Protective Relay Fundamentals

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Protection Review

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

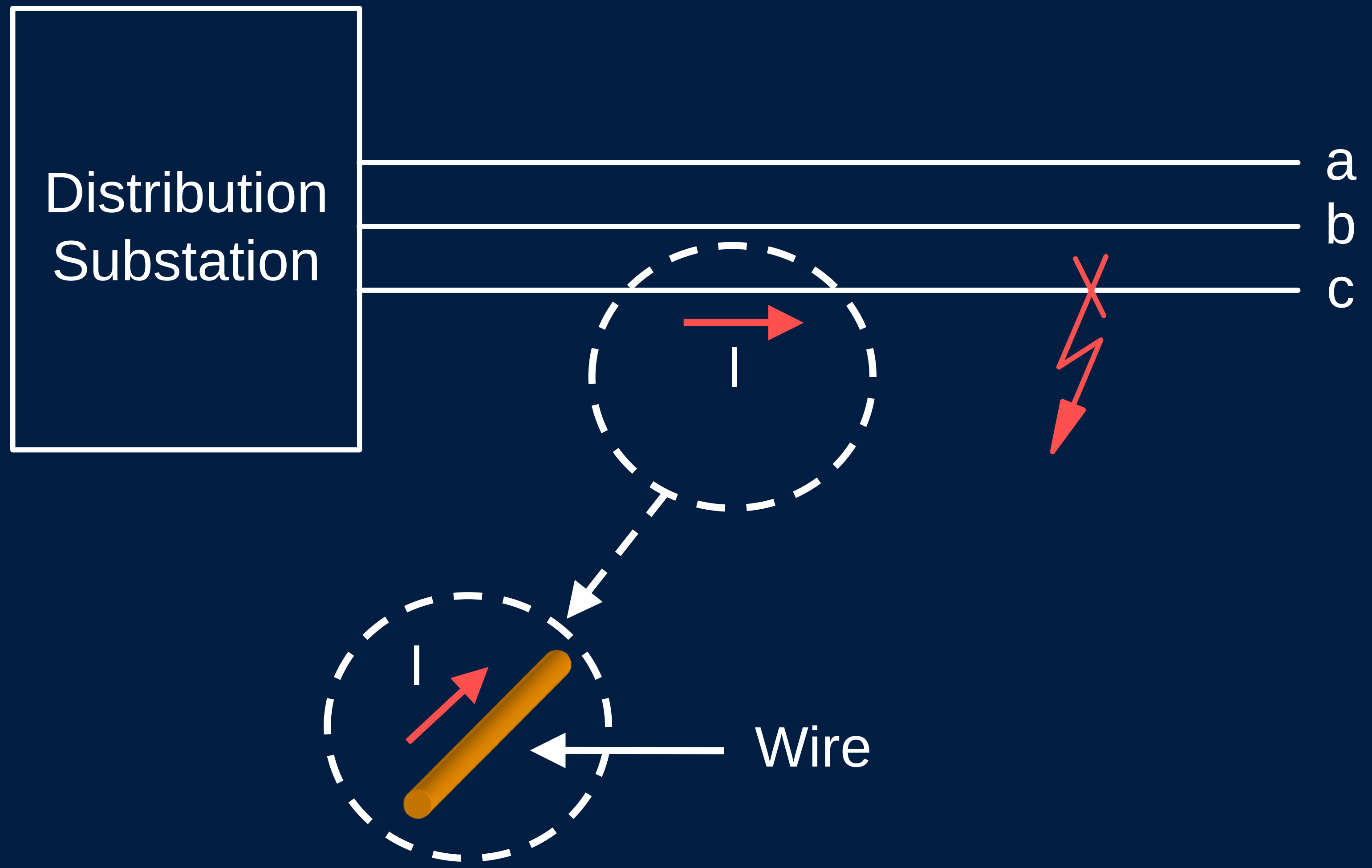
Power System Faults

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

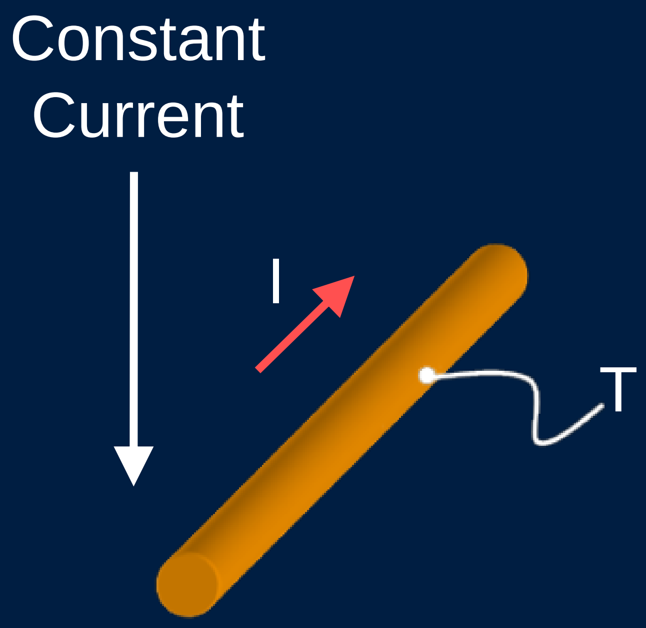
Typical Short-Circuit-Type Distribution

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

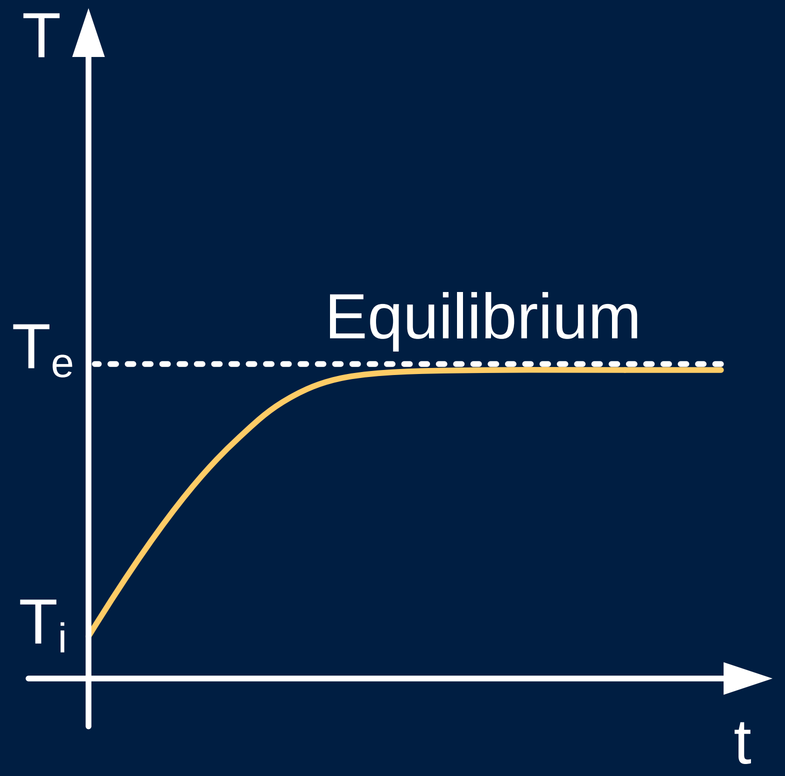
Faults in Electrical Systems Produce Current Increments



Temperature Rise From Current

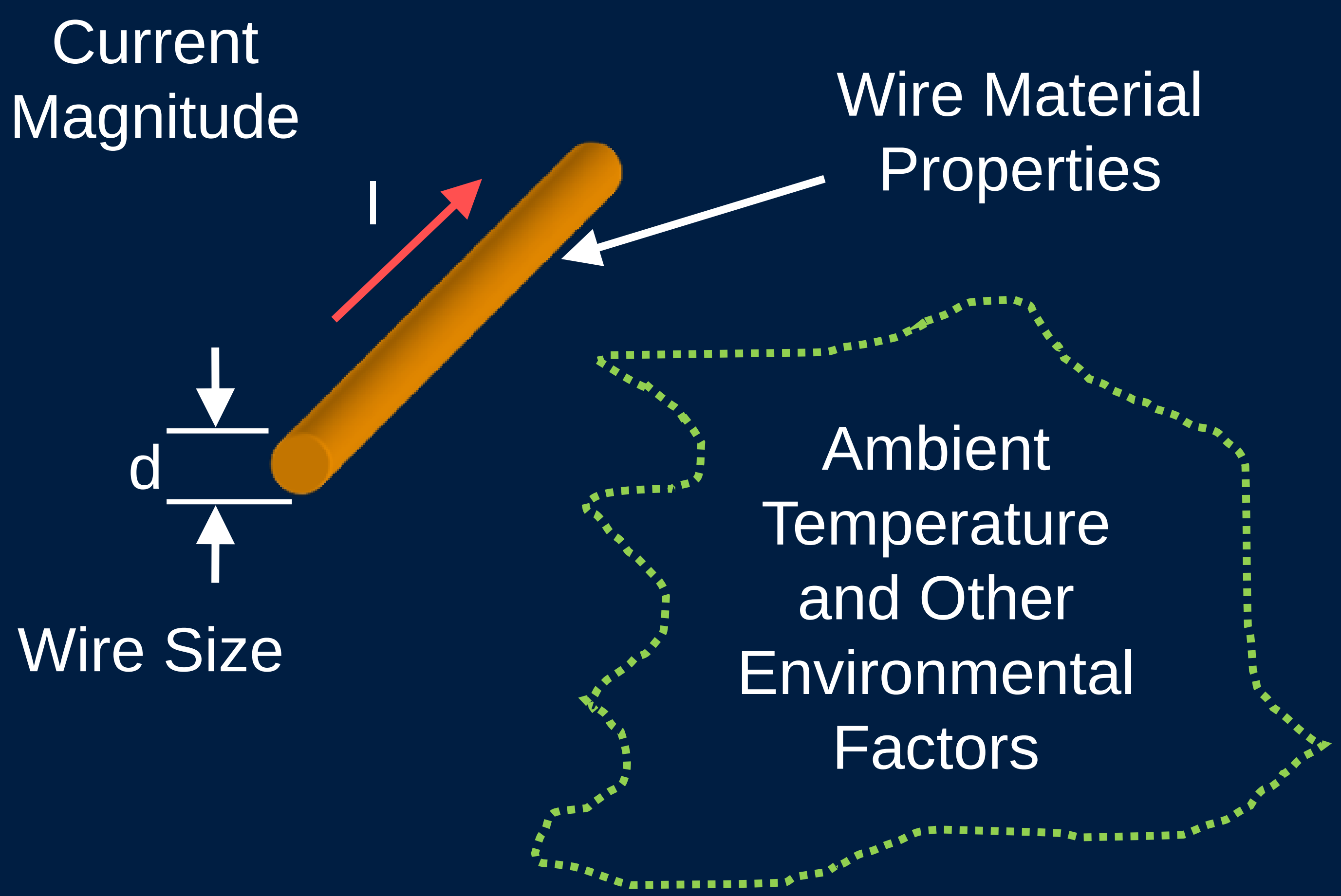


$$\frac{dW}{dt} = I^2R$$

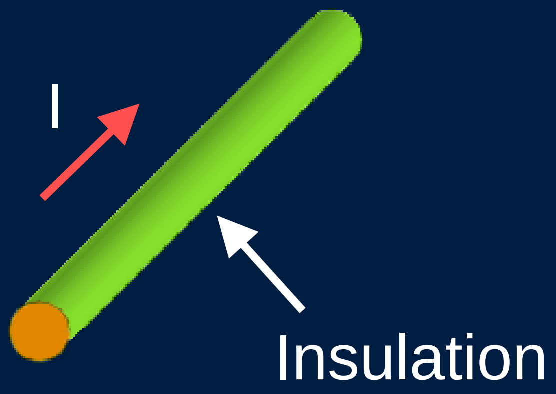


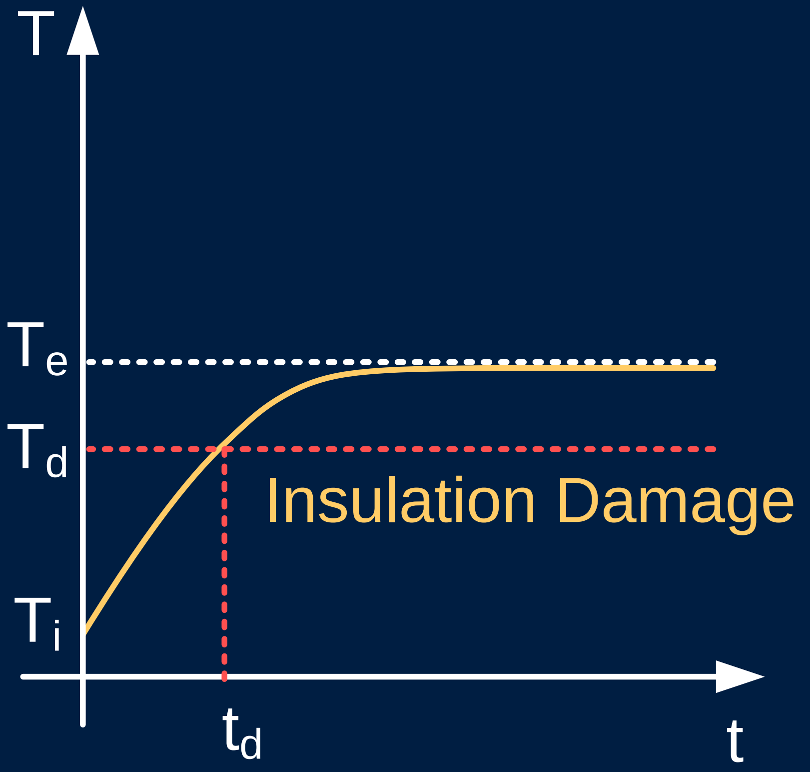
$$T(t) = (T_i - T_e)e^{-t/\tau} + T_e$$

Factors Influence Wire Heating

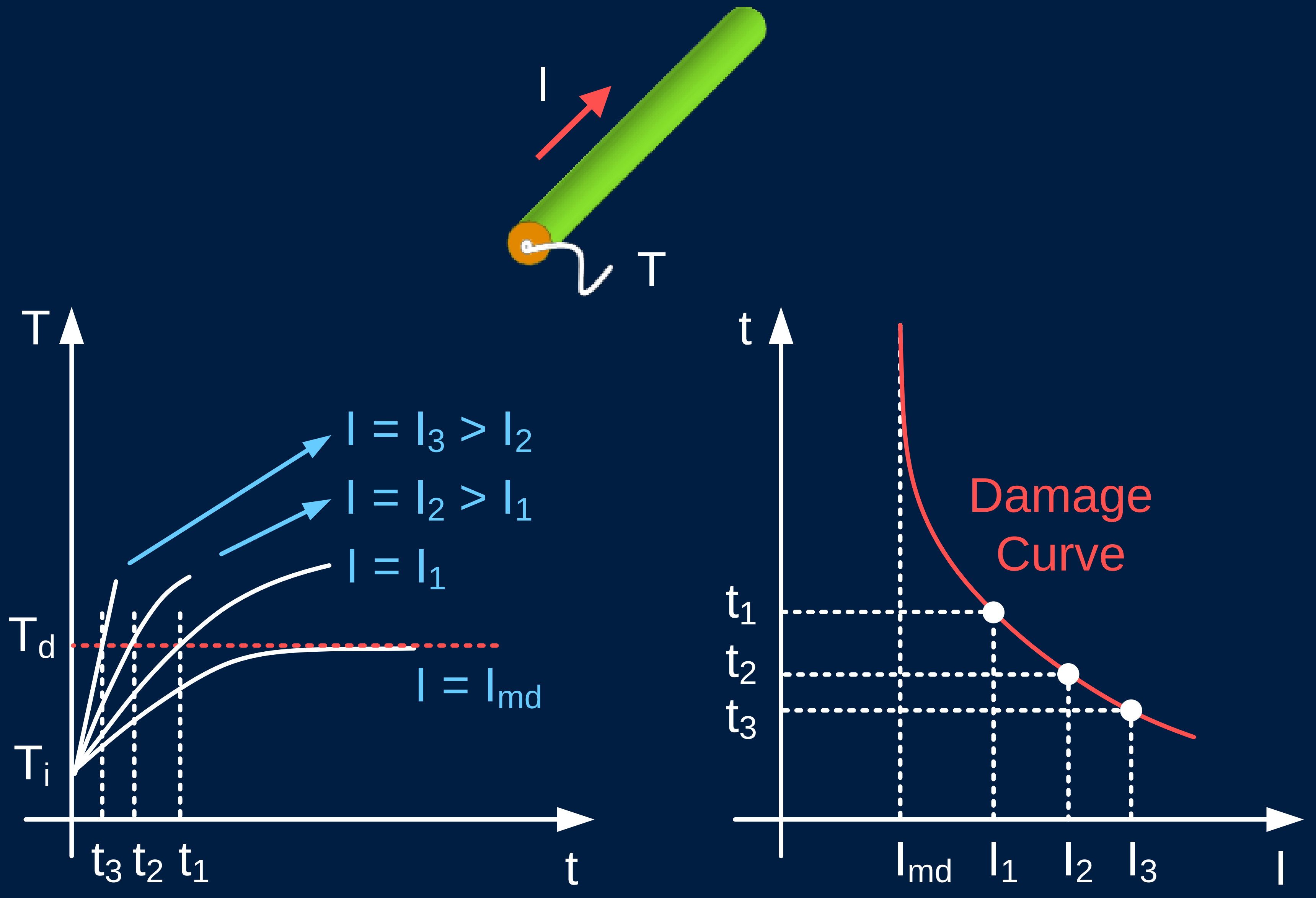


Insulated Conductor (Cable) Thermal Damage

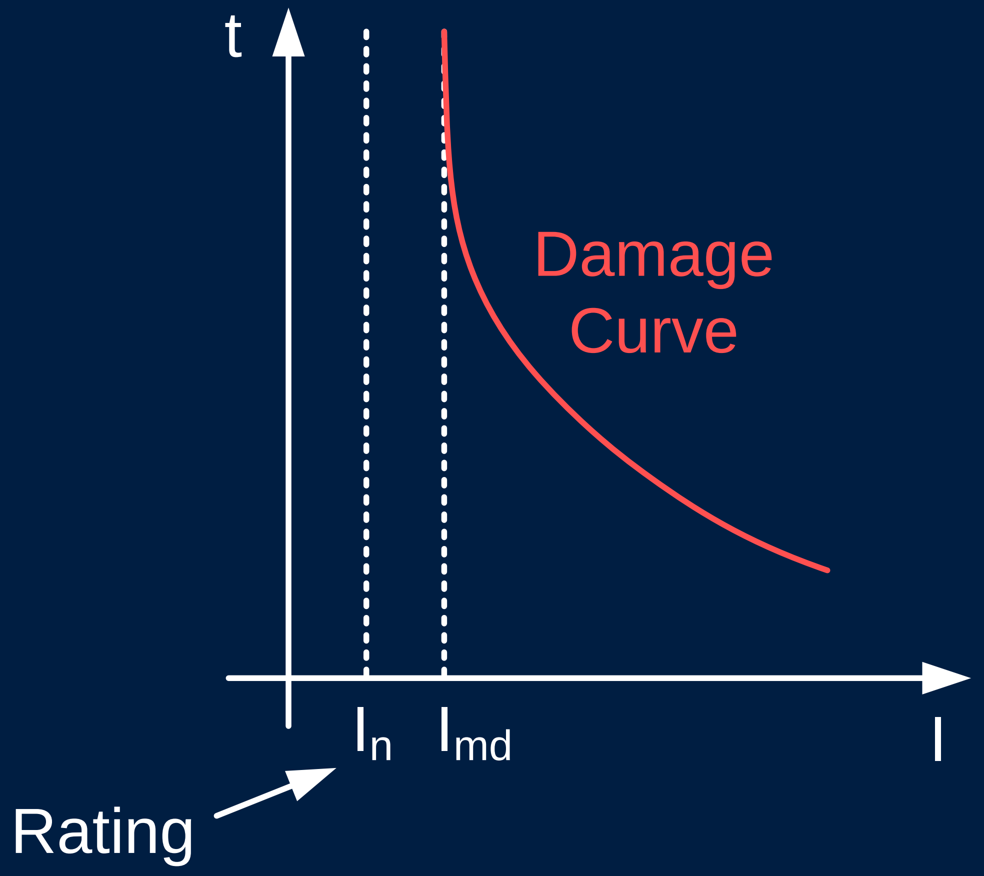




Insulated Conductor Thermal Damage

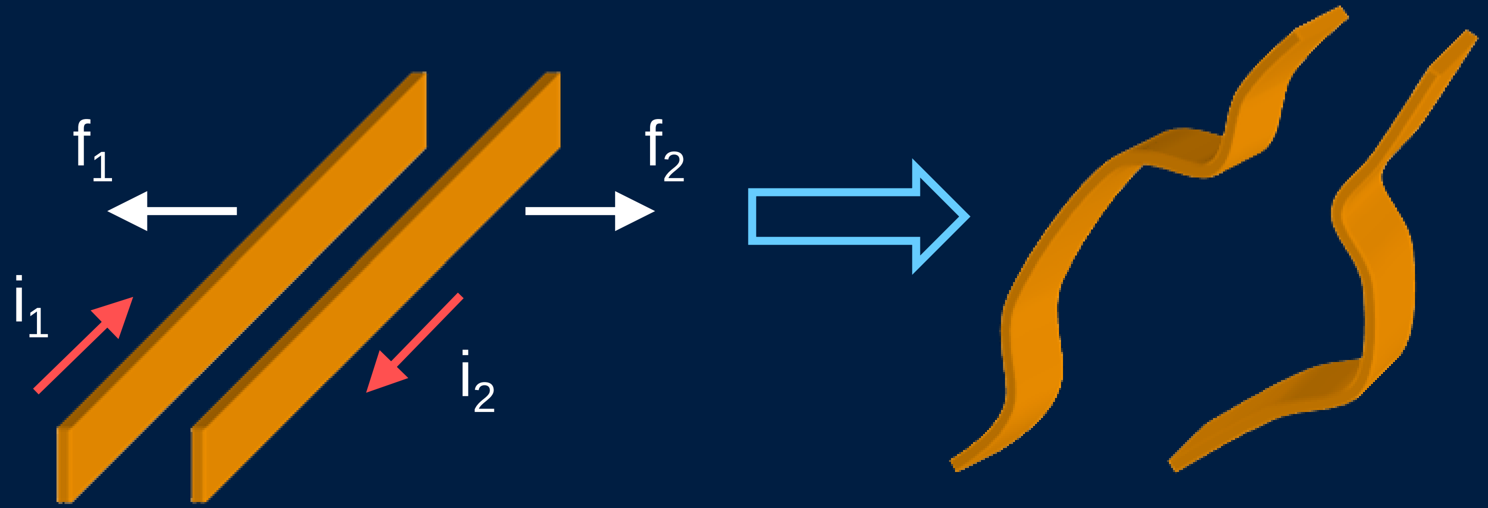


Electrical Equipment Component Thermal Damage Curve



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

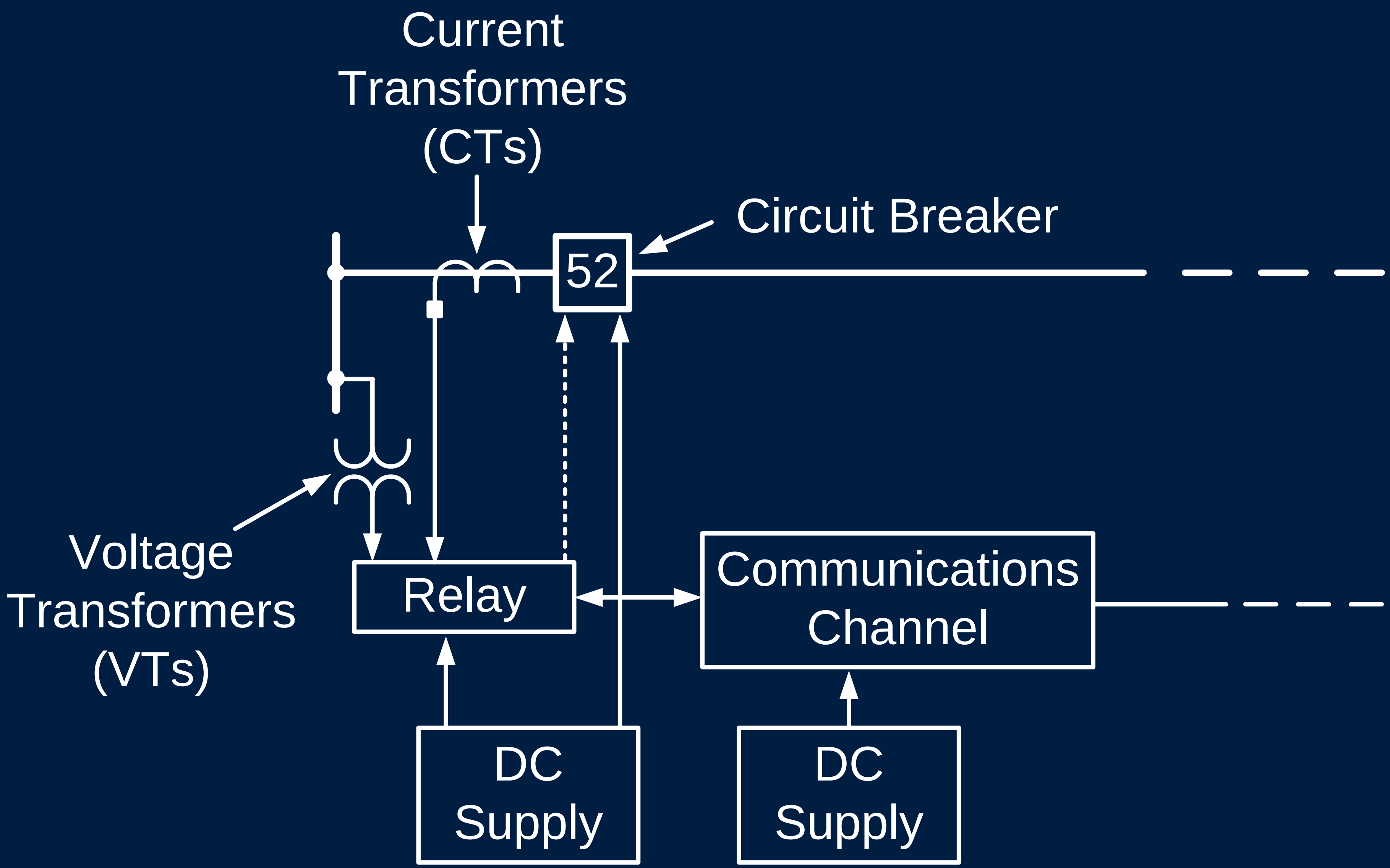
Relay Classification

- 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

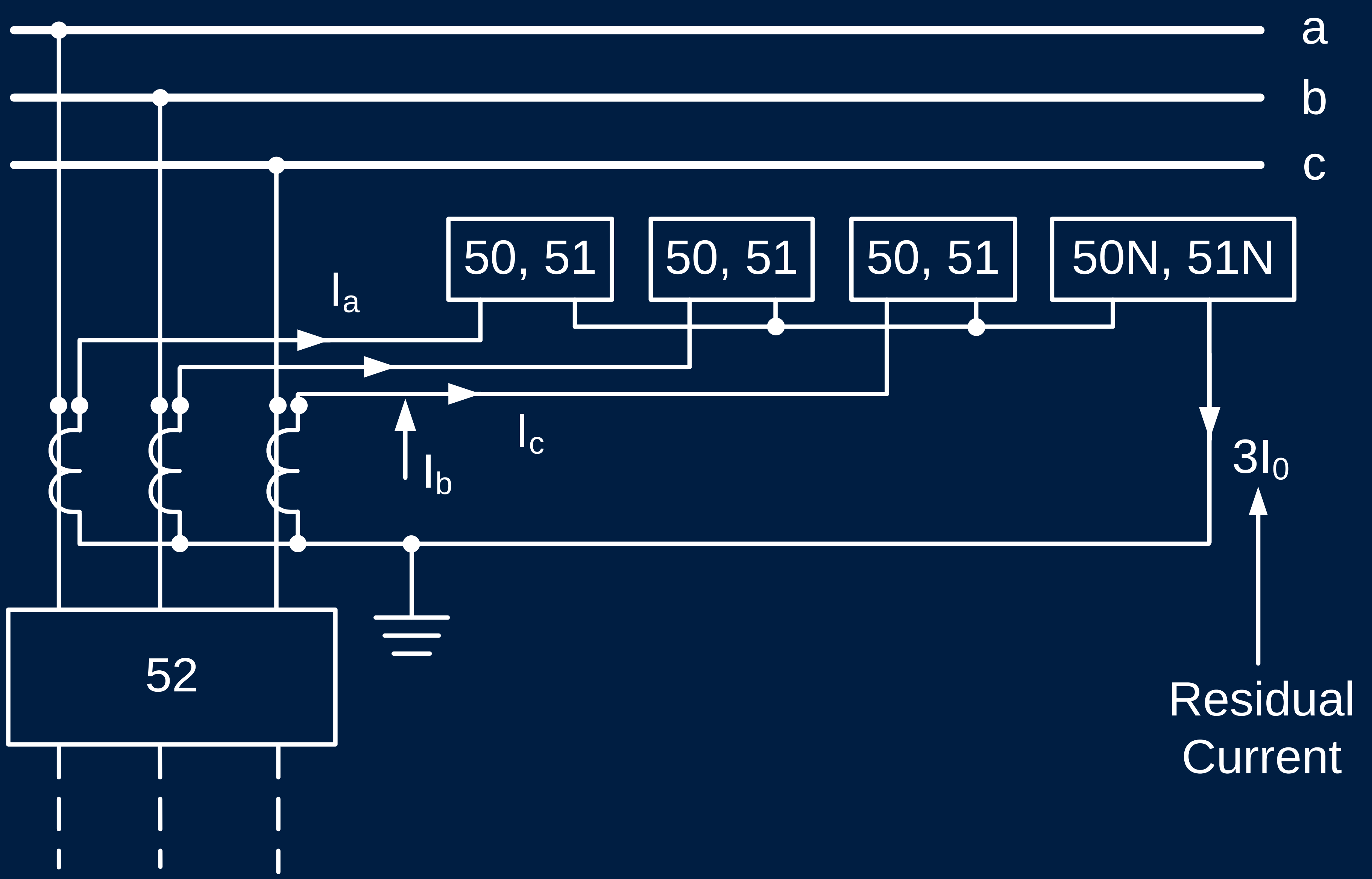
Protection System Elements

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

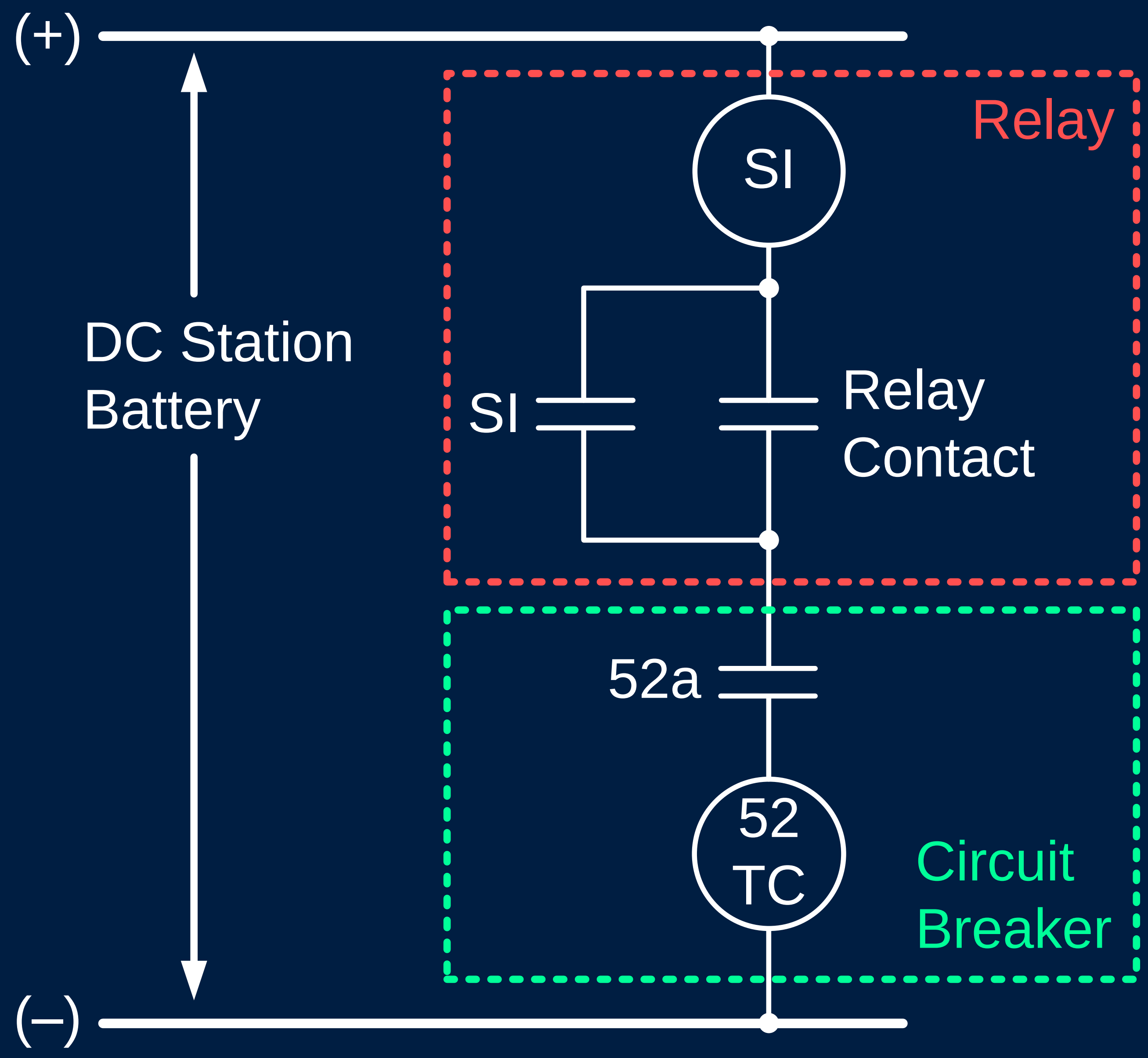
Instrument Transformers

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

Overcurrent Relay Connections



DC Tripping Circuit



Overcurrent Relay Setting

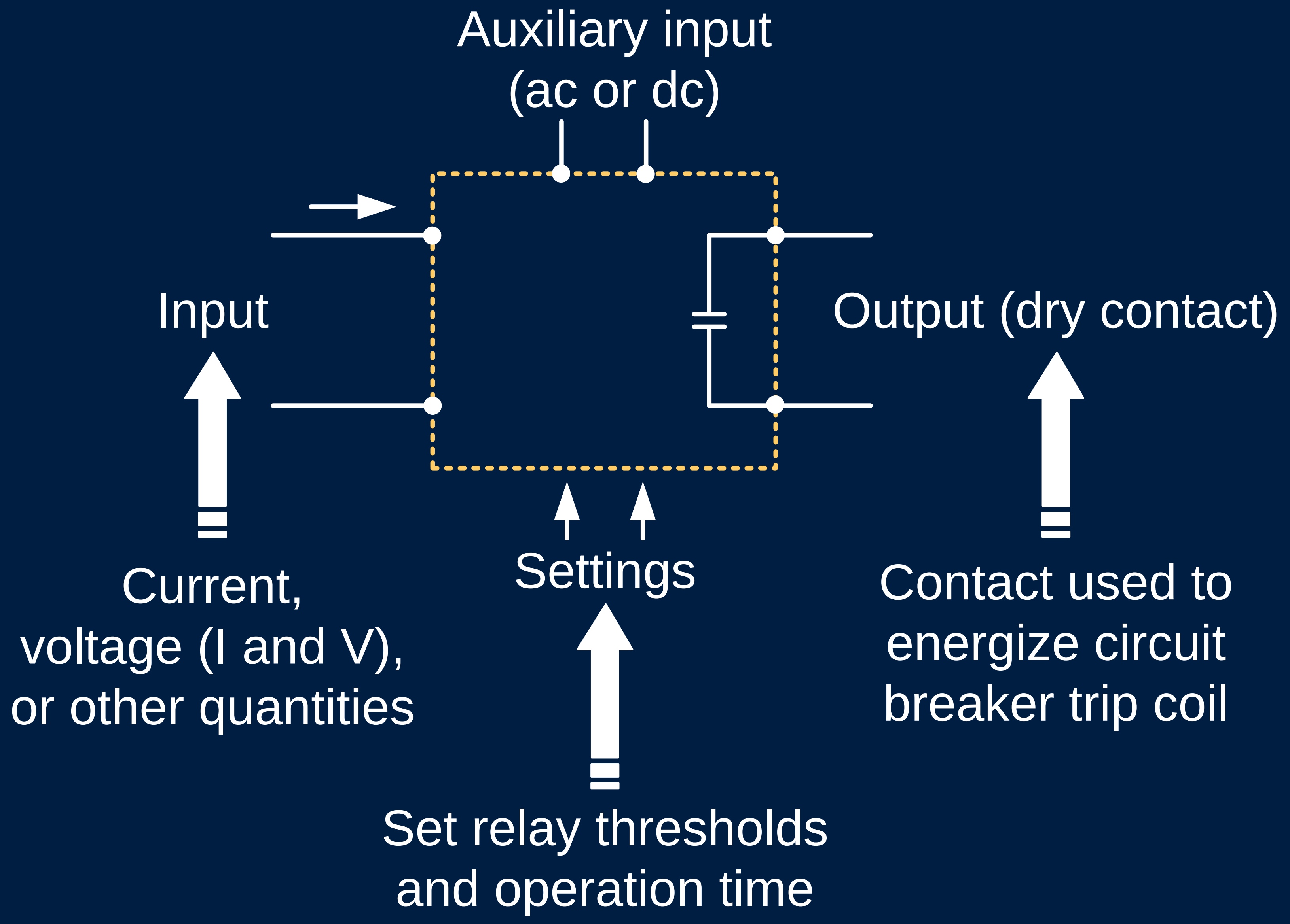
- 51 elements
  - Pickup setting
  - Time-dial setting
- 50 elements
  - Pickup setting
  - Time delay

Review

- What is the function of power system protection?
- Name two protective devices
- For what purpose is IEEE device 52 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?

Digital Relay Basics

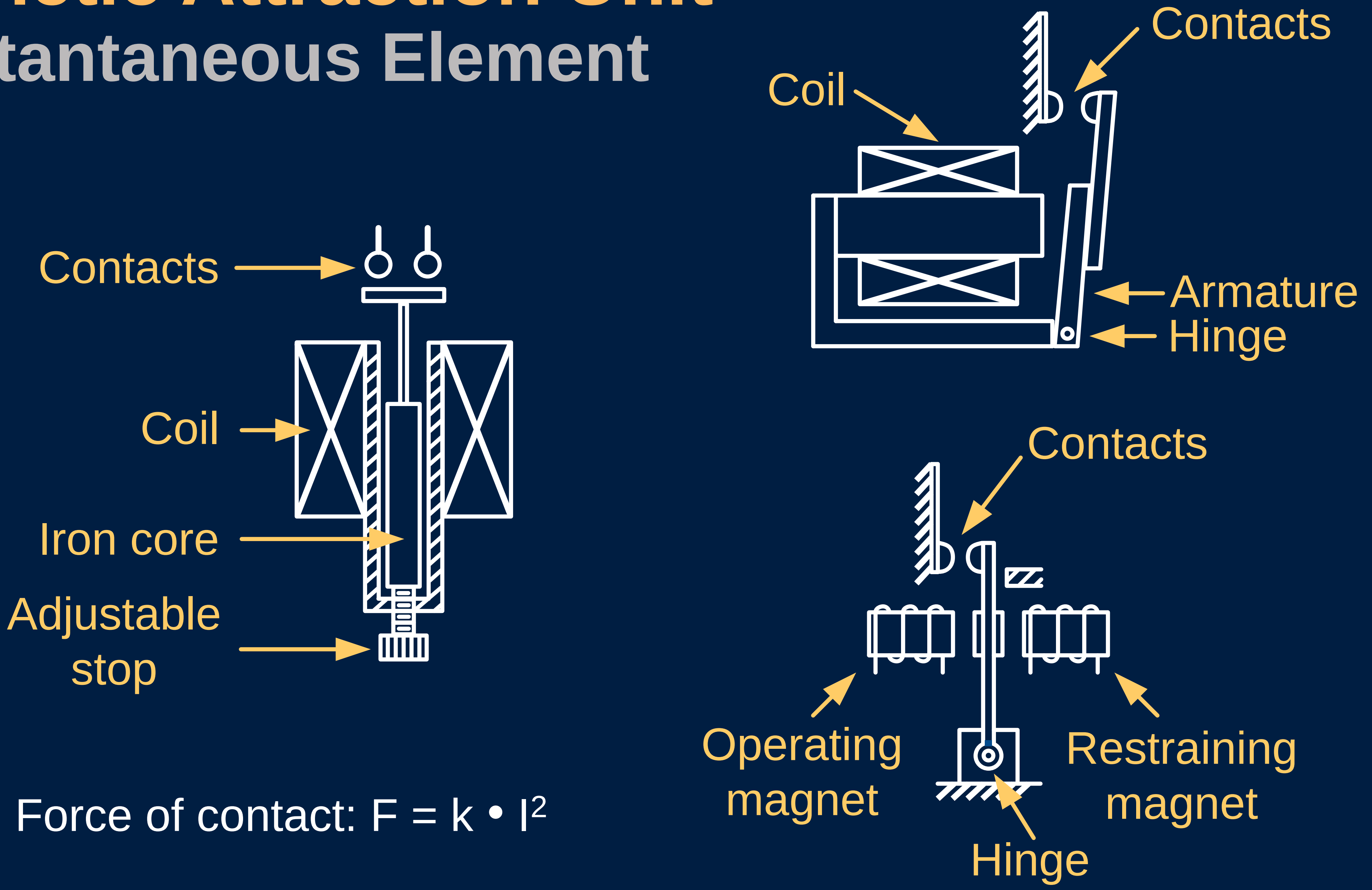
Simple Protective Relay



Electromechanical Instantaneous Overcurrent Elements

Magnetic Attraction Unit

Instantaneous Element



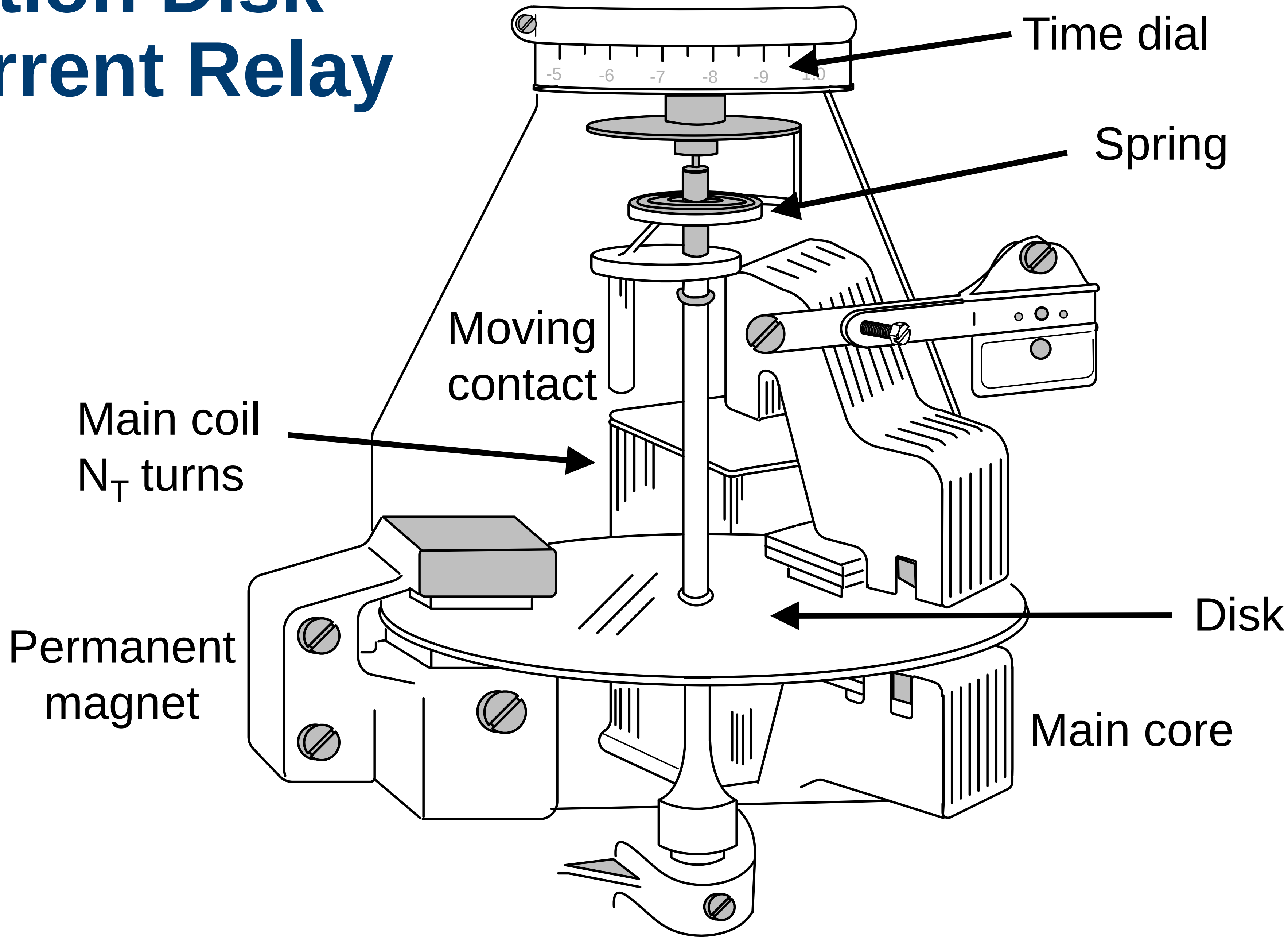
Force of contact: $F = k \bullet I^2$

Alternatives for Setting Pickup Current

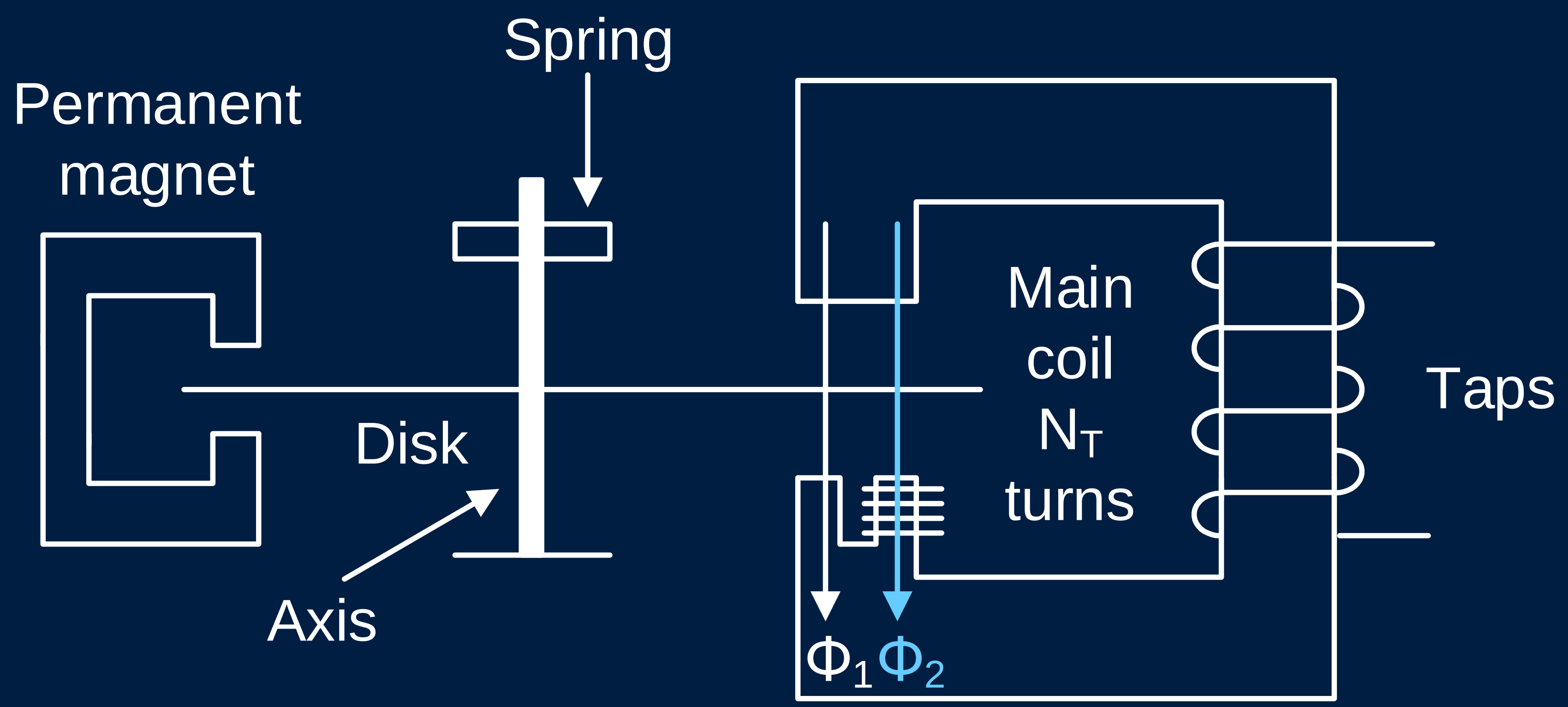
- Tap in relay current coil
- Adjust air gap
- Adjust spring

Electromechanical Inverse-Time Overcurrent Elements

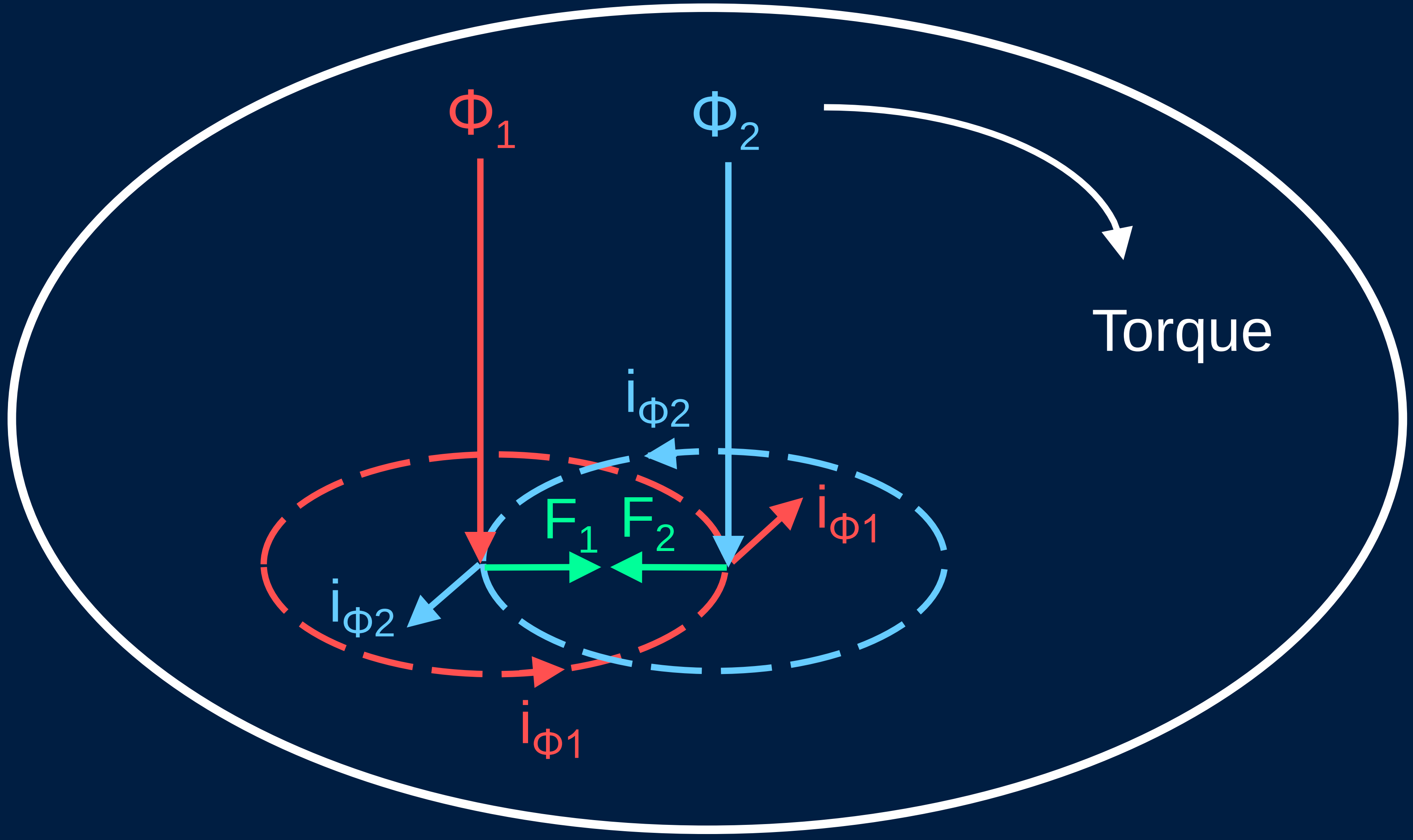
Induction Disk Overcurrent Relay



Simplified View
Shaded Pole Element



Electromagnetic Induction Principle

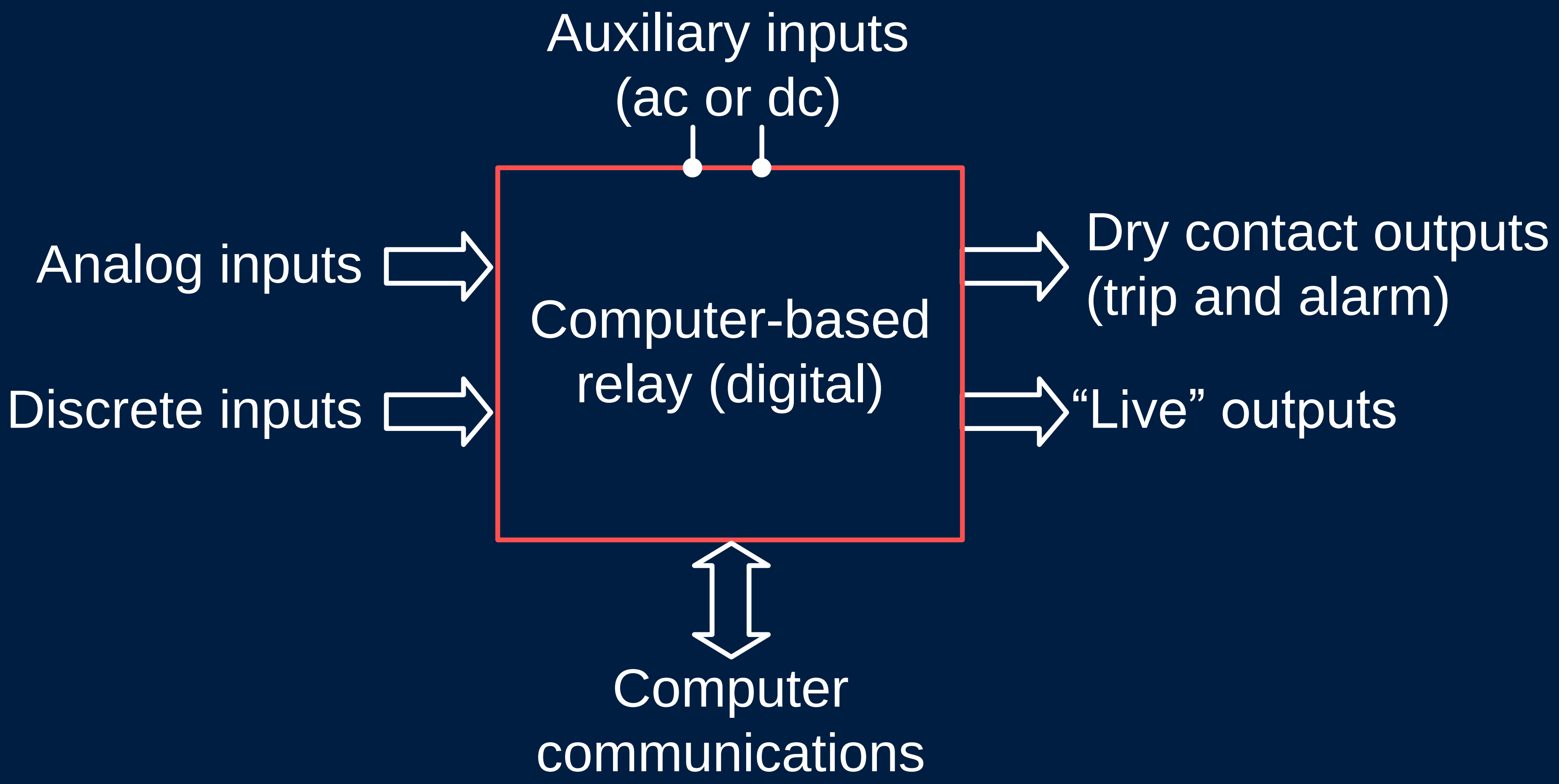


Summary of Induction 51 Element Settings

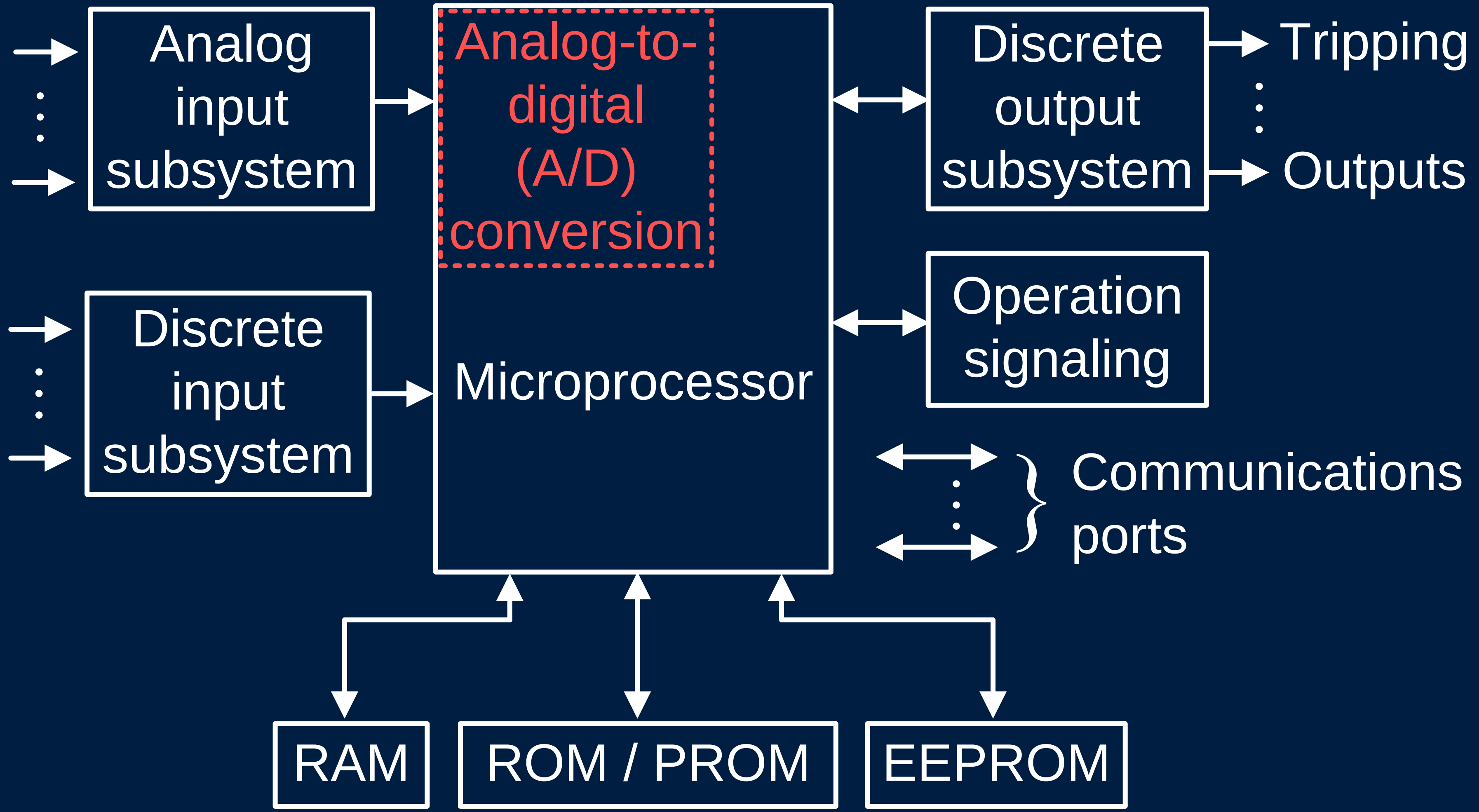
- Pickup current setting – taps in relay current coil
- Time-current curve setting – controls initial disk position (time-dial setting)

Microprocessor-Based Protection

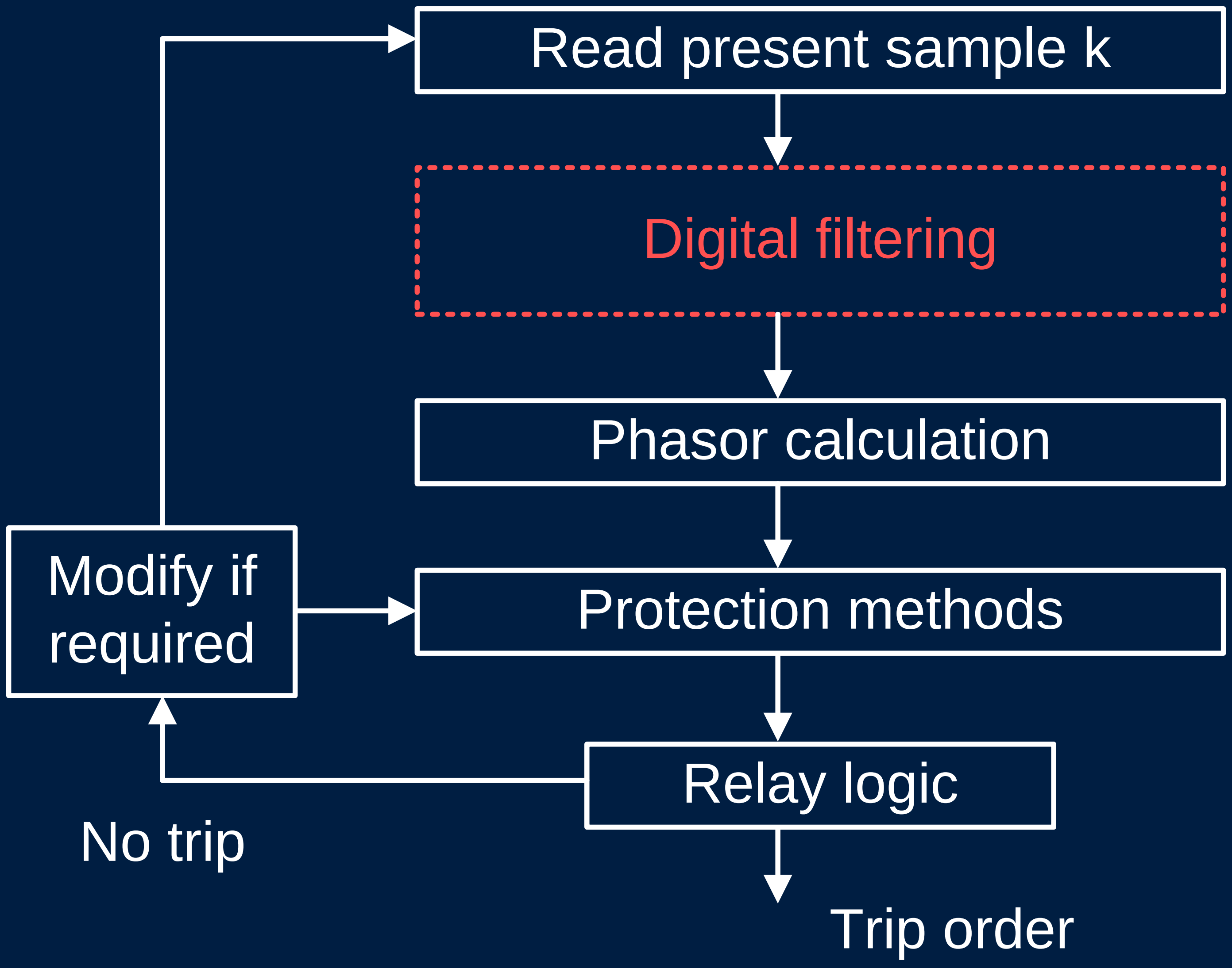
Digital Relay I/O Scheme



Digital Relay Architecture



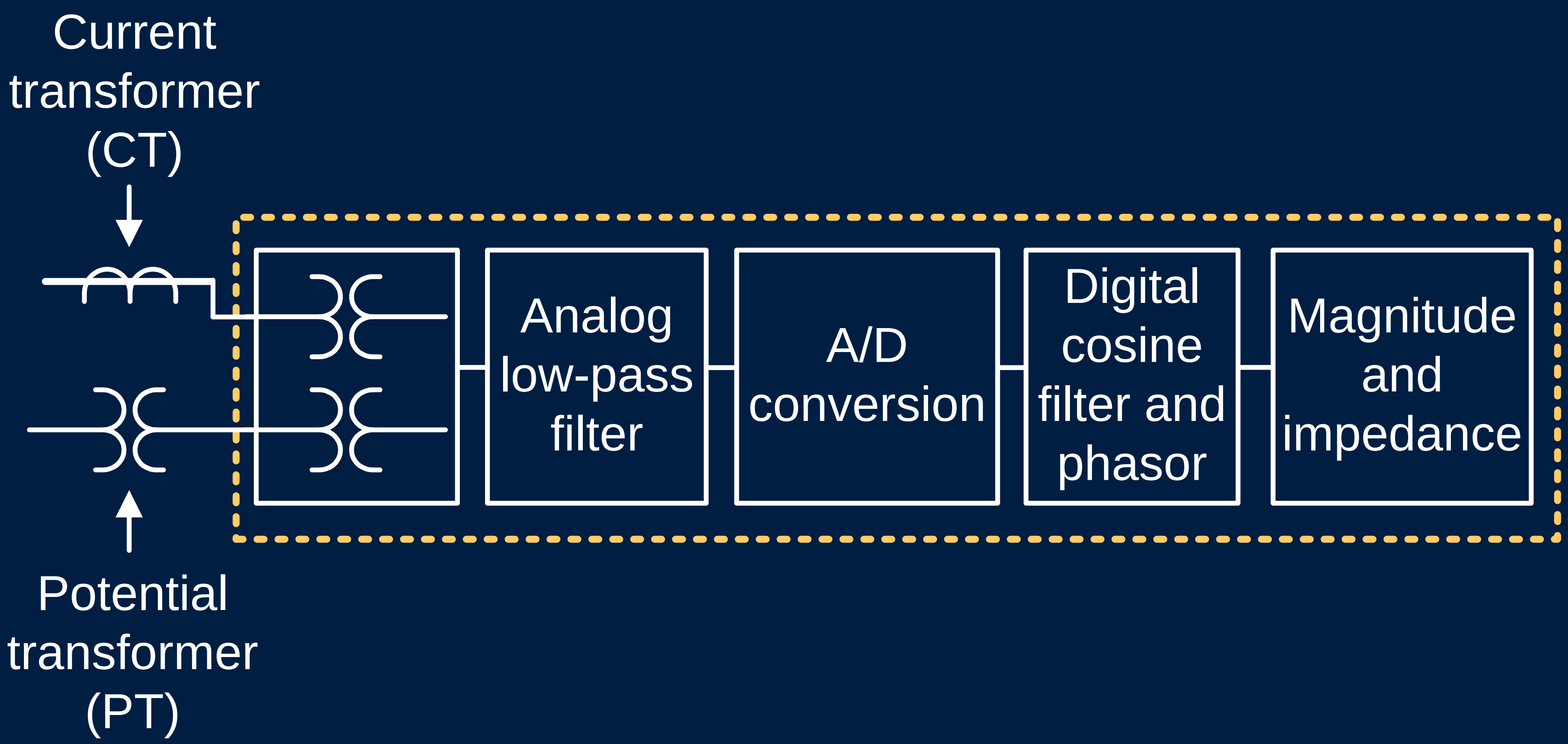
Digital Relay Algorithm



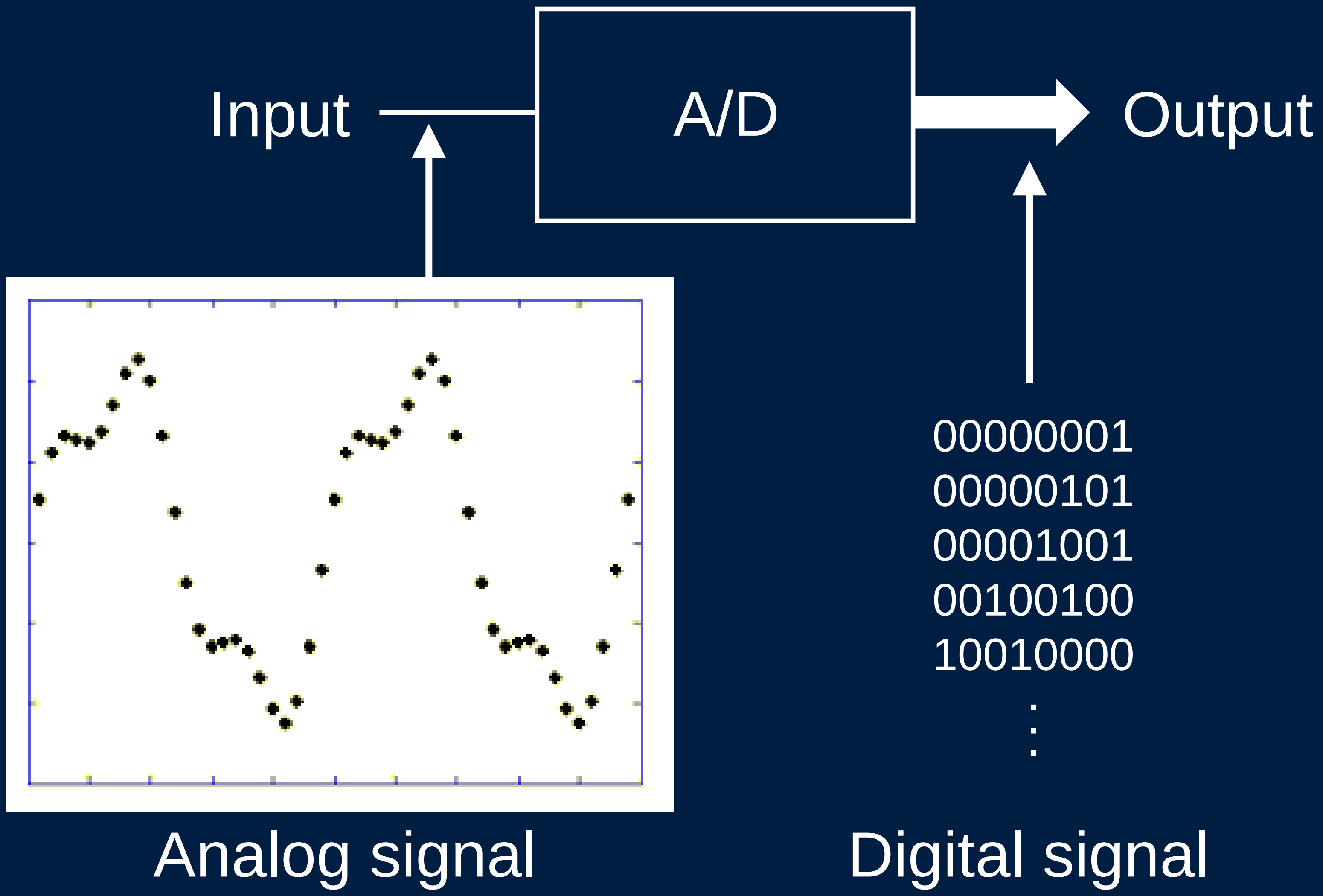
Relay Operation

Analog Inputs

Signal Path for Microprocessor-Based Relays

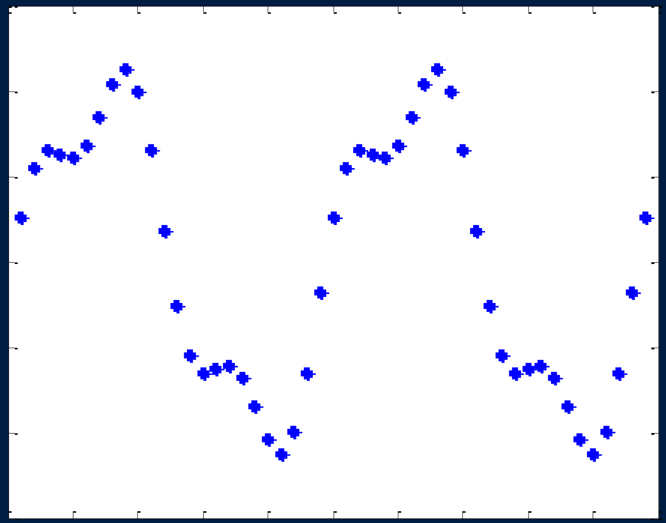


A/D Conversion



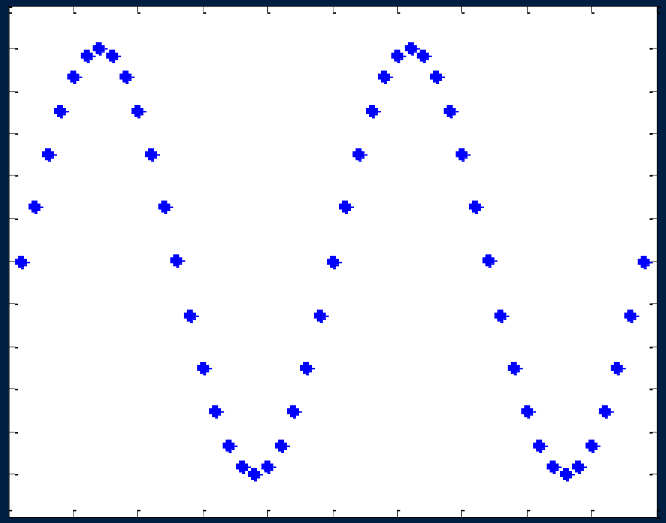
Digital Filtering

Nonfiltered signal
(samples)



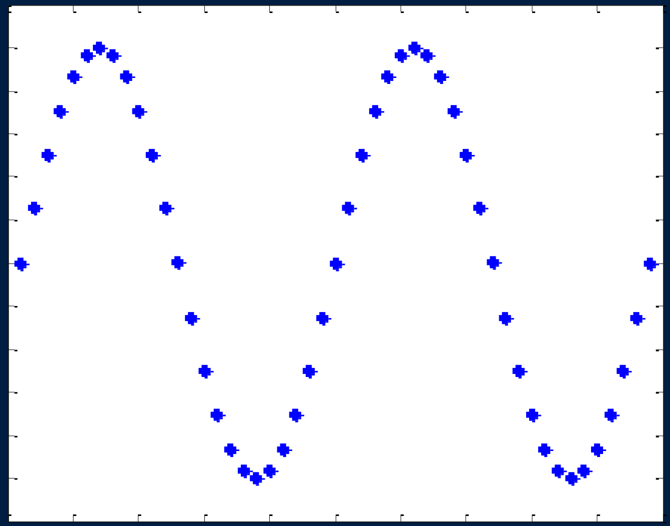
Digital filtering

Filtered signal
(samples)



Phasor Calculation

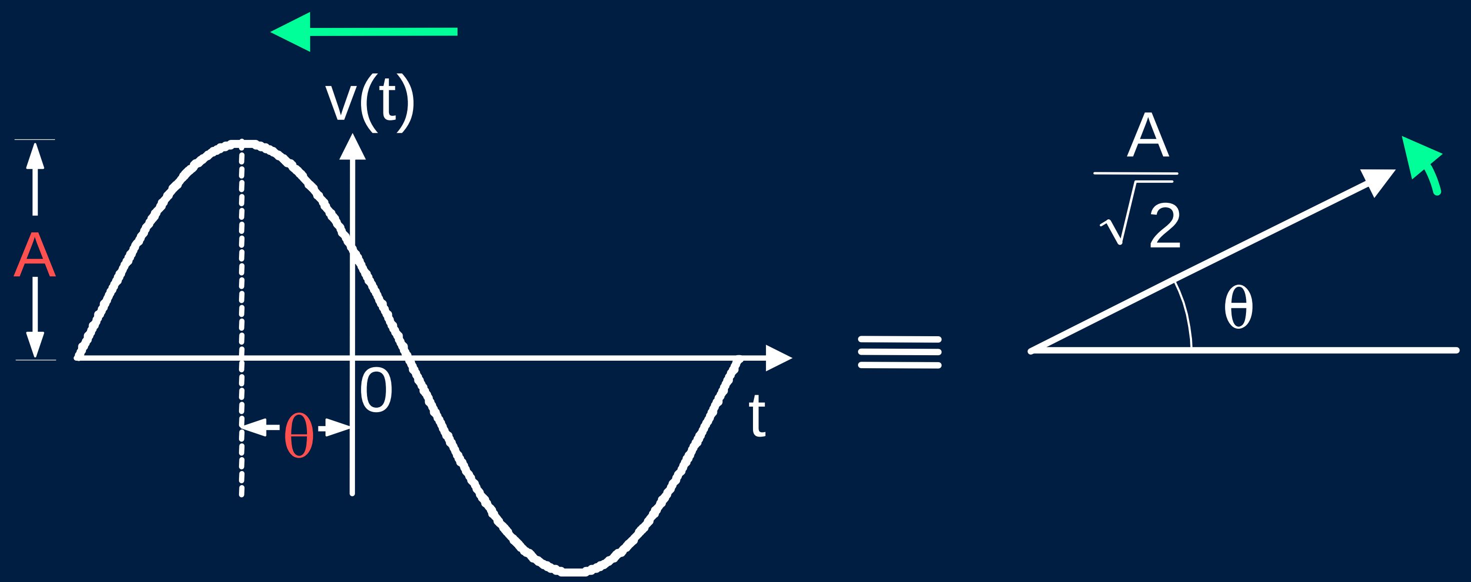
Filtered signal
(samples)



Phasor calculation

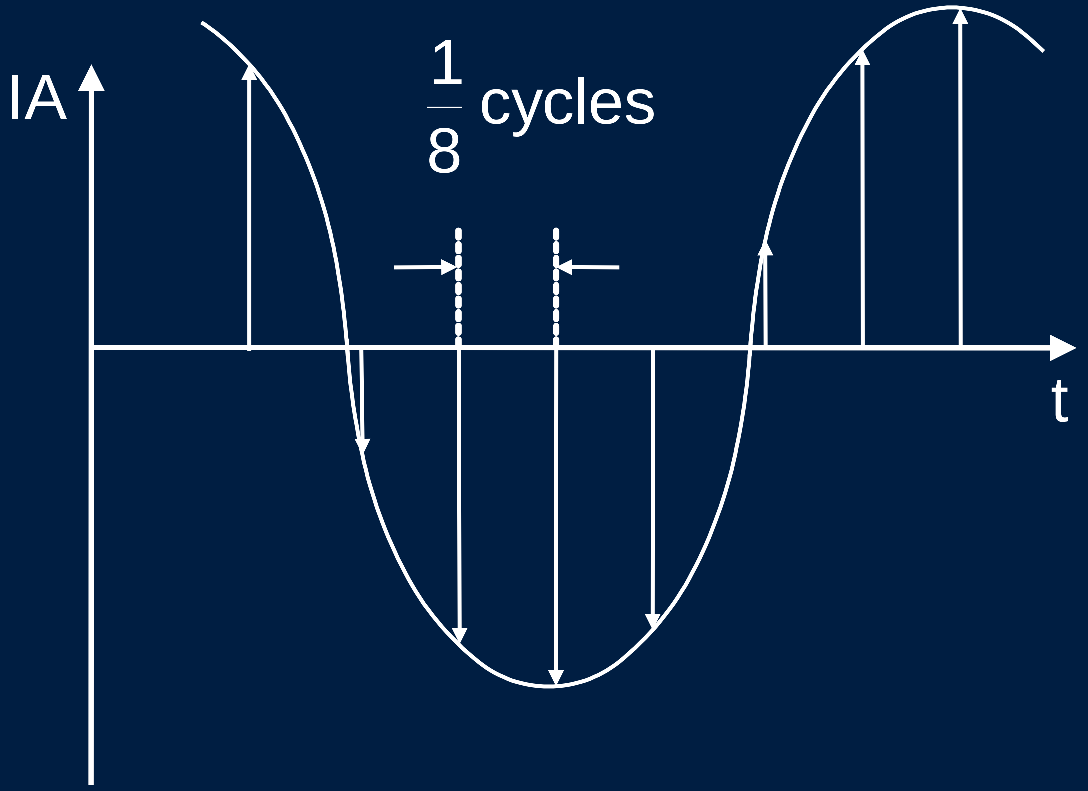
Phasor samples:
magnitude and angle
versus reference

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

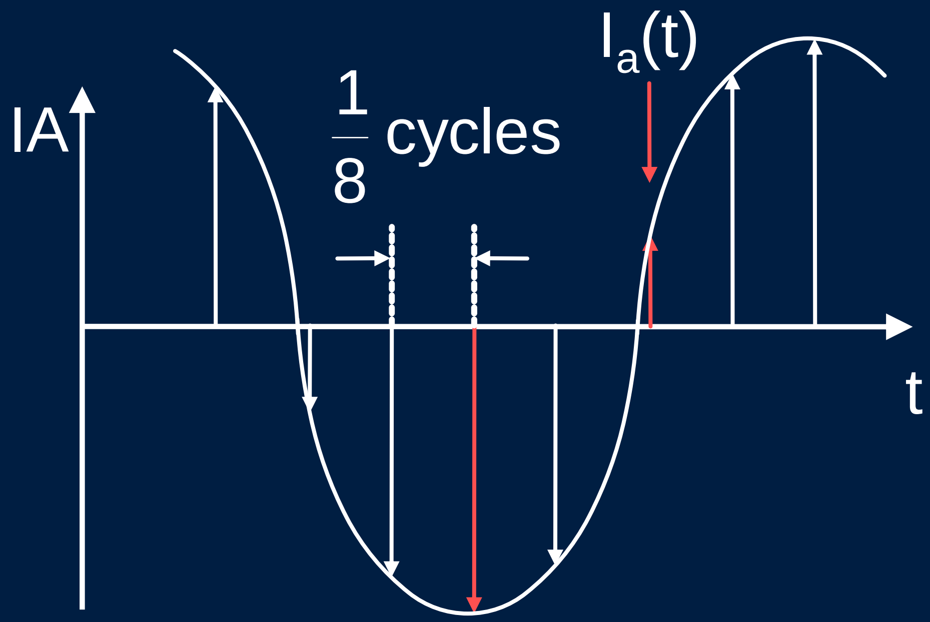
$$\text{Magnitude} = \sqrt{x^2 + y^2}$$

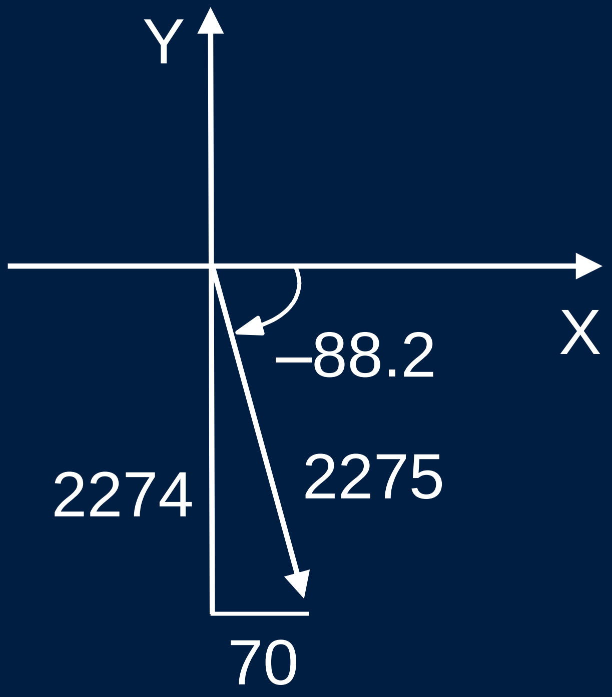
$$\text{Angle} = \arctan\left(\frac{y}{x}\right)$$

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

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

$$IA = 70 + -2274j \quad = \quad 2275\angle -88.2^\circ$$





Relay Operation

Relay Word Bits and Logic

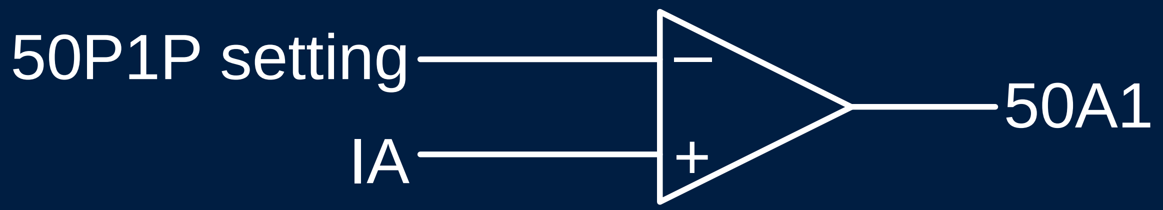
Relay Word Bits

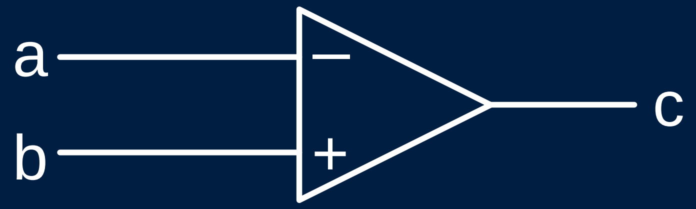
- Instantaneous overcurrent
- Time overcurrent
- Voltage elements
- Inputs
- Internal relay logic – SELOGIC® variable (SV) and latches
- Outputs

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

Instantaneous Overcurrent Element

- 50P1P = instantaneous phase overcurrent setting
- IA = Phase A measured current
- 50A1 = 1 if IA ≥ 50P1P; 50A1 = 0 if IA < 50P1P



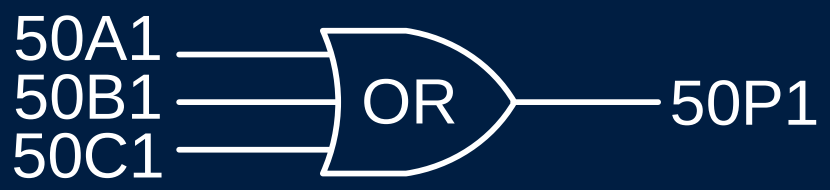


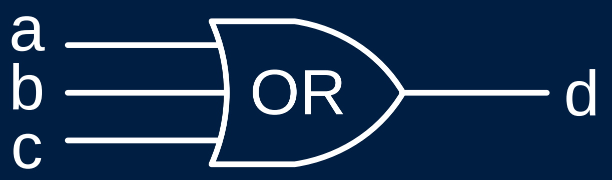
Comparator

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

Instantaneous Overcurrent Element

- 50P1 = 1 if 50A1, 50B1, or 50C1 = 1
- 50P1 = 0 if 50A1, 50B1, and 50C1 = 0

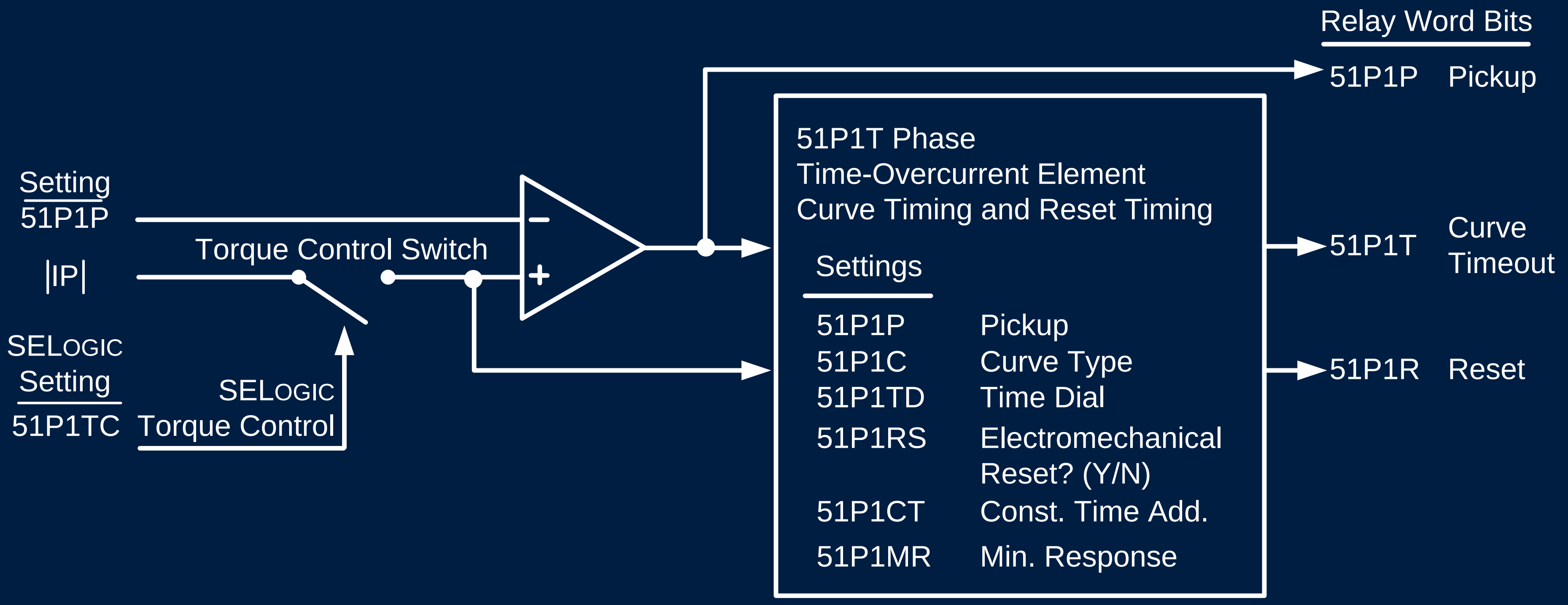




When a, b, or c terminal is logical 1,
output d is logical 1

Phase Time-Overcurrent Element

SEL-751 Feeder Protection Relay



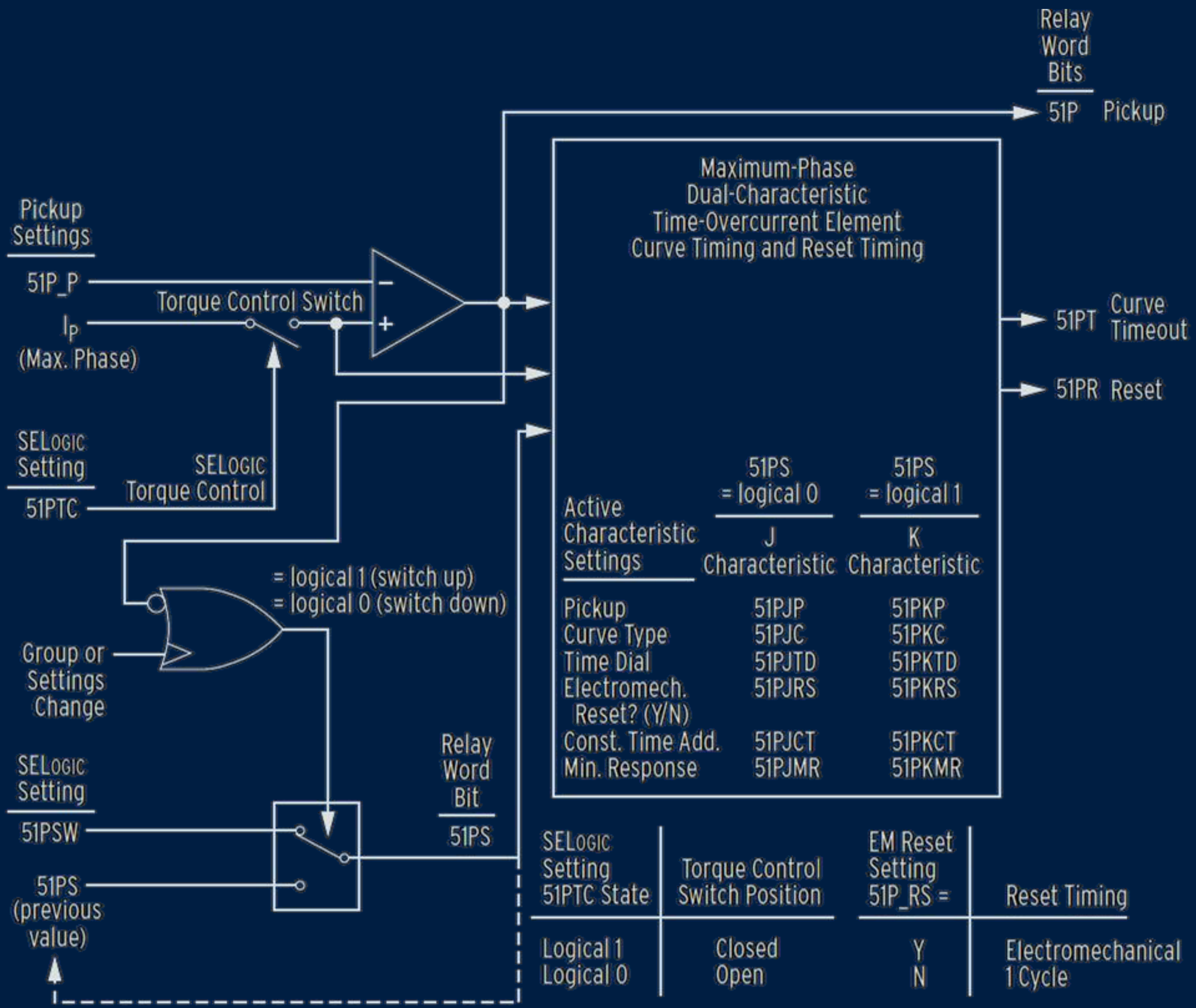
Controls the Torque Control Switch

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

Setting 51P1RS=	Reset Timing
Y	Electromechanical
N	1 Cycle

Phase Time-Overcurrent Element

SEL-651R-2



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)	$t_p = TD \cdot \left(0.00262 + \frac{0.00342}{M^{0.02} - 1} \right)$	$t_r = TD \cdot \left(\frac{0.323}{1 - M^2} \right)$

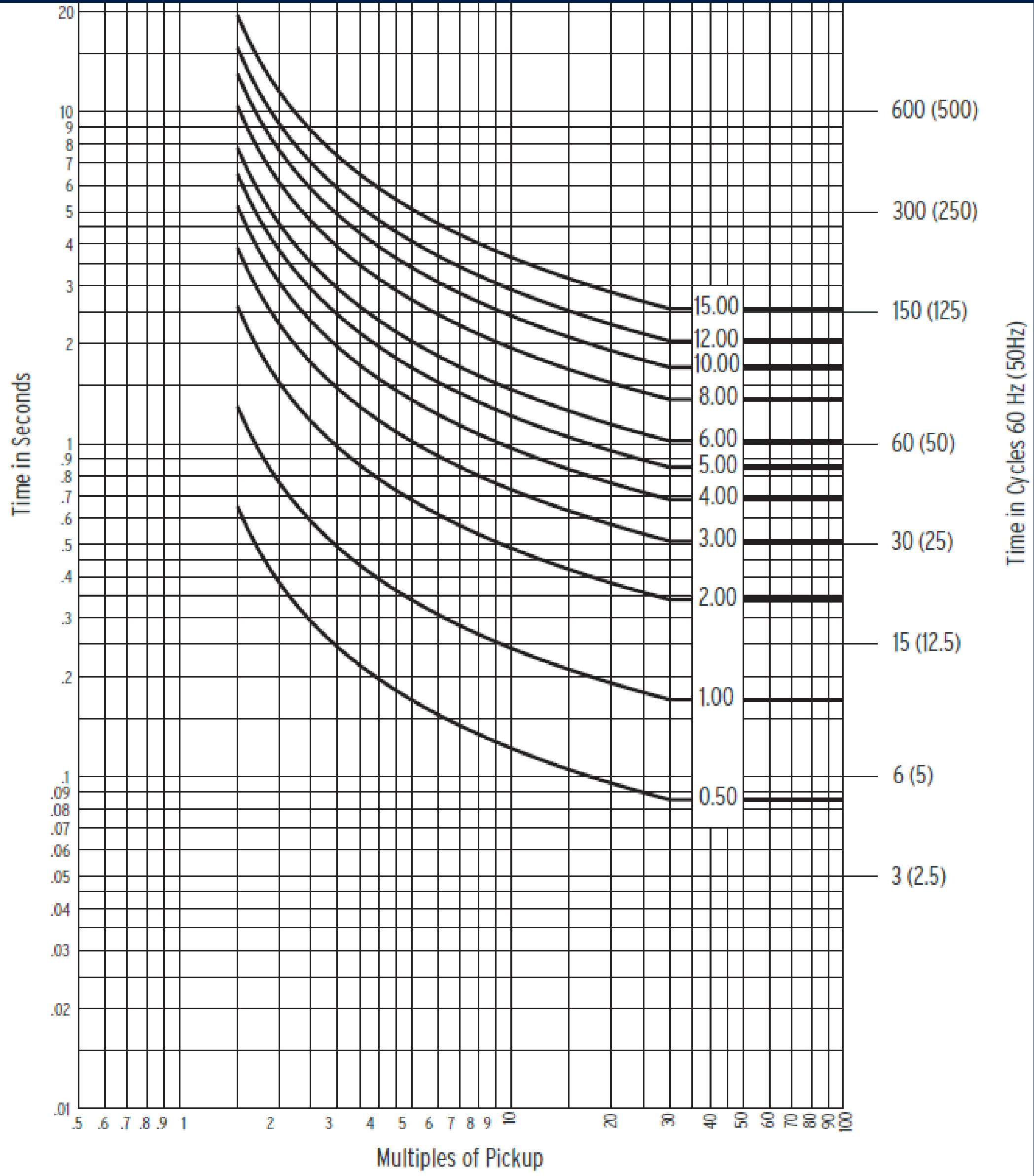
U1 Moderately Inverse Curve

M = multiples of pickup

I_P = max phase current

M = I_P / 51P1P

Time dial shifts curve up / down (slower / faster)



SEL-651R Time-Overcurrent Curves

- Standard U.S. curves (U1–U5)
- Standard IEC curves (C1–C5)
- Recloser curve:

A/101	H/122	R/105	2/135	8+/111	16/139
B/117	J/164	T/161	3/140	9/131	17/103
C/133	KP/162	V/137	4/106	KG/165	18/105
D/166	L/107	W/138	5/114	11/141	
E/132	M/118	Y/120	6/136	13/142	
F/163	N/104	Z/134	7/152	14/119	
G/121	P/115	1/102	8/113	15/112	

Relay Word Bit Tables

8 Relay Word Bits Per Numbered Row

Row	Relay Word Bits							
1	TLED_08	TLED_07	TLED_06	TLED_05	TLED_04	TLED_03	TLED_02	TLED_01
2	TLED_16	TLED_15	TLED_14	TLED_13	TLED_12	TLED_11	TLED_10	TLED_09
3	TLED_24	TLED_23	TLED_22	TLED_21	TLED_20	TLED_19	TLED_18	TLED_17
4	50A1	50B1	50C1	50P1	50A2	50B2	50C2	50P2
5	50A3	50B3	50C3	50P3	50A4	50B4	50C4	50P4
6	50G1	50G2	50G3	50G4	50Q1	50Q2	50Q3	50Q4

Logic

Boolean Logic

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

SELogic Control Equation Operators

Operator	Symbol	Functionality
Parentheses	( )	Group terms
Negation	–	Change sign of numerical value
NOT	NOT (!)	Invert the logic
Rising edge	R_TRIG (/)	Assert output for one processing interval on input rising-edge transition
Falling edge	F_TRIG (\)	Assert output for one processing interval on input falling-edge transition
Multiply	*	Multiply numerical values

SELogic Control Equation Operators

Operator	Symbol	Functionality
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

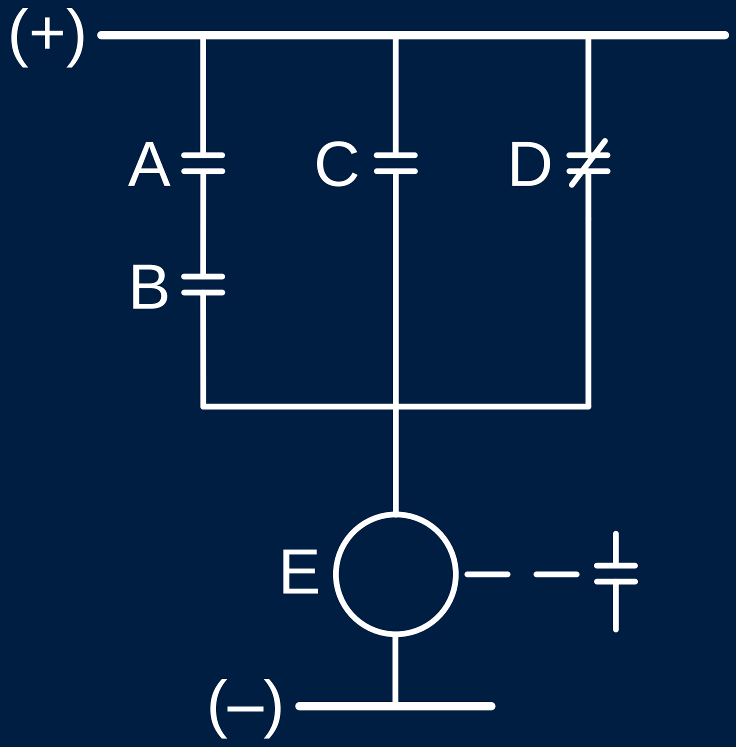
SELogic Control Equation Examples

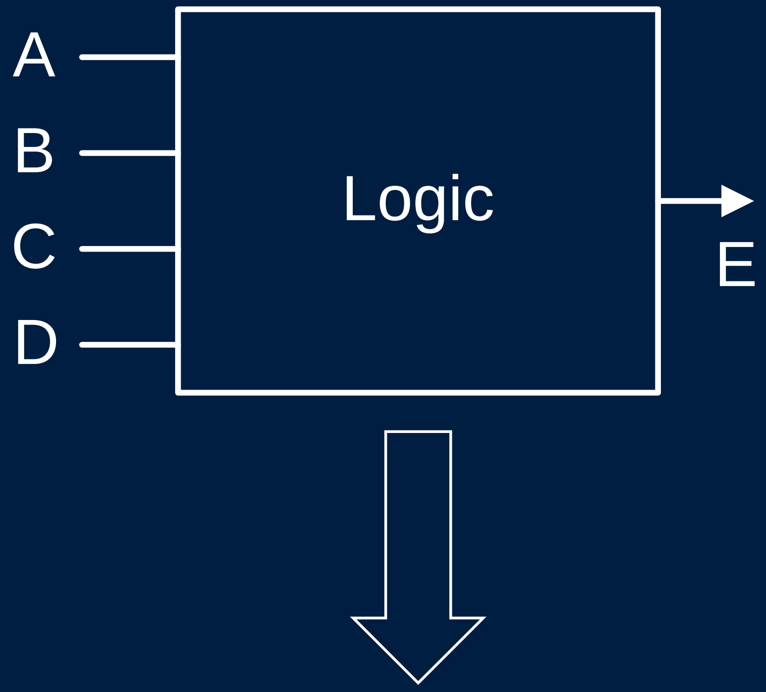
C = A OR B

C = A AND B

C = A AND NOT B

Programmable Logic





Equation implemented

E = A AND B OR C OR NOT D

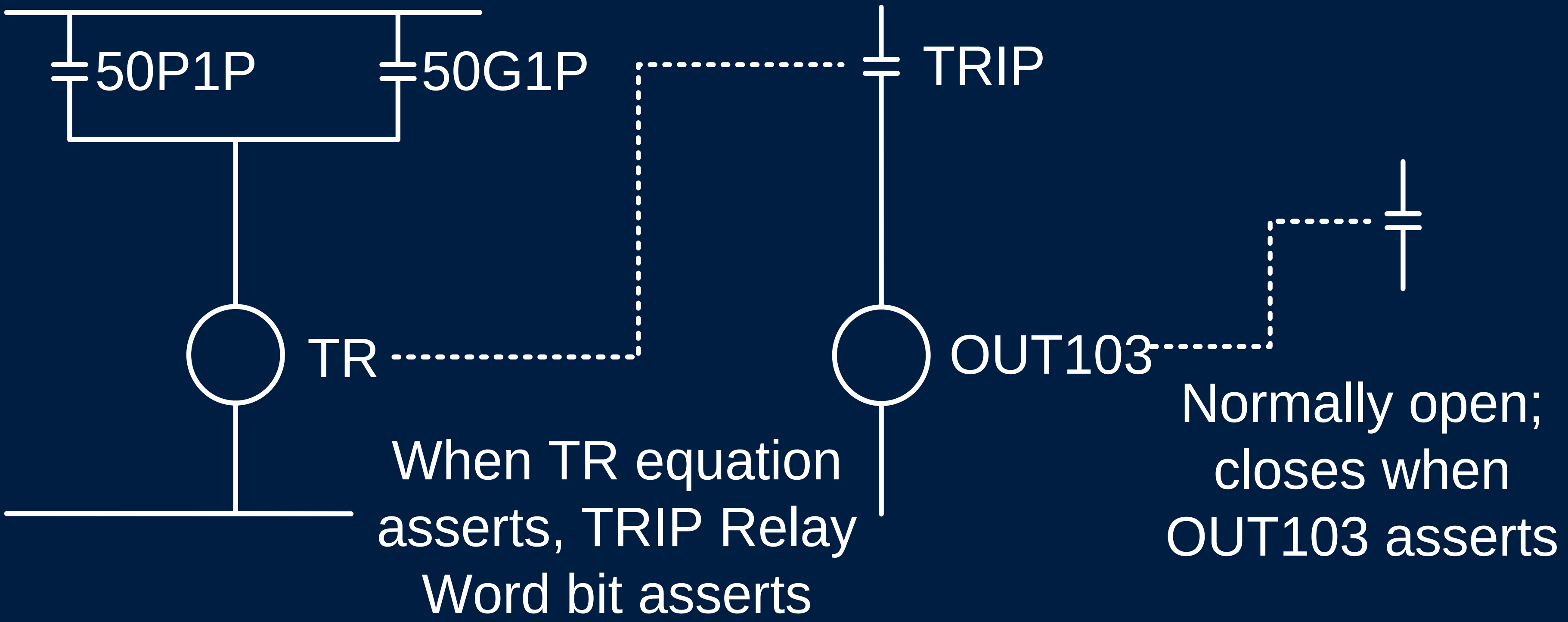
SELogic Control Equation Examples

Trip (SELogic)
TR 50P1P OR 50G1P

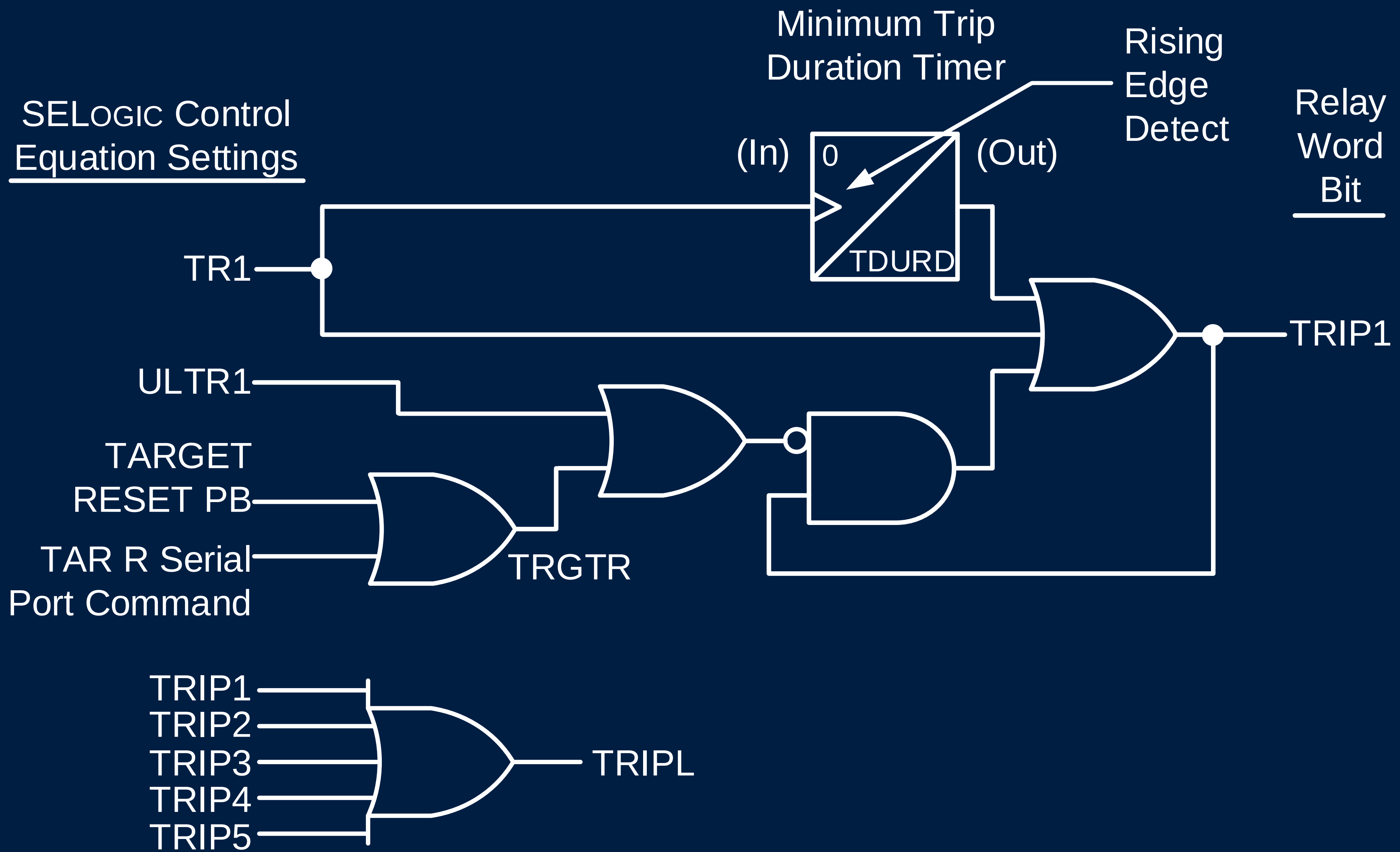
Remote Trip (SELogic)
REMTRIP 0

OUT103 Fail-Safe
OUT103FS N Select: Y, N

(SELogic)
OUT103 TRIP

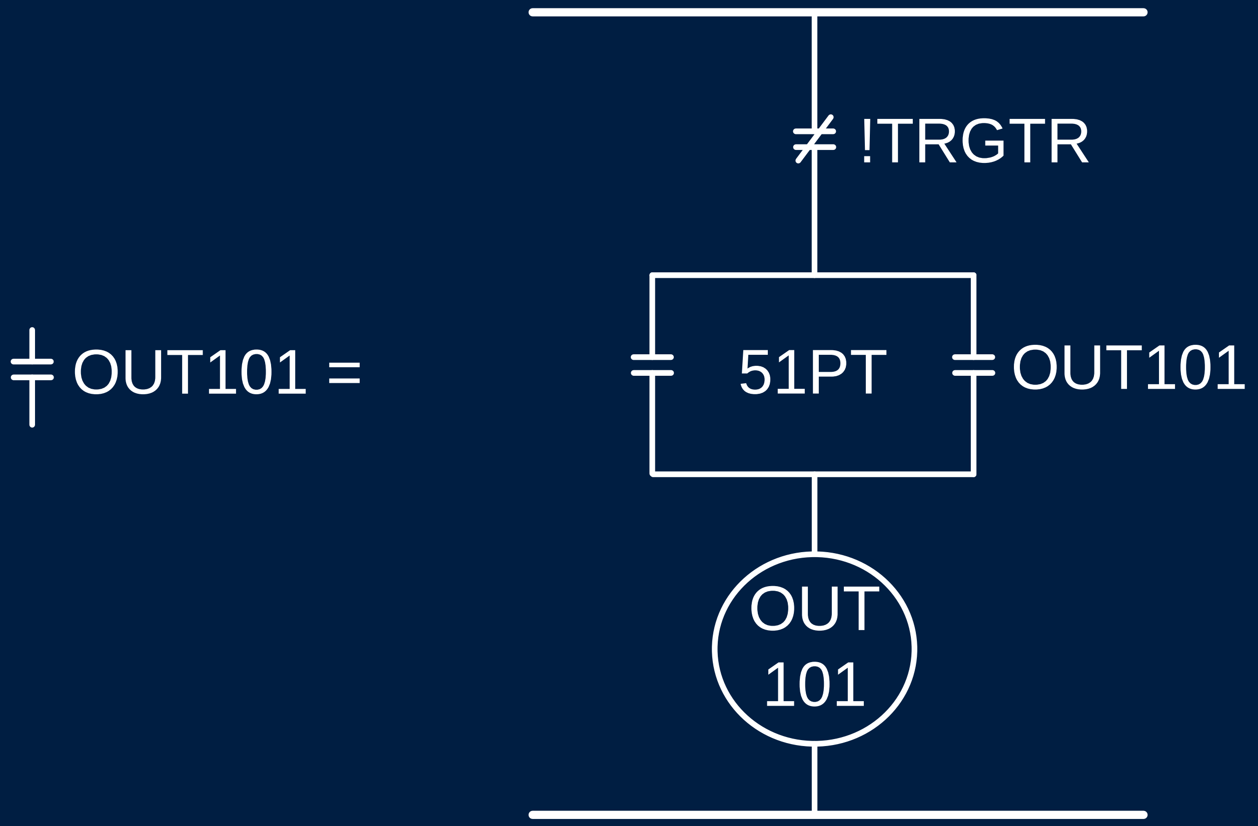


SEL-387A Internal Trip Logic

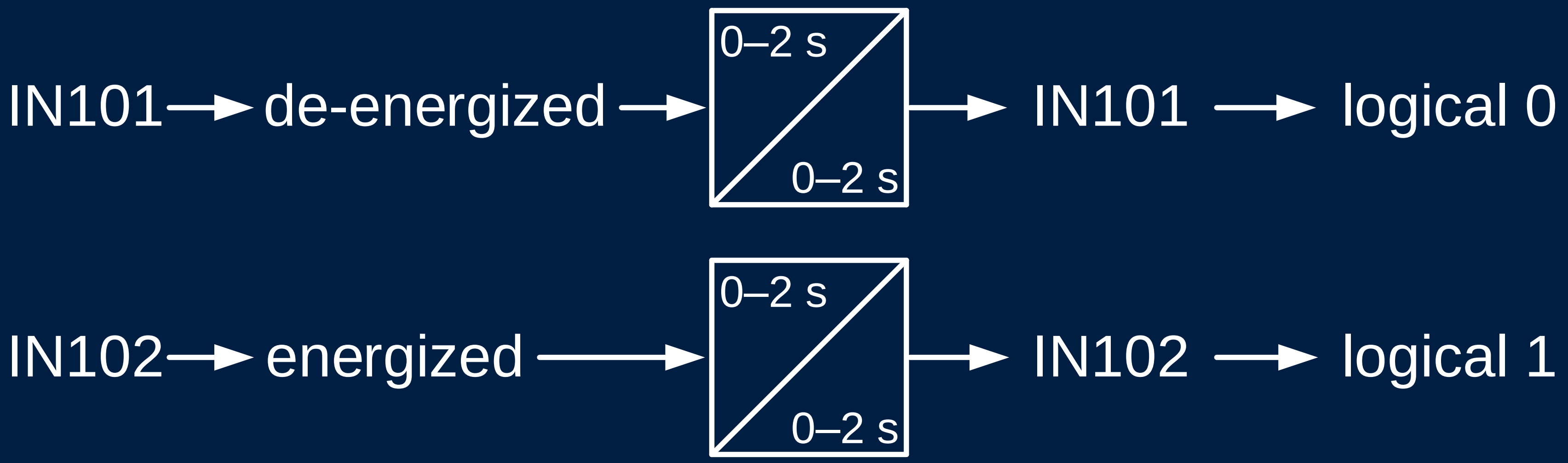


SELogic Control Equation Example

OUT101 = (51PT OR OUT101) AND NOT TRGTR

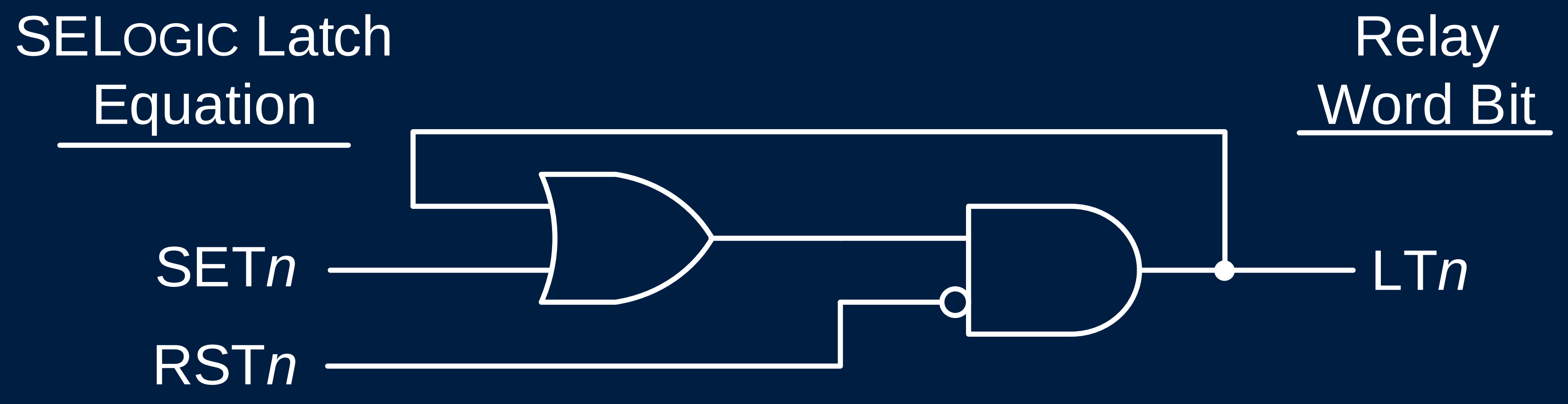


Optoisolated Inputs



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

Latching Control Logic

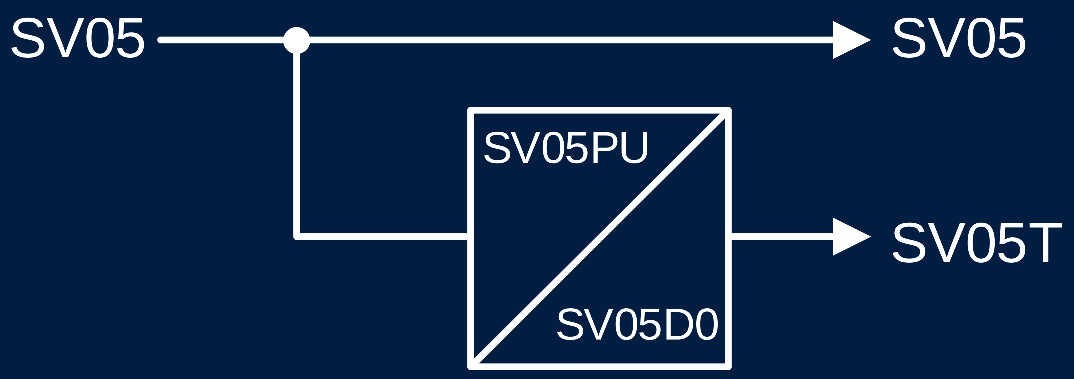


n = 1, 2, 3, etc.

SET01 = CLOSE   RST01 = TRIP   LT01 = 52A

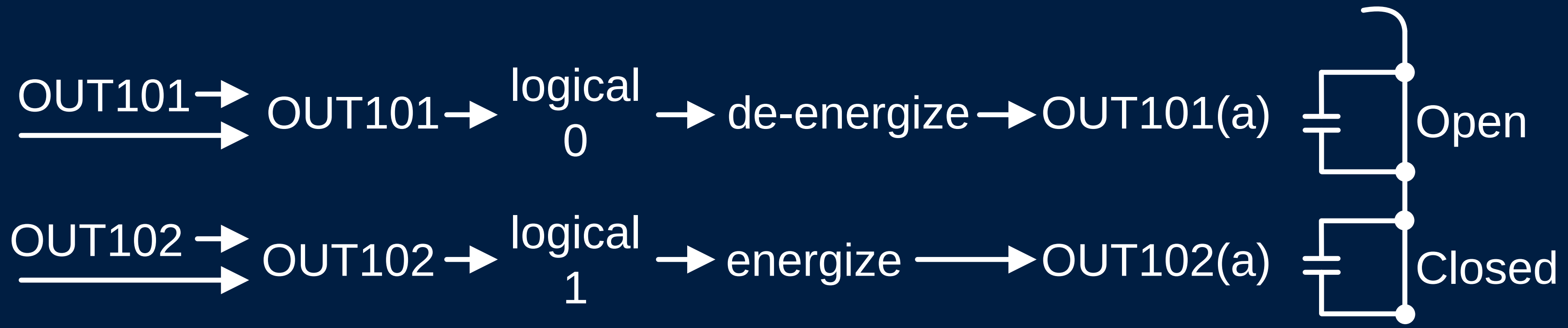
SV Timer

- Set as logic placeholder and timer
- Example settings
  - SV05 = 50P1
  - SV05PU = 6 cycles
  - SV05DO = 60 cycles



- Operation
  - SV05 asserts when 50P1 asserts
  - SV05T asserts 0.1 s after 50P1 asserts
  - SV05T deasserts 1 s after 50P1 deasserts

Outputs



- When OUT101 equation is true (logical 1), OUT101 closes
- Example setting: OUT101 = SV05T
- Operation: OUT101 closes after 50P1 has been asserted for 0.1 s

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

Example: 50P1 = 4 A; CTR = 1,000; Primary PU = 4,000 A

```
=>SER

FEEDER 1                                Date: 04/17/2015  Time: 15:17:13.714
STATION A                               Time Source: internal

FID=SEL-651R-2-R405-V0-Z005003-D20140306   CID=A281

 #       Date          Time              Element            State

    8   04/17/2015   15:14:54.474    50P1               Asserted
    7   04/17/2015   15:14:54.474    SV05               Asserted
    6   04/17/2015   15:14:54.574    SV05T              Asserted
    5   04/17/2015   15:14:54.574    OUT103             Asserted
    4   04/17/2015   15:14:54.965    50P1               Deasserted
    3   04/17/2015   15:14:54.965    SV05               Deasserted
    2   04/17/2015   15:14:55.965    SV05T              Deasserted
    1   04/17/2015   15:14:55.965    OUT103             Deasserted

=>
```

Event Reporting

- Event reports are helpful in fault analysis
- Relays collect 15-cycle (settable) event reports when ER or any TRIP Relay Word bit asserts, or whenever TRI or PUL serial port command is executed
- **HIS** command provides summary of events

```
=>HIS

FEEDER 1                              Date: 04/17/2015  Time: 15:31:24.444
STATION A                             Time Source: internal

#       DATE         TIME       EVENT LOCAT   CURR FREQ GST           TARGETS
                                                        RHR    COLUMN 1      COLUMN 2
1    04/17/2015 15:31:07.524 TRIG  $$$$$      1 60.0 131 111110001000 001000000000
2    04/17/2015 15:30:54.725 ABC T -0.00 15756 60.0 131 111110001000 001100000000
3    04/17/2015 15:30:21.354 BC T    0.06  6183 60.0 131 110110001000 001100111000
4    04/17/2015 15:30:09.602 AB T    0.02  6191 60.0 131 111100001000 001100111000

=>
```

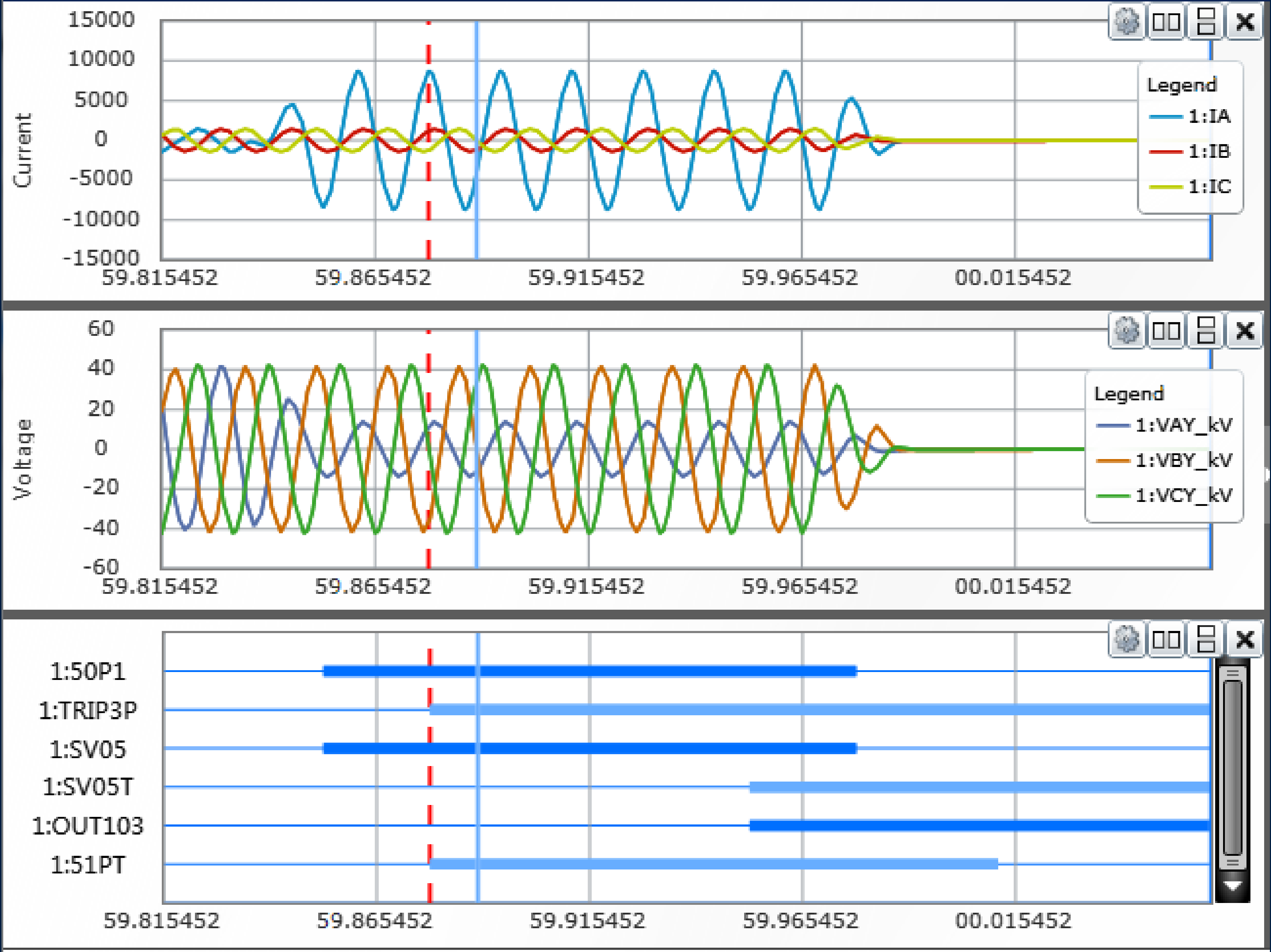
Event Reporting

```
=>EVE

FEEDER 1                                  Date: 04/17/2015  Time: 15:44:59.878
STATION A                                 Time Source: internal

FID=SEL-651R-2-R405-V0-Z005003-D20140306   CID=A281
Event Number = 10049

                                                                                                        5G
     Currents (Amps Pri)                                  Voltages (kV Pri)                           TC2N
     IA        IB        IC        IG       VAY      VBY      VCY      VAZ      VBZ      VCZ   Freq   RLAD
[1]
 -1030       573       456         0     16.5     13.5    -30.0      0.0      0.0      0.0  60.00  ...N
   -71      -857       924        -0    -25.1     26.9     -1.7     -0.0     -0.0     -0.0  60.00  ...N
  1029      -575      -457        -0    -16.5    -13.5     30.0     -0.0     -0.0     -0.0  60.00  ...N
    71       857      -925         0     25.1    -26.9      1.7      0.0      0.0      0.0  60.00  ...N
[2]
 -1029       573       456         0     16.5     13.5    -30.0      0.0      0.0      0.0  60.00  ...N
   -73      -857       924        -0    -25.1     26.9     -1.7     -0.0     -0.0     -0.0  60.00  ...N
  -289      -574      -457        -0    -11.1    -13.5     30.0     -0.0     -0.0     -0.0  60.00  ...N
  2891       857      -925         0     17.4    -26.9      1.7      0.0      0.0      0.0  60.00  ...N
[3]
  1014       574       456         0      5.6     13.5    -30.0      0.0      0.0      0.0  60.00  ...N
 -5943      -858       924     -5877     -9.0     26.9     -1.8     -0.0     -0.0     -0.0  59.92  ...G
  -424      -574      -457     -1455     -5.5    -13.5     30.0     -0.0     -0.0     -0.0  59.92  ...G
  6177       857      -925      6109      8.4    -26.9      1.7      0.0      0.0      0.0  59.87  ...G
[4]
   423       573       456      1452      5.5     13.5    -30.0      0.0      0.0      0.0  59.87  ...G
 -6177      -858       924     -6111     -8.4     26.9     -1.8     -0.0     -0.0     -0.0  59.87  ...G
  -424      -575      -457     -1456     -5.5    -13.5     30.0     -0.0     -0.0     -0.0  59.87  ...G
  6176       857      -925      6108      8.4    -26.9      1.7      0.0      0.0      0.0  59.94 >*..G
[5]
   422       574       456      1452      5.5     13.5    -30.0      0.0      0.0      0.0  59.94  *..G
 -6178      -858       924     -6112     -8.4     26.9     -1.7     -0.0     -0.0     -0.0  59.94  *..G
  -420      -575      -457     -1452     -5.5    -13.5     30.0     -0.0     -0.0     -0.0  59.94  *..G
  6177       857      -925      6109      8.4    -26.9      1.7      0.0      0.0      0.0  59.94  *..G
[6]
   414       573       457      1444      5.5     13.5    -30.0      0.0      0.0      0.0  59.94  *..G
 -6179      -859       923     -6115     -8.4     26.9     -1.7     -0.0     -0.0     -0.0  60.00  *..G
  -409      -573      -459     -1441     -5.5    -13.6     30.0     -0.0     -0.0     -0.0  60.00  *..G
  6179       859      -924      6114      8.4    -26.9      1.7      0.0      0.0      0.0  60.00  *..G
```

Event Reporting

```
[7]
   402    571    459   1432    5.5   13.6  -30.0    0.0    0.0    0.0 60.00 *..G
 -6181   -860    922  -6119   -8.4   26.8   -1.6   -0.0   -0.0   -0.0 60.00 *..G
  -396   -571   -461  -1428   -5.5  -13.6   30.0   -0.0   -0.0   -0.0 60.00 *..G
  6180    860   -923   6117    8.4  -26.8    1.6    0.0    0.0    0.0 60.00 *..G
[8]
   386    569    461   1416    5.5   13.7  -30.0    0.0    0.0    0.0 60.00 *..G
 -6182   -861    921  -6122   -8.4   26.8   -1.6   -0.0   -0.0   -0.0 60.00 *..G
  -379   -569   -463  -1411   -5.5  -13.7   30.0   -0.0   -0.0   -0.0 60.00 *..G
  6181    861   -922   6120    8.4  -26.8    1.5    0.0    0.0    0.0 60.00 *..G
[9]
   371    567    464   1402    5.4   13.7  -30.0    0.0    0.0    0.0 60.00 *..G
 -6182   -863    920  -6125   -8.4   26.8   -1.5   -0.0   -0.0   -0.0 60.00 *..G
  -364   -566   -466  -1396   -5.4  -13.8   30.0   -0.0   -0.0   -0.0 60.00 *..G
  6182    863   -921   6124    8.4  -26.7    1.4    0.0    0.0    0.0 60.00 *..G
[10]
   355    564    465   1384    5.4   13.8  -30.0    0.0    0.0    0.0 60.00 *..G
 -6183   -864    919  -6128   -8.4   26.7   -1.4   -0.0   -0.0   -0.0 60.00 *..G
   672   -294   -491   -113   -2.8  -14.4   22.8   -0.0   -0.0   -0.0 60.00**..G
  3508    493   -519      0    4.8  -15.0    0.6    0.0    0.0    0.0 60.00 *..N
[11]
  -848     11    257      0    0.1    7.5   -7.7    0.0    0.0    0.0 60.00 *..N
  -418    -62     57     -0   -0.6    1.6    0.1   -0.0   -0.0   -0.0 60.00 *..N
    -2     -2     -2     -0   -0.0   -0.0   -0.0   -0.0   -0.0   -0.0 60.00 *..N
     1      0      0      0    0.0    0.0    0.0    0.0    0.0    0.0 60.00 *..N
[12]
     1      1      0      0    0.0    0.0    0.0    0.0    0.0    0.0 60.00 *..N
    -1     -1     -1     -0   -0.0   -0.0   -0.0   -0.0   -0.0   -0.0 60.00 *..N
    -1     -1     -1     -0   -0.0   -0.0   -0.0   -0.0   -0.0   -0.0 60.00 *..N
     1      1      1      0    0.0    0.0    0.0    0.0    0.0    0.0 60.00 *..N
[13]
     1      1      1      0    0.0    0.0    0.0    0.0    0.0    0.0 60.00 *..N
    -1     -1     -1     -0   -0.0   -0.0   -0.0   -0.0   -0.0   -0.0 60.00 *..N
    -1     -1     -1     -0   -0.0   -0.0   -0.0   -0.0   -0.0   -0.0 60.00 *..N
     1      1      1      0    0.0    0.0    0.0    0.0    0.0    0.0 60.00 *..N
[14]
     1      1      1      0    0.0    0.0    0.0    0.0    0.0    0.0 60.00 *..N
    -1     -1     -1     -0   -0.0   -0.0   -0.0   -0.0   -0.0   -0.0 60.00 *..N
    -1     -1     -1     -0   -0.0   -0.0   -0.0   -0.0   -0.0   -0.0 60.00 *..N
     1      1      1      0    0.0    0.0    0.0    0.0    0.0    0.0 60.00 *..N
[15]
     1      1      1      0    0.0    0.0    0.0    0.0    0.0    0.0 60.00 *..N
    -1     -1     -1     -0   -0.0   -0.0   -0.0   -0.0   -0.0   -0.0 60.00 *..N
    -1     -1     -1     -0   -0.0   -0.0   -0.0   -0.0   -0.0   -0.0 60.00 *..N
     1      1      1      0    0.0    0.0    0.0    0.0    0.0    0.0 60.00 *..N
```

SYNCHROWAVE EVENT 2015



Review Questions

- How do microprocessor-based relays create phasors?
- What tools do microprocessor-based relays offer for fault analysis?
- How do SEL relays create control circuits?
- What are Relay Word bits used for in SEL relays?

Summary

- Microprocessor-based relays create phasors from sinusoid (waveform) inputs
- 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?