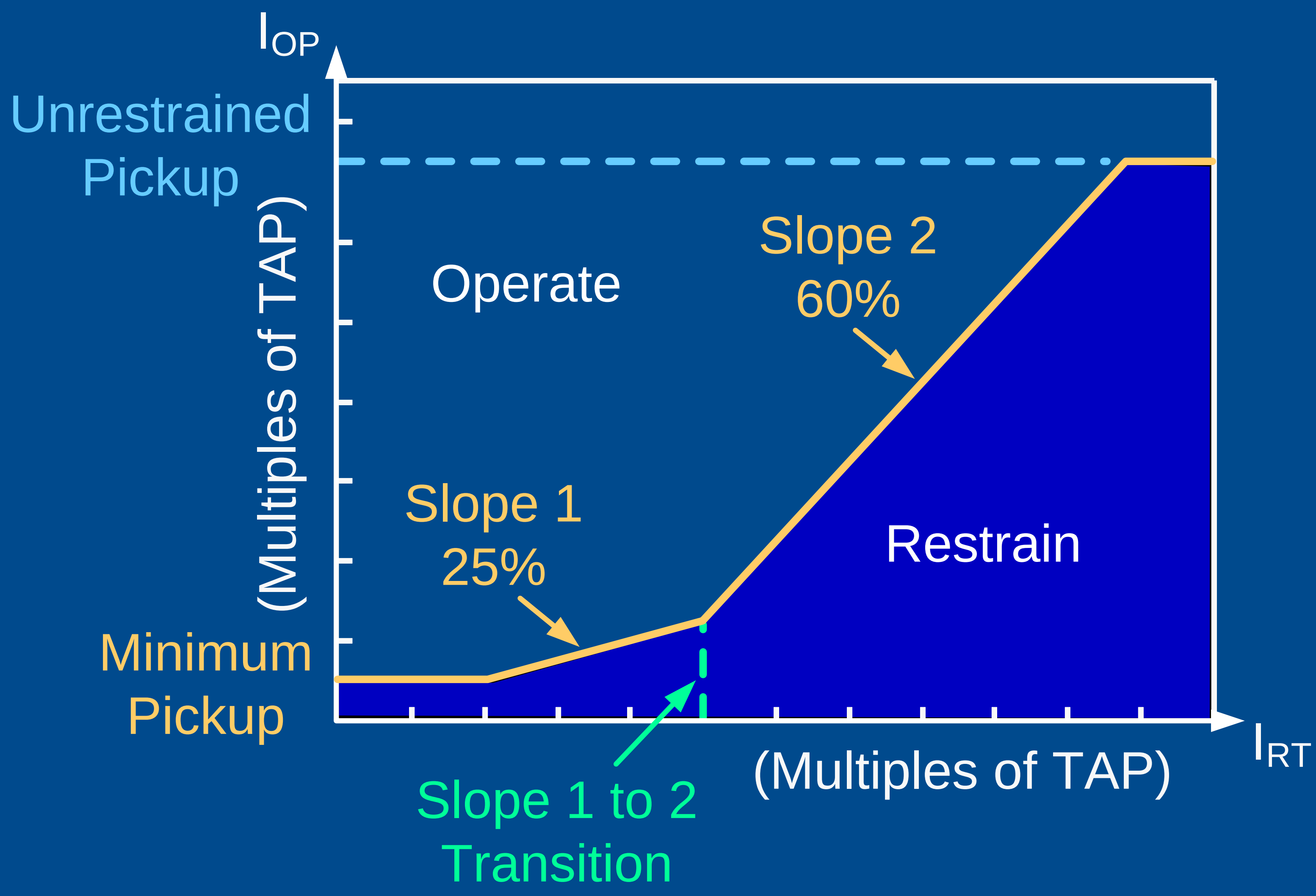
Phase Percentage Differential (87R)



O = operating coil

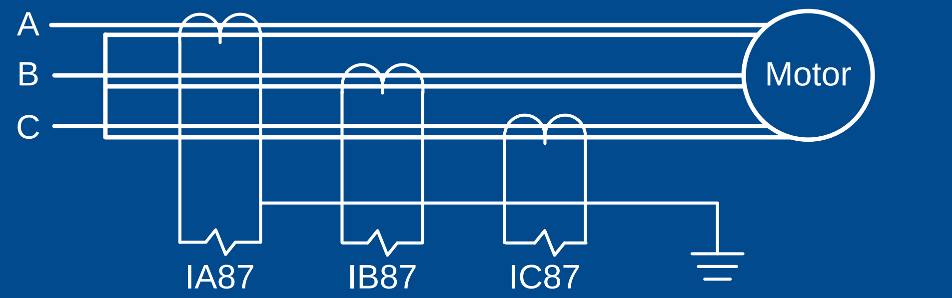
R = restraining coil

Percentage Restraint (87) Differential Characteristic

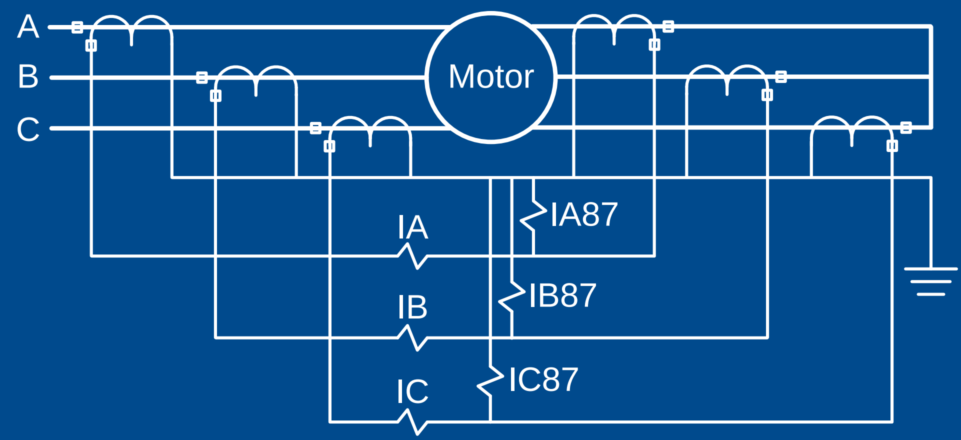


Self-Balancing (87M) Differential Protection

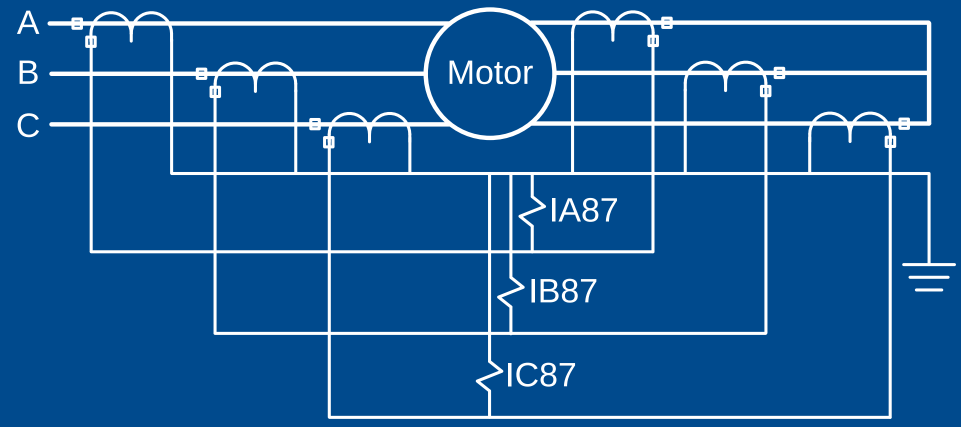
Core-balance CT



Neutral-side CT with IA, IB, and IC connected



Neutral-side CT with IA, IB, and IC not connected



Phase Sequence Protection (47)

Phase Sequence

- Also referred to as phase reversal
- Operates on voltage or current
- Checks that phase rotation signals applied to relay match phase rotation setting

RTD Thermal Protection (49R)

RTD Thermal Element Detects Loss-of-Cooling Efficiency

- Cooling pump failure
- Inlet air reduction
- Detection using direct temperature measurement (RTDs)

Thermal Overload Protection (49)

Thermal Protection

- Running overload
- Starting / stalling
- Running unbalance

Running Protection

- Load greater than service factor causes excessive I^2R heating in stator windings
- Unbalance current causes excessive heating in rotor

Thermal Model Protection

- Electromechanical relays using bimetal and solder-pot elements do not match motor time constants
- Microprocessor-based relays can match thermal properties identified by motor data and can monitor RTDs embedded in stator winding

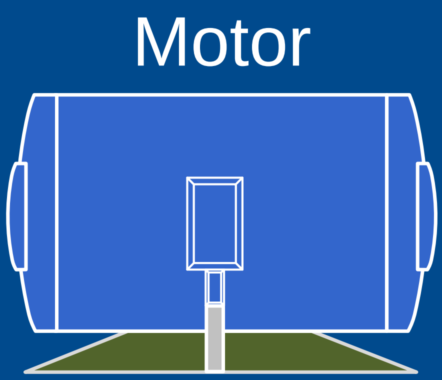
Integrated Motor Thermal Protection

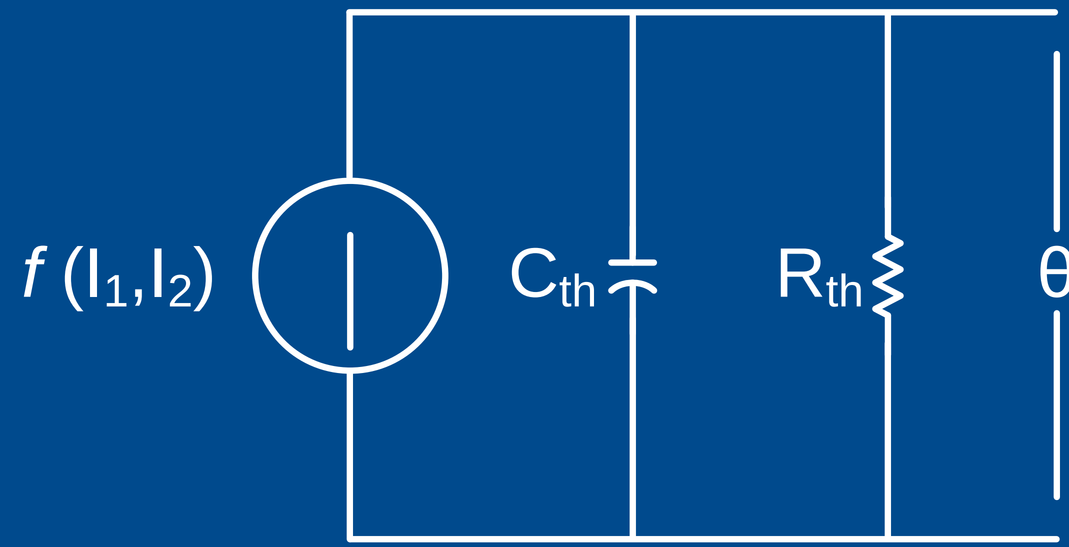
- Provides locked rotor, overload, and unbalance protection
- Defines operating characteristics by motor characteristics

Bimetallic Overload Element

- I^2R heating opens contacts to trip motor
- Reset characteristic not related to motor
- This element has
  - Uncertain response to unbalance
  - Sensitivity to cabinet ambient temperature

Motor First Order Thermal Model

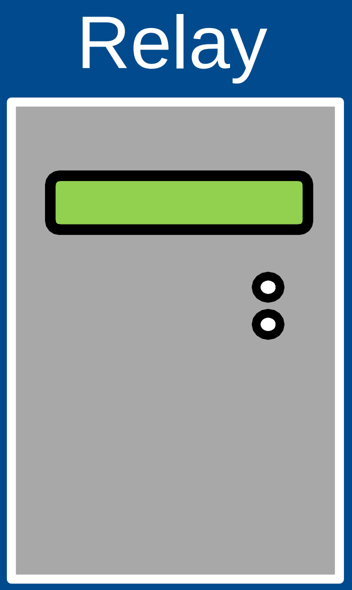




C_{th} = equivalent thermal capacity
R_{th} = equivalent thermal resistance
θ = temperature rise with respect to ambient

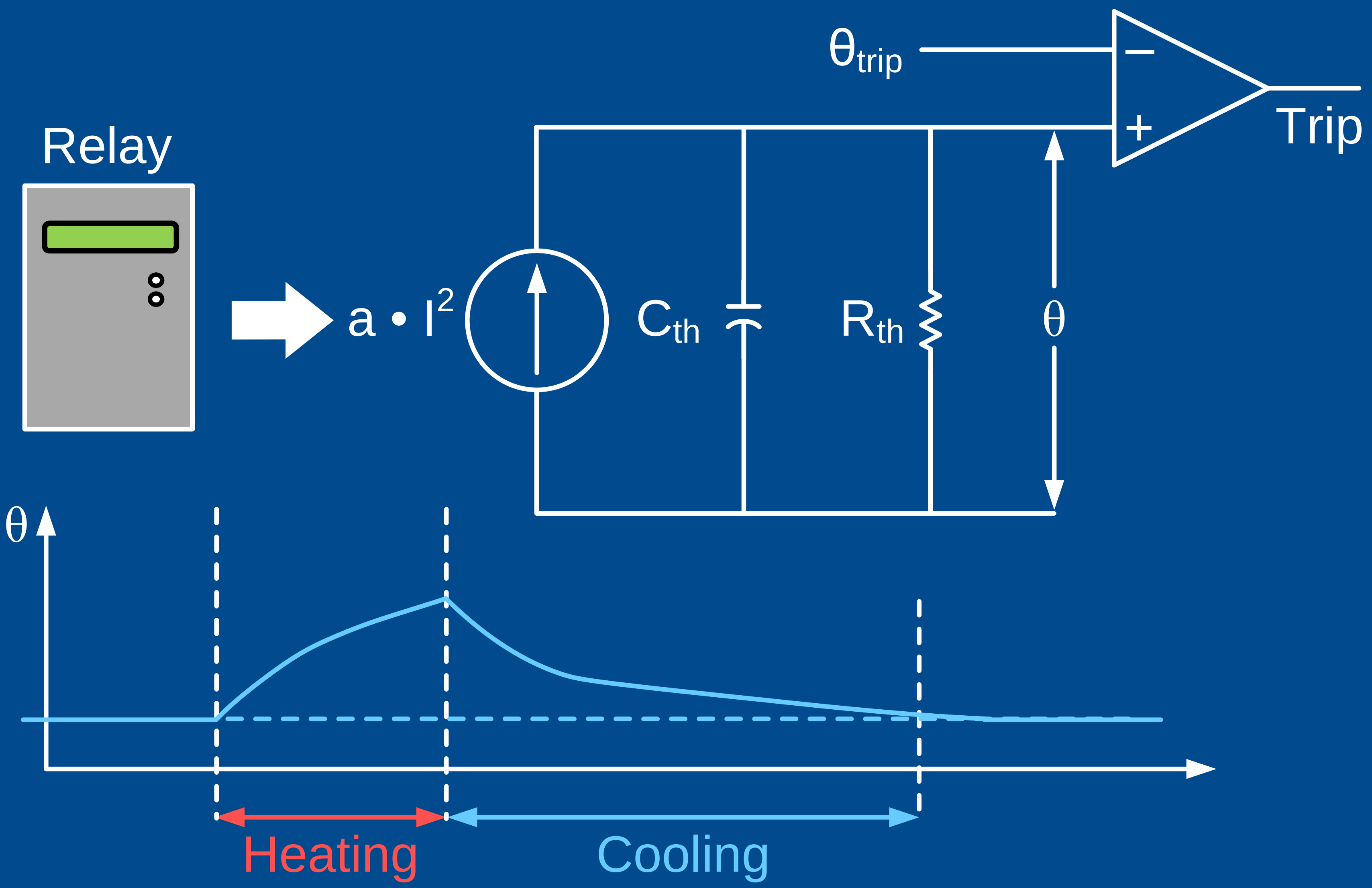
Motor Thermal Image or Thermal Model Relays

- Use single-state model
- Use double-state model
  - Starting
  - Running



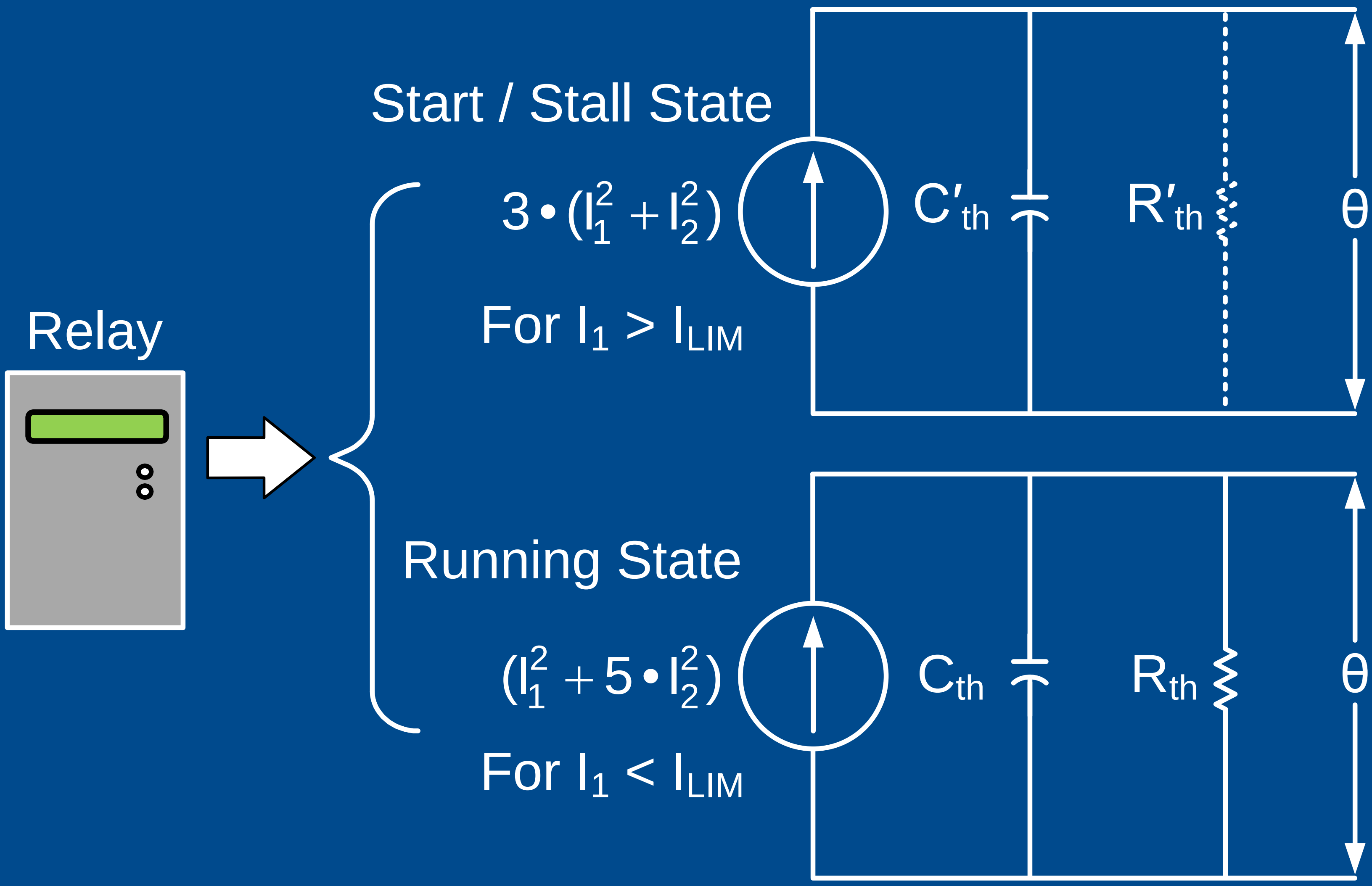
Single-State Thermal Model

Relay Principle

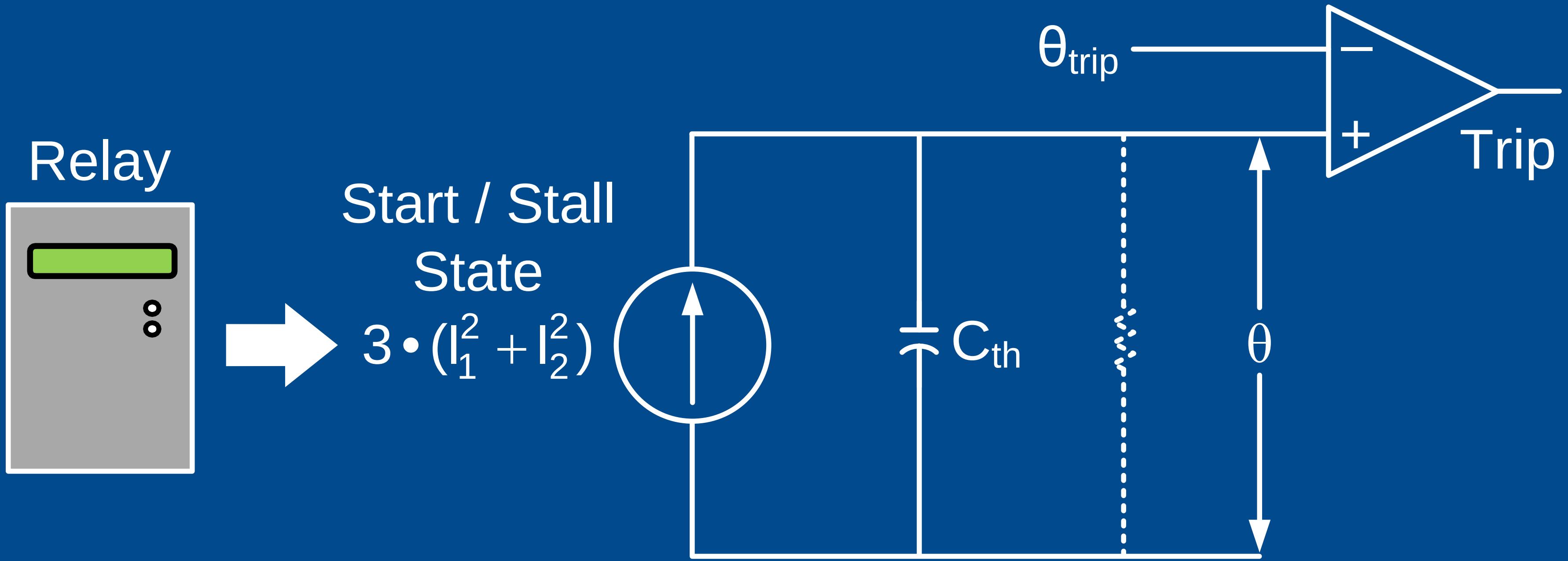


Two-State Thermal Model

Protection Element

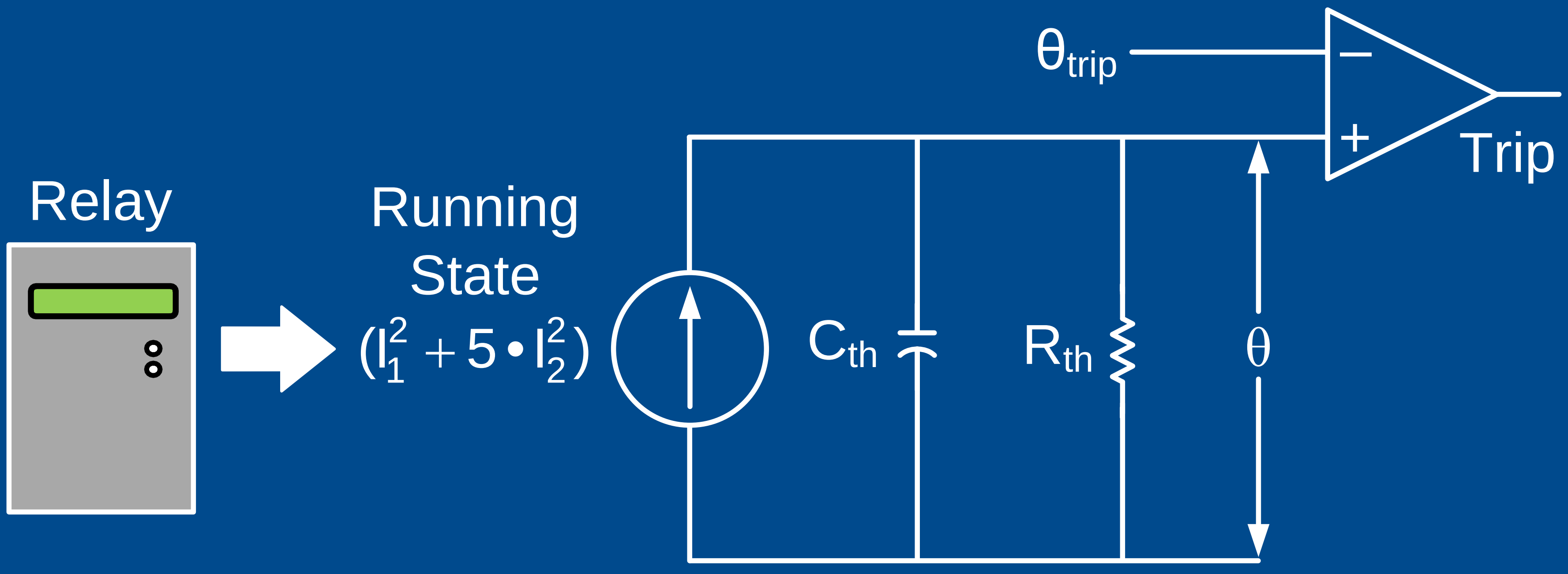


Thermal Model Relay
Starting State



- If C_{th} is fixed, determine only one setting, θ_{trip}
- Use locked rotor safe stall times

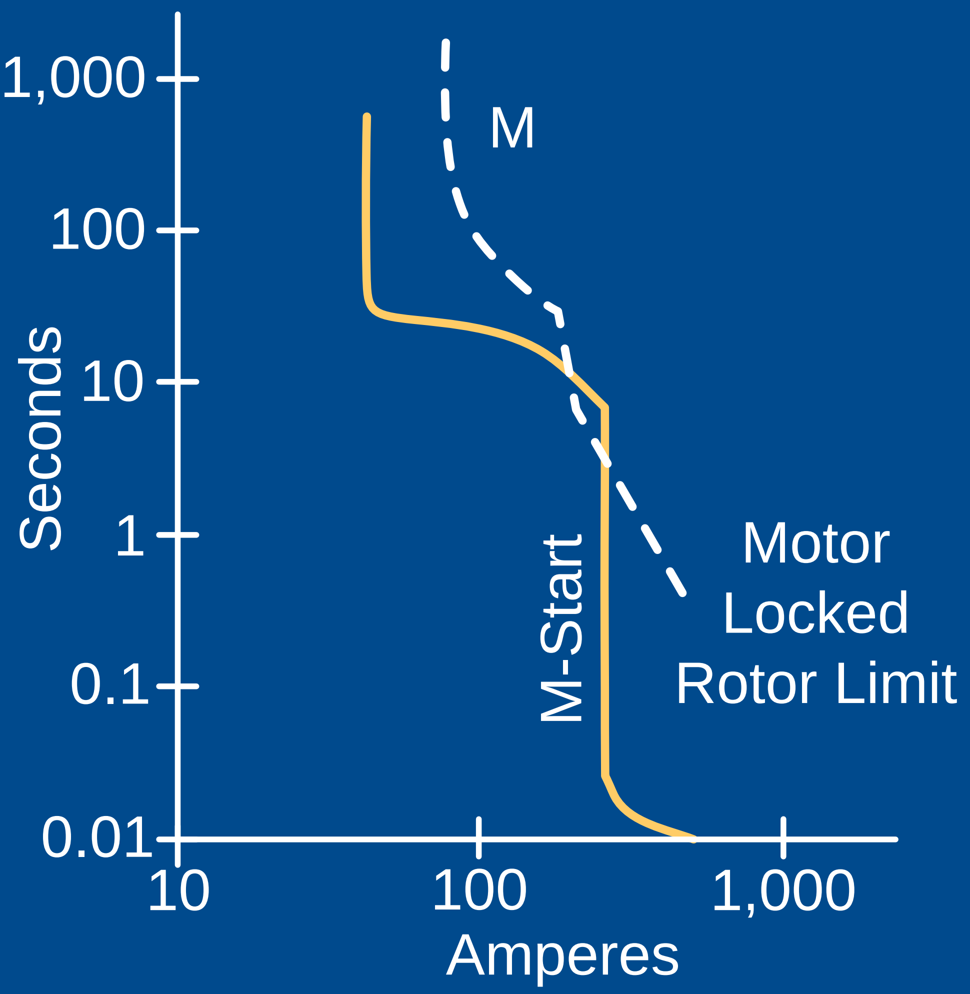
Thermal Model Relay
Running State



- Determine settings: C_{th}, R_{th}, θ_{trip}
- Use motor damage curves to fit model

High-Inertia Starting

- High-inertia loads, such as induced draft fans, require long acceleration times
- Starting time may exceed locked rotor limit

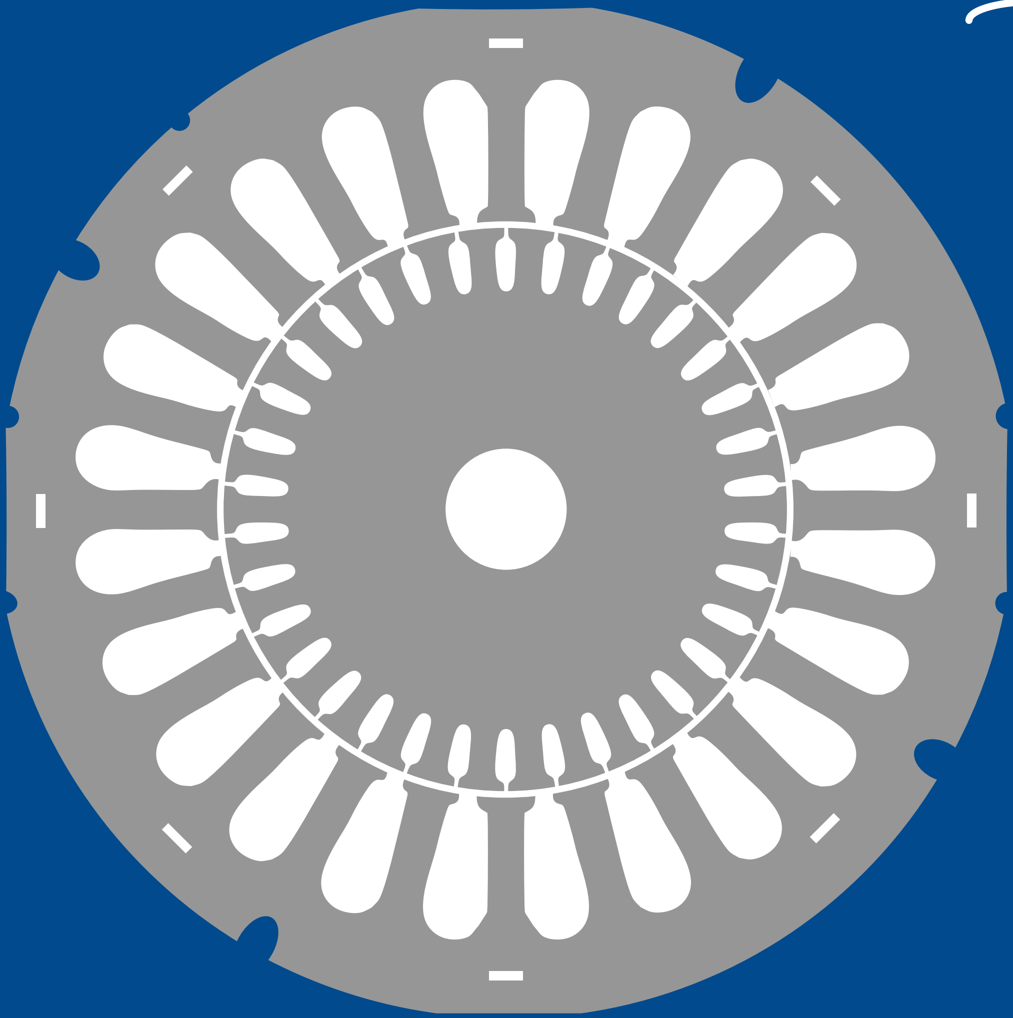


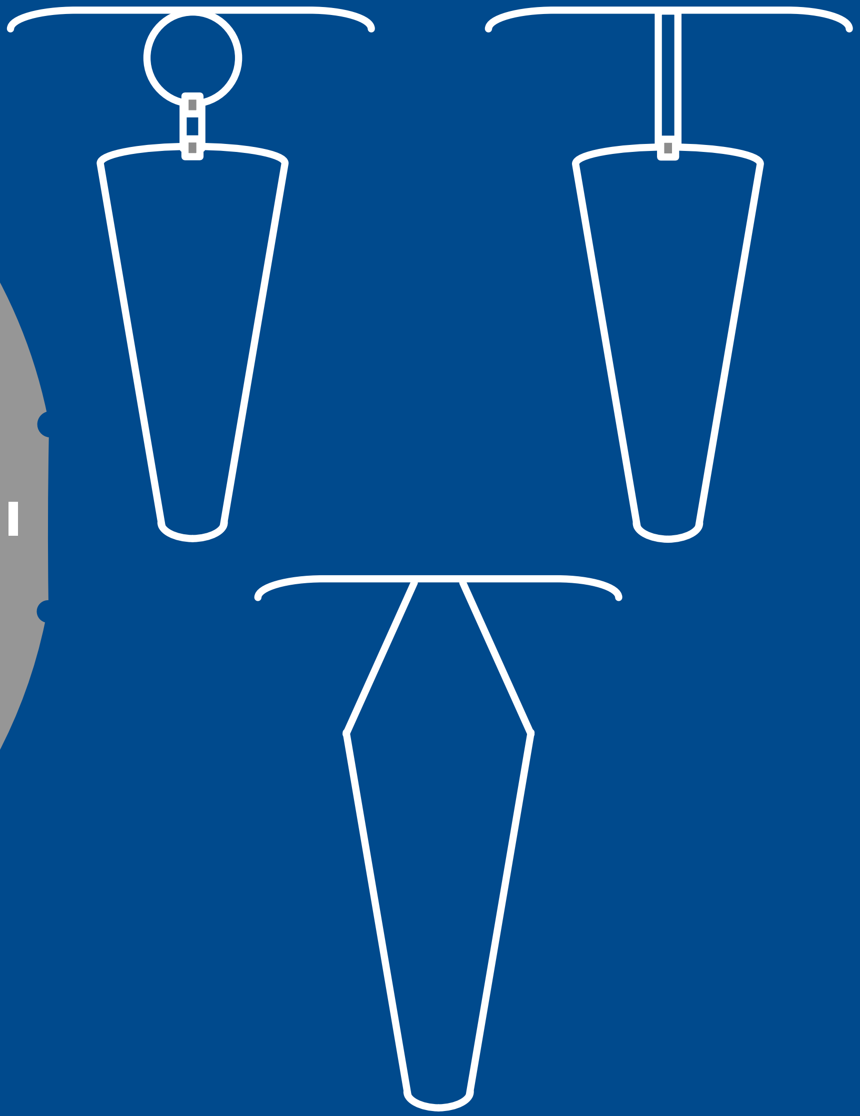
Traditional Solution: Speed Switch

Proximity Probe and Rotating Disk

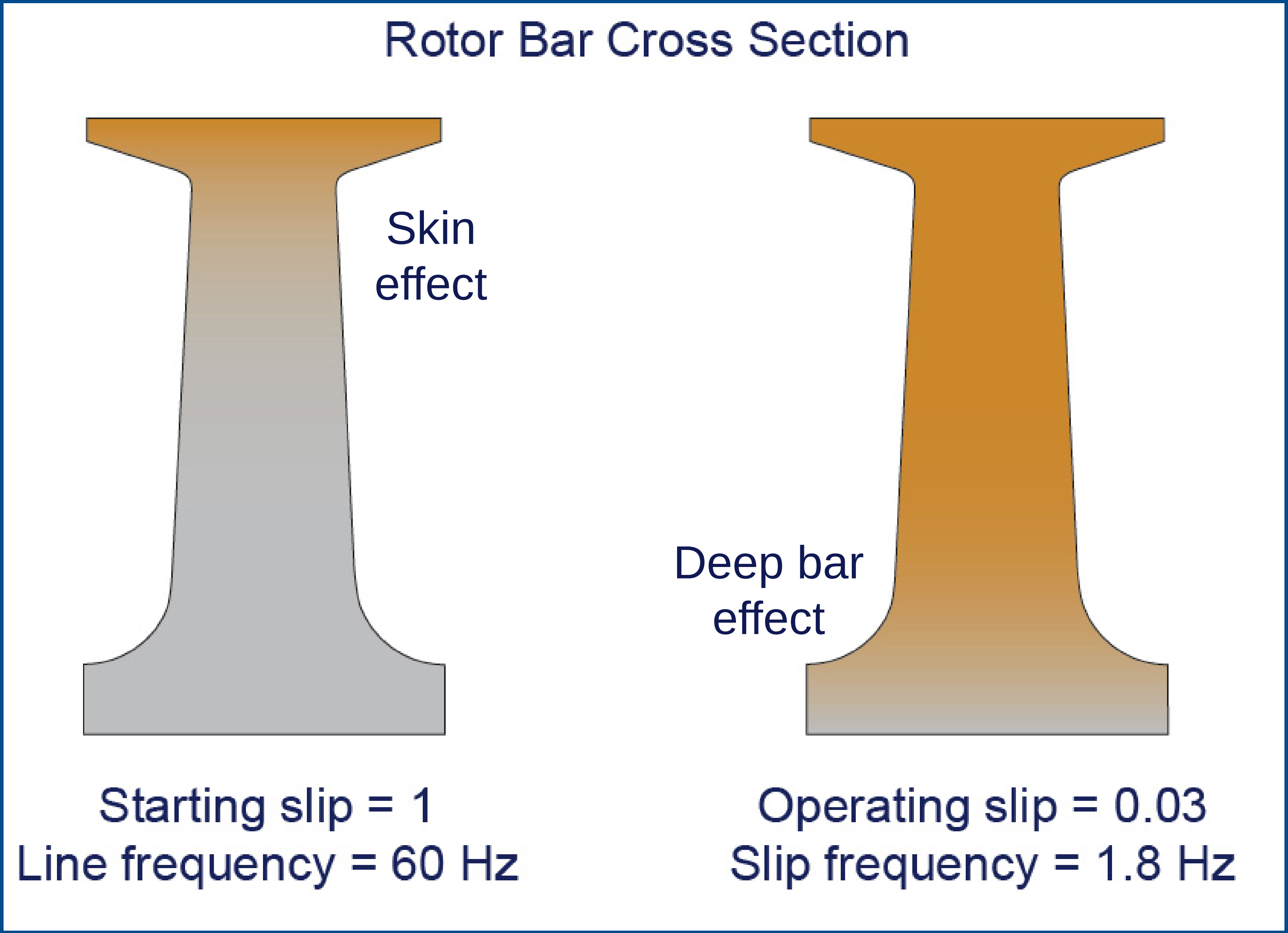
- Proximity probe is magnetic
- Rotating disc uses laser
- Safe stall time setting is increased to accommodate acceleration – supervised by detection of shaft rotation (25 to 35% of speed) within set time limit

Rotor Design

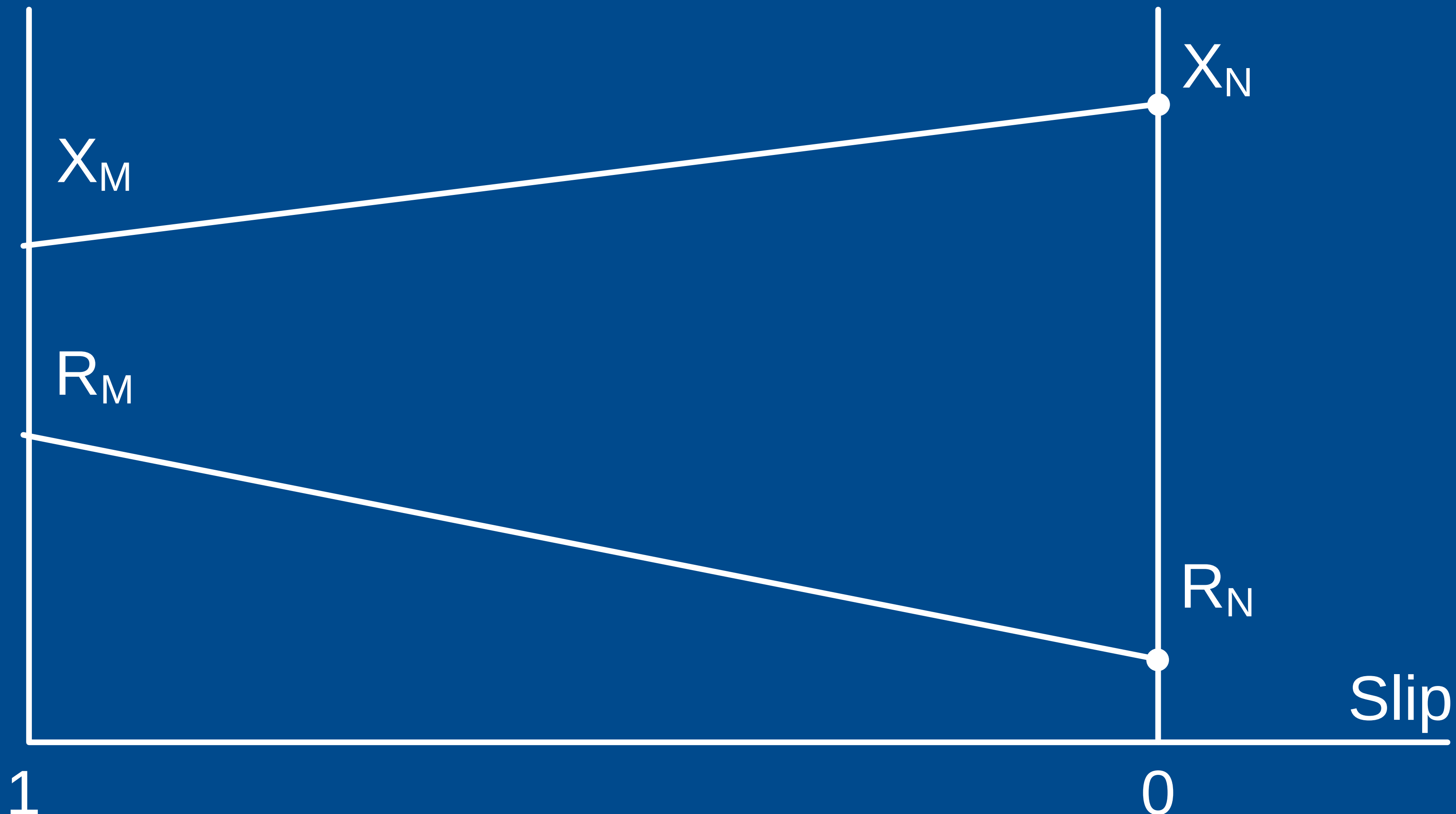




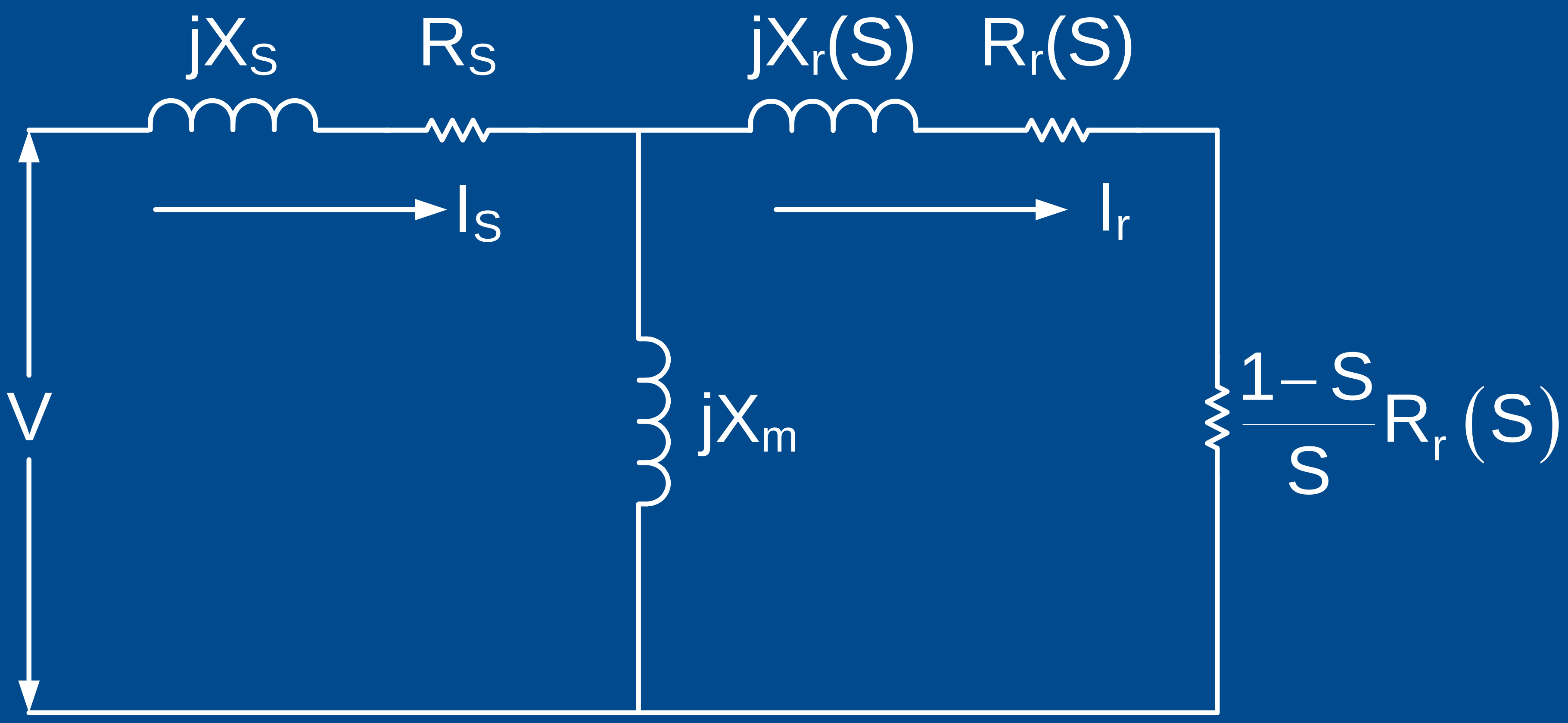
Rotor Resistance Variation



Linear Approximation of Slip-Dependent Rotor Resistance and Reactance



Steinmetz Electrical Model



Slip-Dependent Rotor Resistance

- Motor heating is caused by watt loss in rotor and stator resistance
- Rotor resistance decreases from high locked rotor value to low value at rated speed (shown in Steinmetz model)

Positive- and Negative-Sequence Rotor Resistances Are Linear Functions of Slip

$$R_1 = \left[\left(R_M - R_N\right)S\right] + R_N$$

$$R_2 = \left[\left(R_M - R_N\right)\left(2 - S\right)\right] + R_N$$

Where:

R_M = resistance at locked rotor

R_N = rotor resistance at rated speed

S = slip

R_M and R_N Defined

- R_M and R_N are defined by
  - Locked rotor current I_L
  - Locked rotor torque LRQ
  - Synchronous speed ω_{syn}
  - Rated speed ω_{rated}
- In Steinmetz model, mechanical power P_M is

$$P_M = \frac{1-S}{S} \bullet I^2 R_r$$

Solving for Rotor Resistance

Torque is power divided by speed

$$Q_M = \frac{P_M}{\omega} = \frac{P_M}{1-S} = I^2\left(\frac{1-S}{S}\right)R_r\left(\frac{1}{1-S}\right) = \frac{I^2 R_r}{S}$$

Solving for rotor resistance R_r

$$R_r = \frac{Q_M}{I^2}S$$

Substitute Known Values

At locked rotor, $S = 1$ and $Q_M = LRQ$

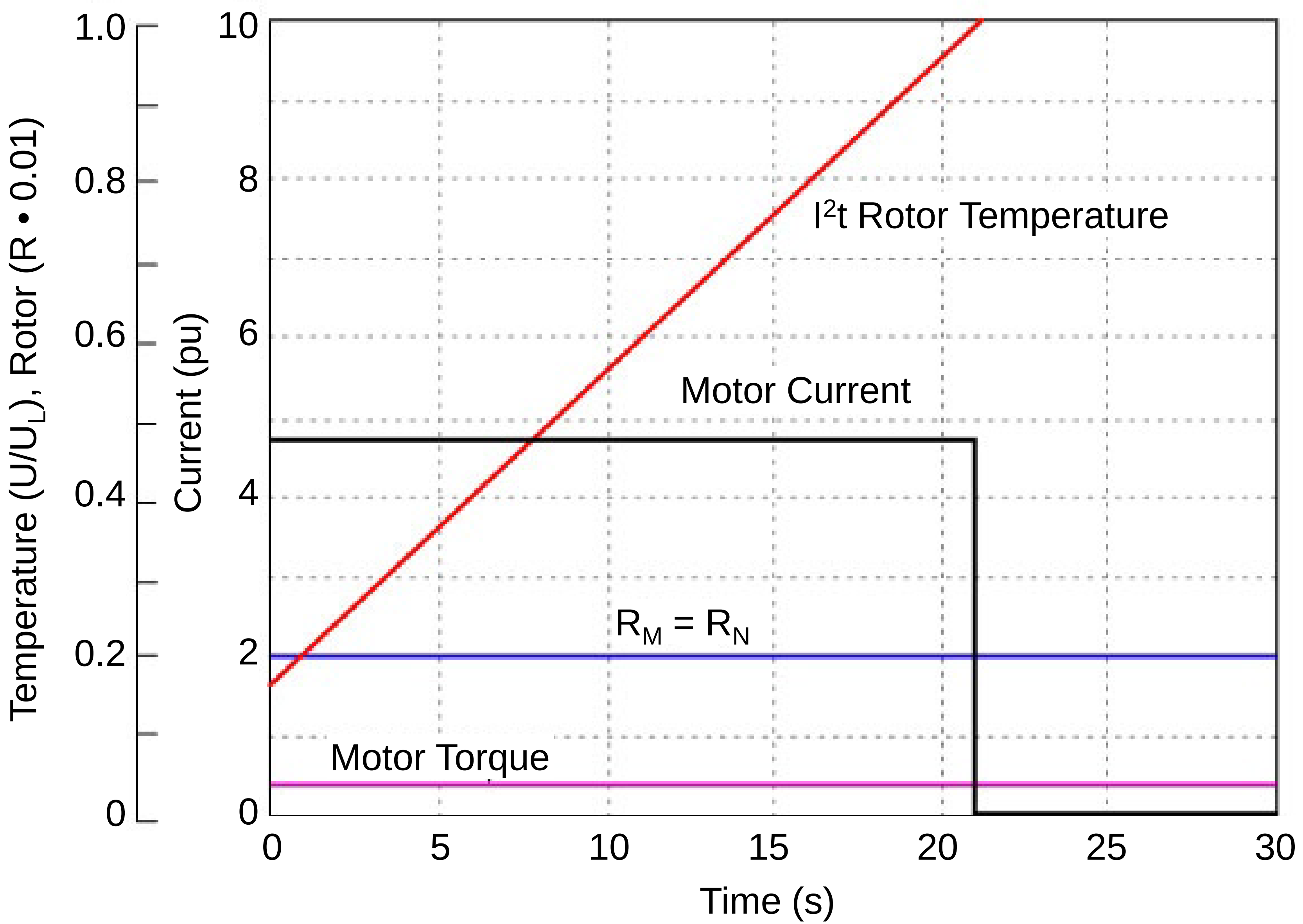
$$R_r = R_M = \frac{LRQ}{I_L^2}$$

S at rated speed is S_N, $I = 1$ and $Q_M = 1$

$$R_N = S_N$$

$$R_N = \frac{\omega_{syn} - \omega_{rated}}{\omega_{syn}}$$

Locked Rotor Case



Derive Slip Using Voltage and Current

When V_1 and I_1 are monitored, apparent positive-sequence impedance looking into the motor is

$$Z = R + jX = \frac{V_1}{I_1}$$

Motor Impedance

From the Steinmetz model

$$Z = R_S + jX_S + \frac{\left(\frac{R_r}{S} + jX_r\right) \bullet jX_m}{\frac{R_r}{S} + jX_r + jX_m}$$

Motor Impedance

Expanding the equation

$$Z = R_S + jX_S + \frac{\frac{R_r}{S} X_m^2 + j\left[X_m \left(\frac{R_r}{S} \right)^2 + X_r X_m \left(X_r + X_m \right) \right]}{\left(\frac{R_r}{S} \right)^2 + \left(X_r + X_m \right)^2}$$

Motor Impedance

The real part of Z is

$$R = R_S + \frac{\frac{R_r}{S} X_m^2}{\left(\frac{R_r}{S}\right)^2 + (X_r + X_m)^2}$$

Motor Impedance

Divide numerator and denominator by $(X_m)^2$

$$R = R_S + \frac{\frac{R_r}{S}}{\left(\frac{R_r}{S}\right)^2 \frac{1}{X_m^2} + \frac{(X_r + X_m)^2}{X_m^2}}$$

But $\left(\frac{R_r}{S}\right)^2 \frac{1}{X_m^2}$ is negligible

Motor Impedance

Let

$$A = \left(\frac{X_r + X_m}{X_m} \right)^2$$

Then

$$R = R_S + \frac{R_r}{A \bullet S}$$

Derive Slip

Consider only the real part of motor impedance

$$R = R_S + \frac{R_r}{A \bullet S}$$

Next, substitute the linear equation for R_{r+} in terms of slip, and solve for slip

$$S = \frac{R_N}{A\left(R - R_S\right) - \left(R_M - R_N\right)}$$

Slip-Dependent Rotor Resistance

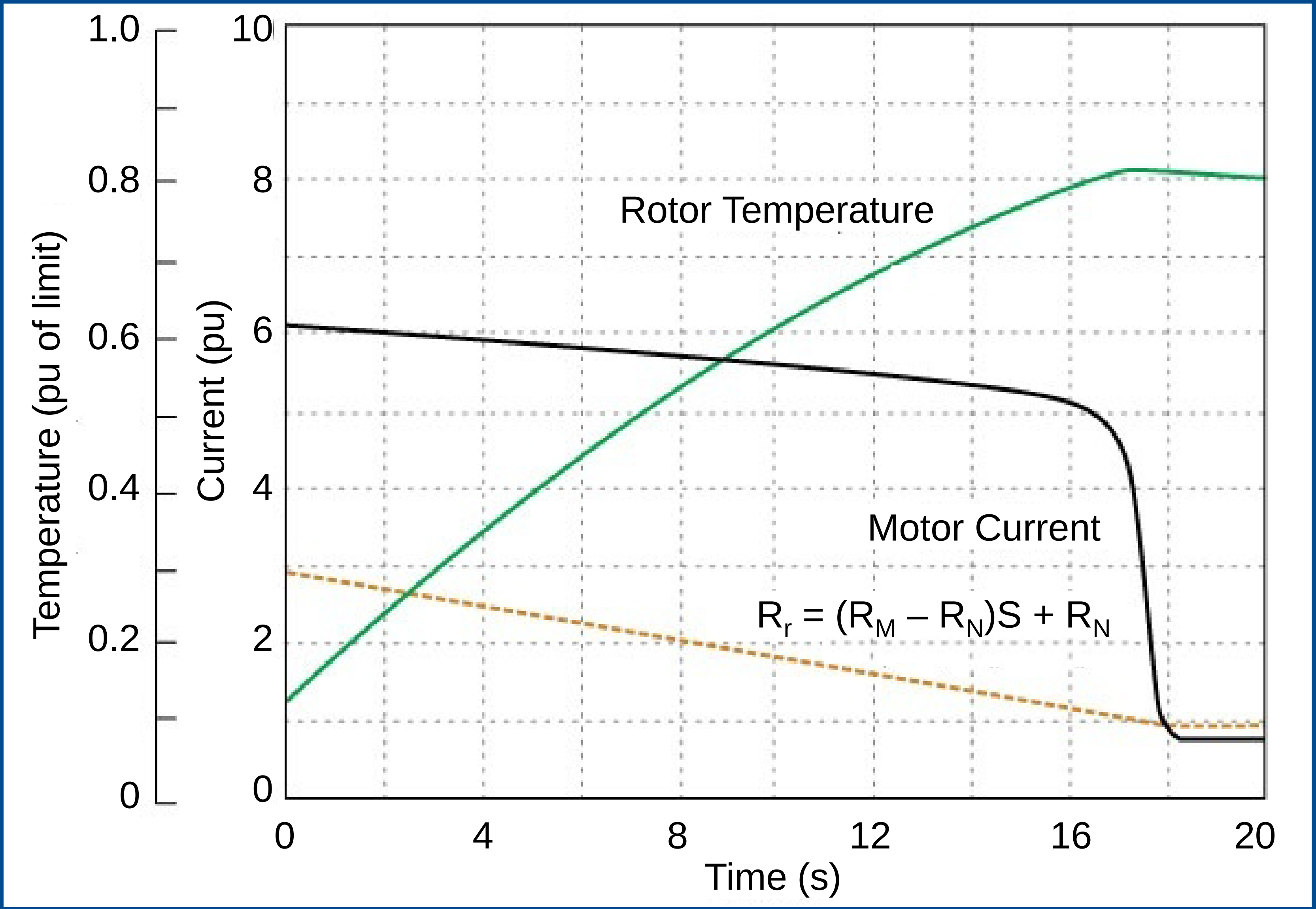
Positive-sequence rotor resistance

$$R_1(s) = [(R_M - R_N)S] + R_N$$

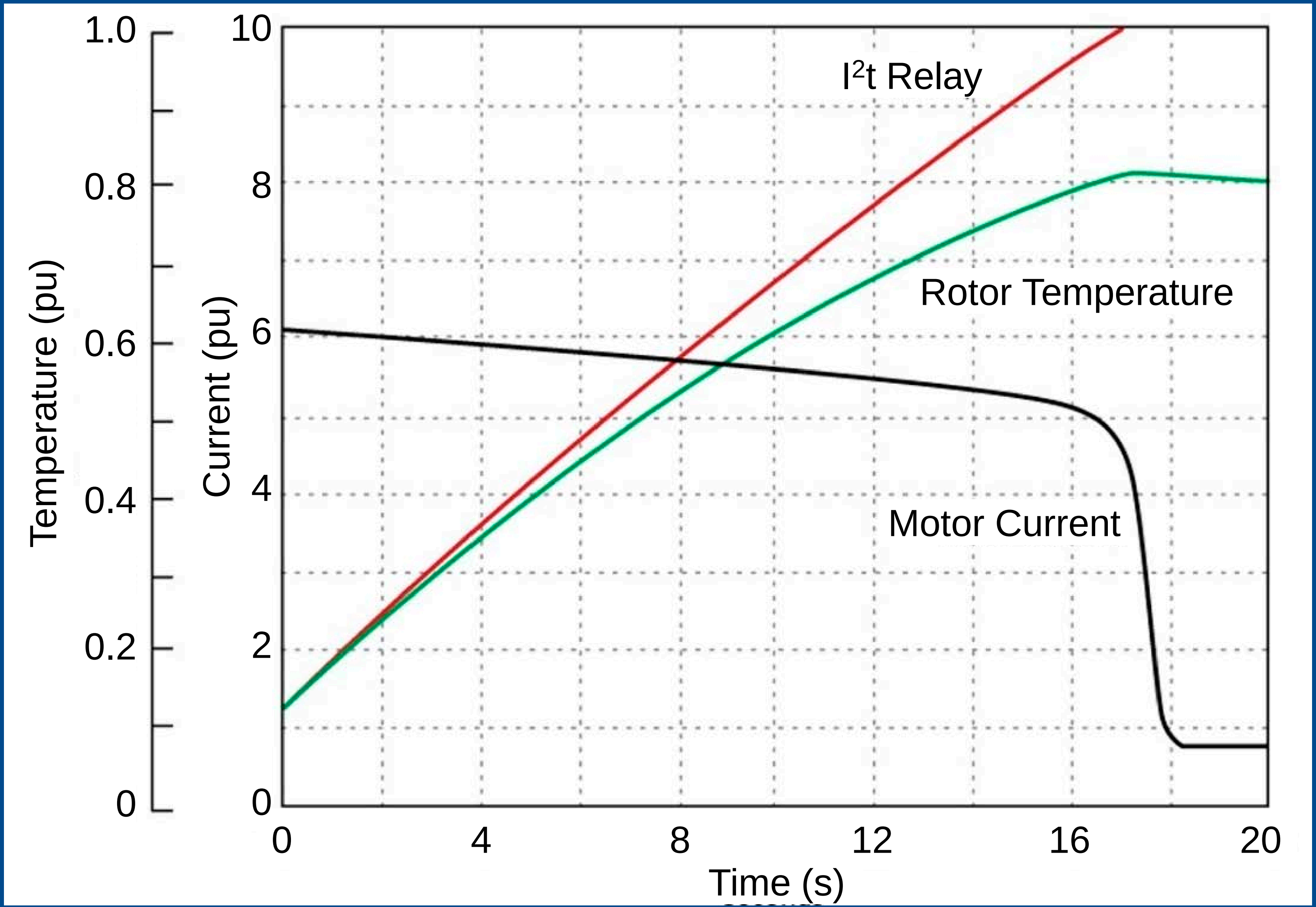
Negative-sequence rotor resistance

$$R_2(s) = [(R_M - R_N)(2 - S)] + R_N$$

Motor Current and Rotor Temperature



Constant Resistance Model Accuracy



Load-Loss / Load-Jam Protection

- Detects load loss on undercurrent or low power
- Trips for safety if load decouples
- Detects load jam using definite-time overcurrent (armed only when motor is running)

Frequent Starts

- Repetitive intermittent operation can cause mechanical stressing of stator or rotor end windings
- Microprocessor-based relays provide for fixed time intervals between starts or limit the number of starts per hour

Frequent Starts or Intermittent Operation

- Starts-per-hour protection limits the number of motor starts in any 60-minute period
- Minimum time between starts prevents immediate restart
- Settings developed using motor data sheet

Frequent Starts or Intermittent Operation

- Induction motors, initially at ambient, usually allow two successive starts – coasting to reset between starts
- One start occurs with motor initially at operating temperature

Antibackspin Protection

- Pump motors can spin backward for a short time after motor shutdown
- Restart during backspin period is dangerous (prevent high torque with premature starts)
- Simple lockout delay follows trip

Synchronous Motor Protection
Loss of Excitation

- Causes
  - Operator error
  - Excitation system failure
  - Flashover across slip rings
  - Incorrect tripping of rotor field breaker
- Consequences
  - Motor operates as induction motor
  - Motor draws reactive power from system

Loss-of-Excitation Detection

Elements detect excessive VAR flow into the motor

- Impedance
- Power factor
- VAR

Synchronous Motor Protection
Loss of Synchronism

- Causes
  - Excessive load
  - Reduced supply voltage
  - Low motor excitation
- Consequences
  - High current pulses may exceed three-phase faults at motor terminals
  - Motor operates at different speed
  - Watts flow out and VAR flows into motor

Loss-of-Synchronism Detection

- Element usually responds to variation on motor power factor angle or reactive power
- Impedance relays available for loss-of-excitation detection may also detect loss of synchronism

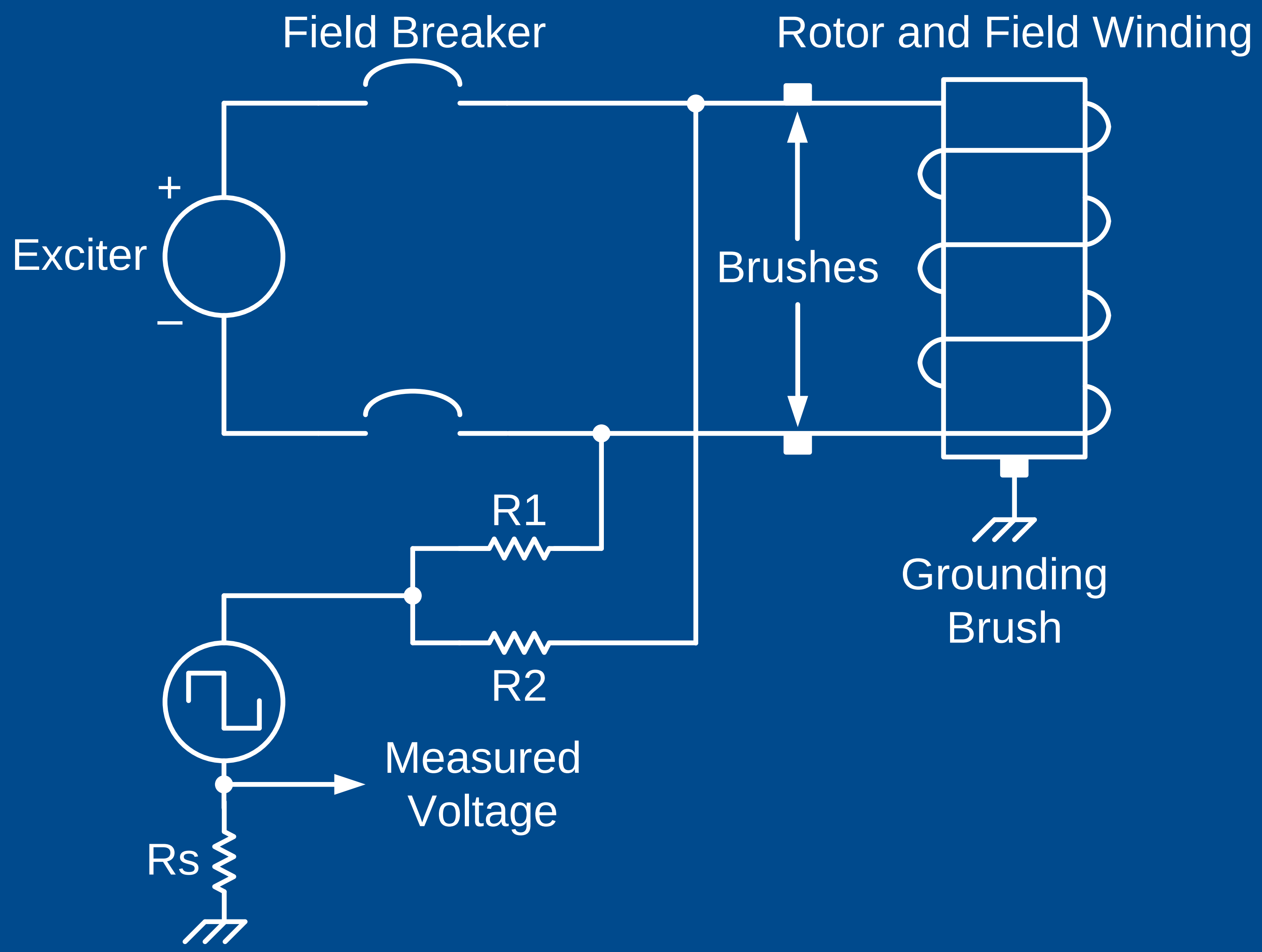
Importance of Field Ground Detection

- Single point-to-ground fault in field winding circuit does not affect motor operation
- Second point-to-ground fault can cause severe damage to machine
  - Excessive vibration
  - Rotor steel and / or copper melting

Rotor Ground Detection Methods

- Voltage divider
- DC injection
- AC injection
- Switched dc injection

Switched DC Injection Method



Questions?