Determining CT Requirements for Generator and Transformer Protective Relays

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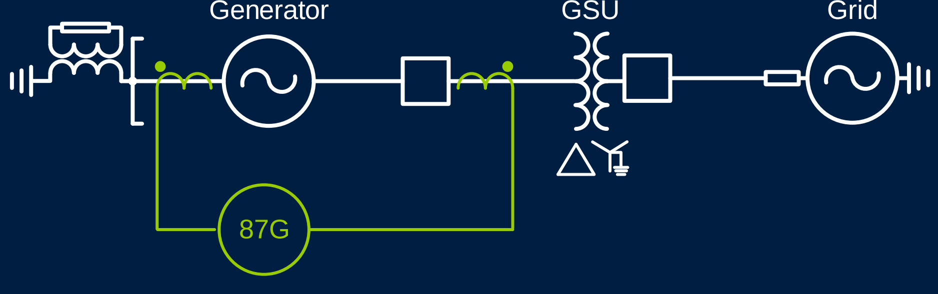
Introduction



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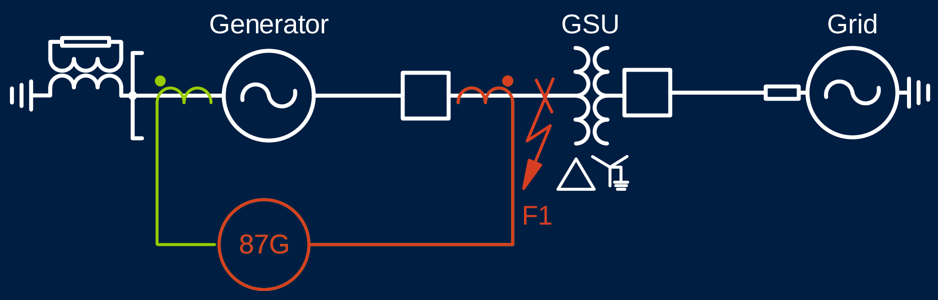

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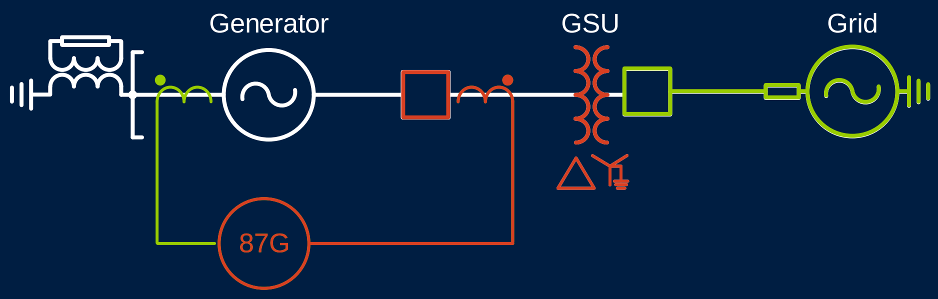

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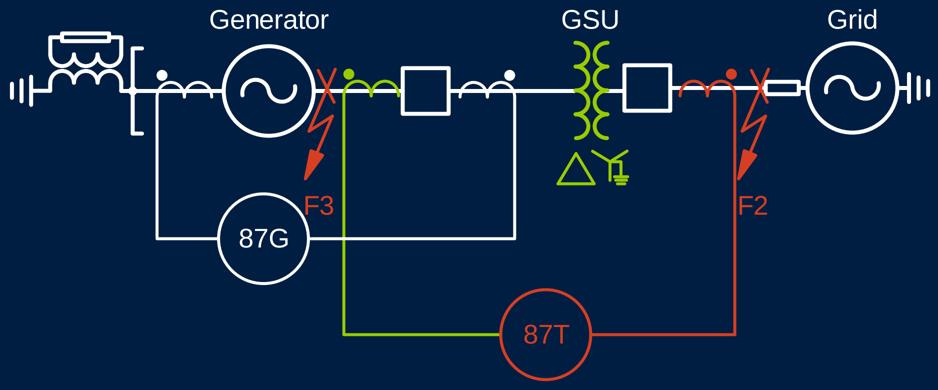

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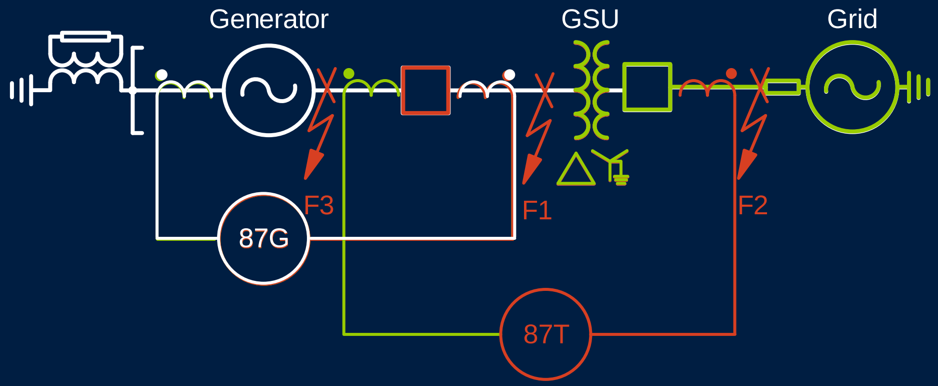

Overview

- IEEE and IEC guidance
  - DC offset
  - Remanence
- CT models
- Differential relay scheme
- Test method and results
  - CT sizing
  - Relay settings

Overview

- IEEE and IEC guidance
  - DC offset
  - Remanence
- ~~CT models~~
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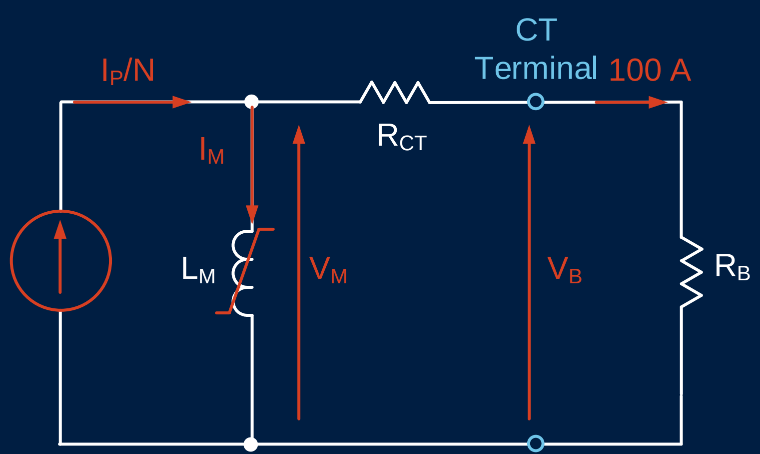
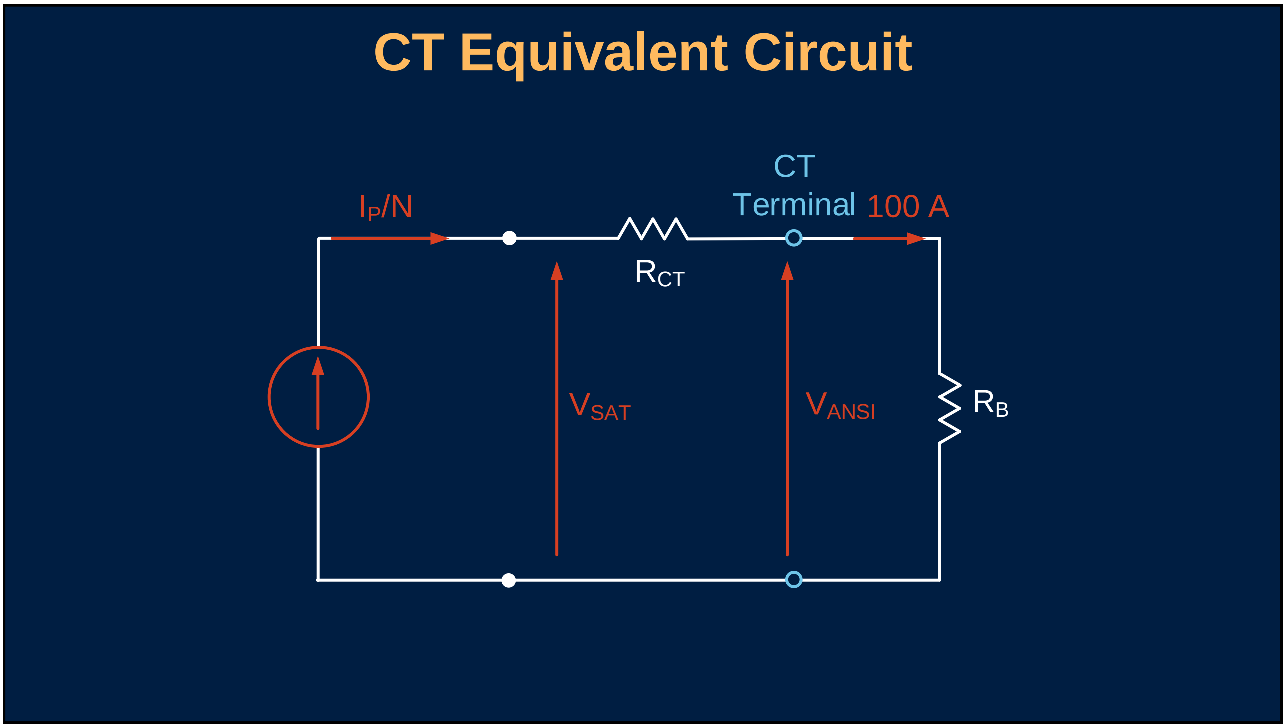
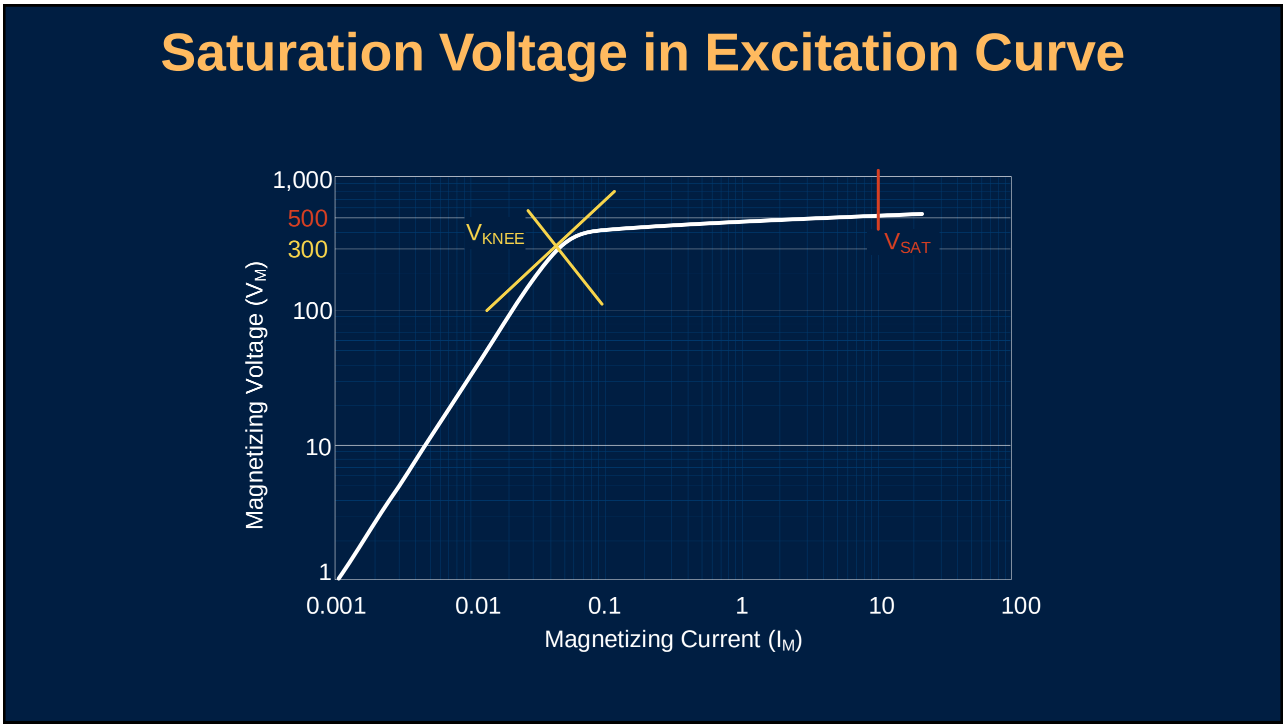
IEEE and IEC Guidance

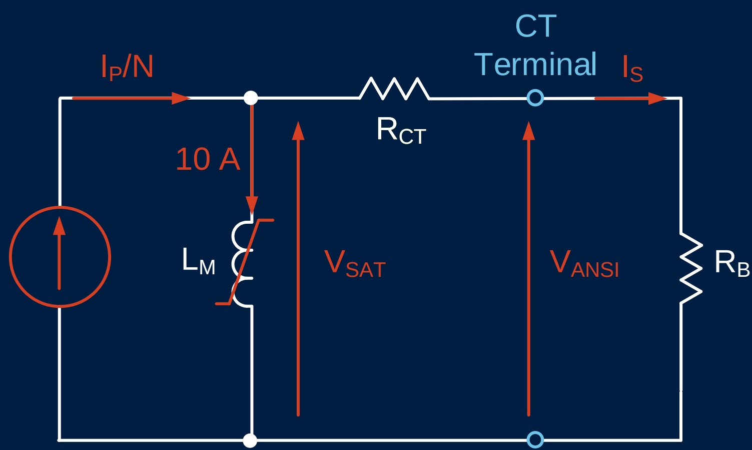
CT Equivalent Circuit



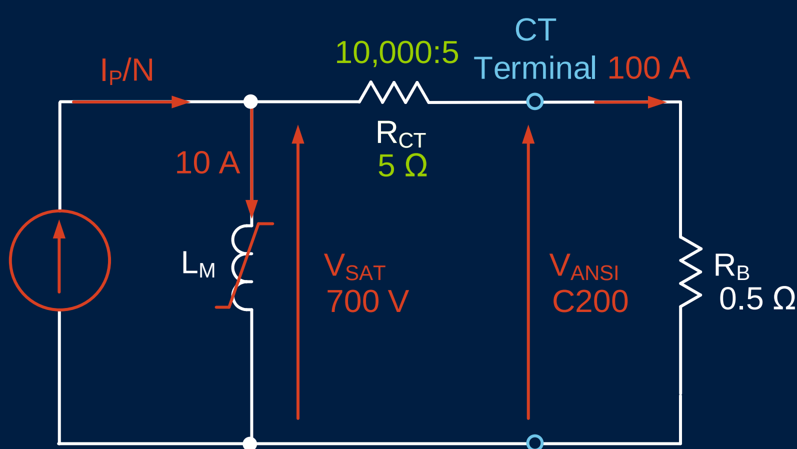

CT Equivalent Circuit
CT
Terminal
100 A
IP/N
RCT
VSAT
VANSI
RB

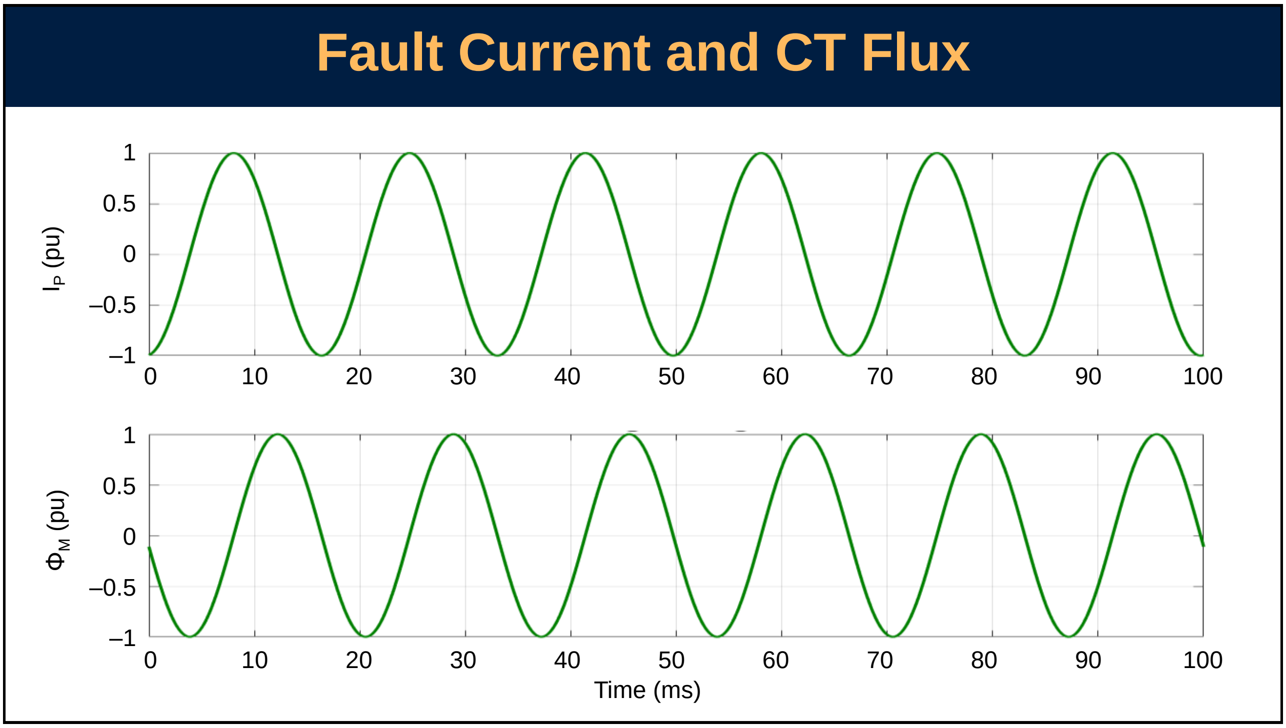

Saturation Voltage in Excitation Curve
1,000
500
300
100
10
1
VKNEE
VSAT
Magnetizing Voltage (VM)
0.001
0.01
0.1
1
10
100
Magnetizing Current (IM)

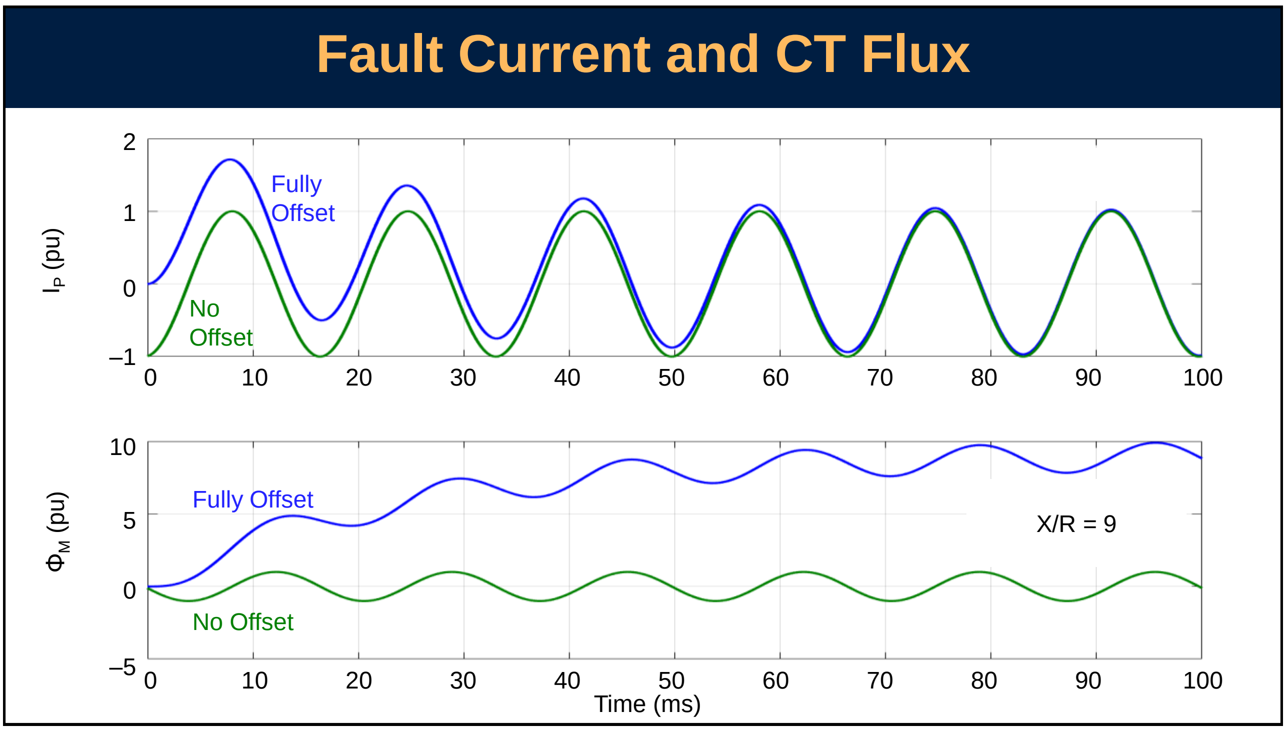
CT Equivalent Circuit



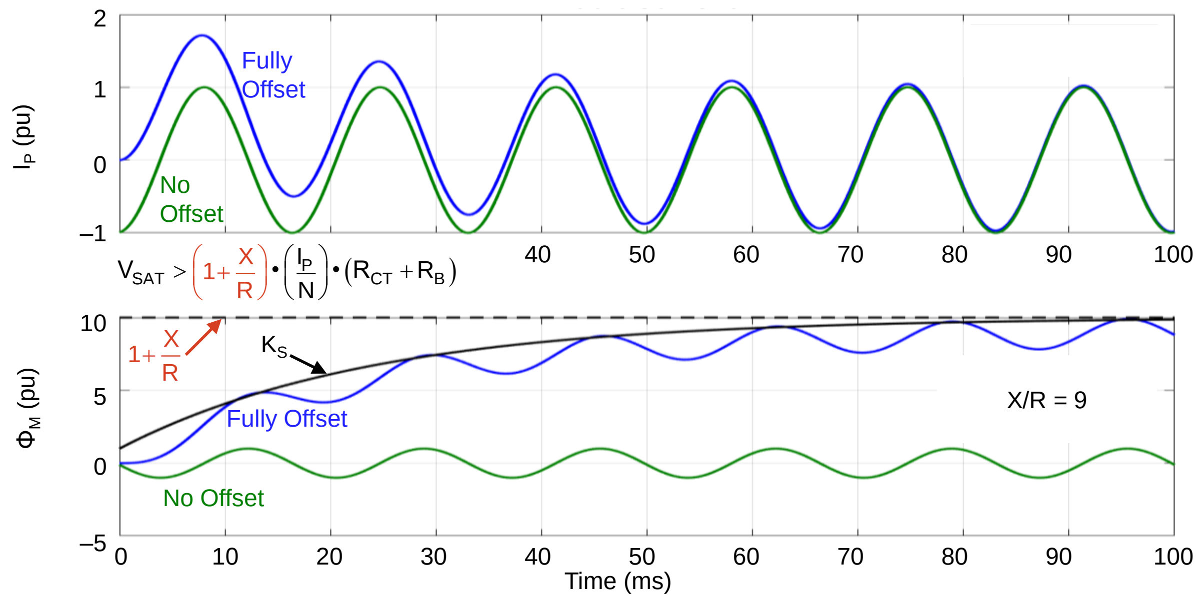
CT Equivalent Circuit



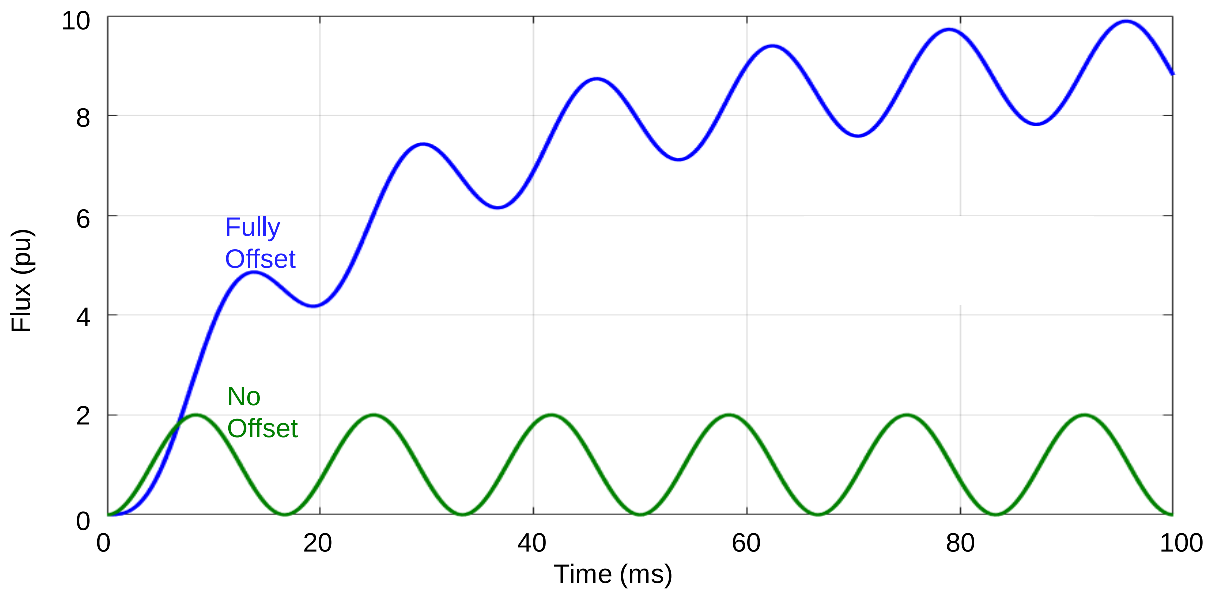

Fault Current and CT Flux
1
0.5
0
–0.5
–1
I_P (pu)
0
10
20
30
40
50
60
70
80
90
100
1
0.5
0
–0.5
–1
Φ_M (pu)
0
10
20
30
40
50
60
70
80
90
100
Time (ms)


Fault Current and CT Flux
2
1
0
–1
I_P (pu)
Fully
Offset
No
Offset
0
10
20
30
40
50
60
70
80
90
100
10
5
0
–5
Φ_M (pu)
Fully Offset
X/R = 9
No Offset
0
10
20
30
40
50
60
70
80
90
100
Time (ms)

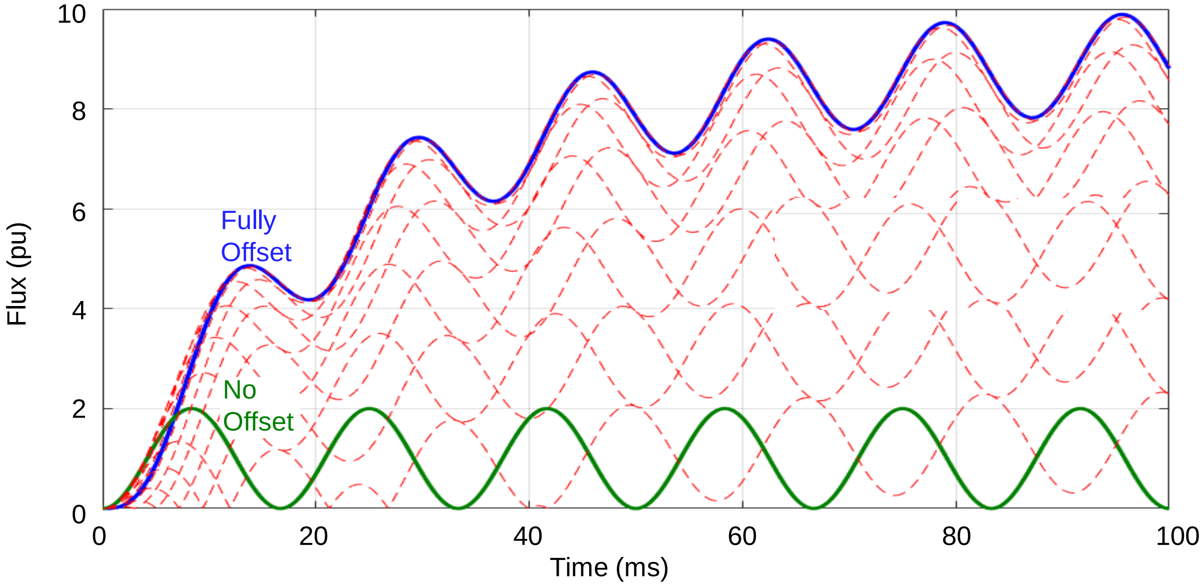
Fault Current and CT Flux



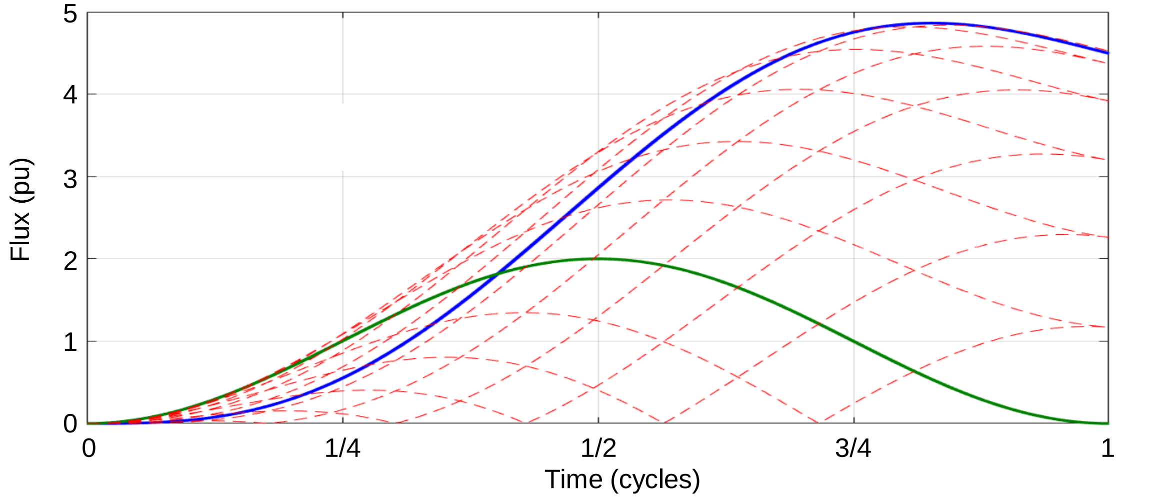
Effect of Fault Inception Angle



Effect of Fault Inception Angle



Effect of Point-on-Wave



$$K_{TD} = K_S = \frac{V_{SAT}}{I_S \cdot (R_{CT} + R_B)}$$

(IEC) (IEEE)

$$\rightarrow V_{ANSI} = K_S \cdot I_S \cdot R_B$$

$$\rightarrow V_{SAT} = K_{TD} \cdot I_S \cdot (R_{CT} + R_B)$$

Remanence

CT Sizing
DC Offset and Remanence

IEEE

$$V_{SAT} = \frac{\left(1 + \frac{X}{R}\right) \bullet I_S \bullet (R_B + R_{CT})}{1 - Rem}$$

DC and Relay

Remanence

Ohm's Law

IEC

$$E_{AL} = (K_{TD} \bullet K_{REM}) \bullet I_S \bullet (R_B + R_{CT})$$

$$K_{REM} = \frac{1}{1 - Rem}$$

IEEE and IEC Surveys

IEEE

Remanent Flux	Percentage of CTs
0–20	39
21–40	18
41–60	16
61–80	27

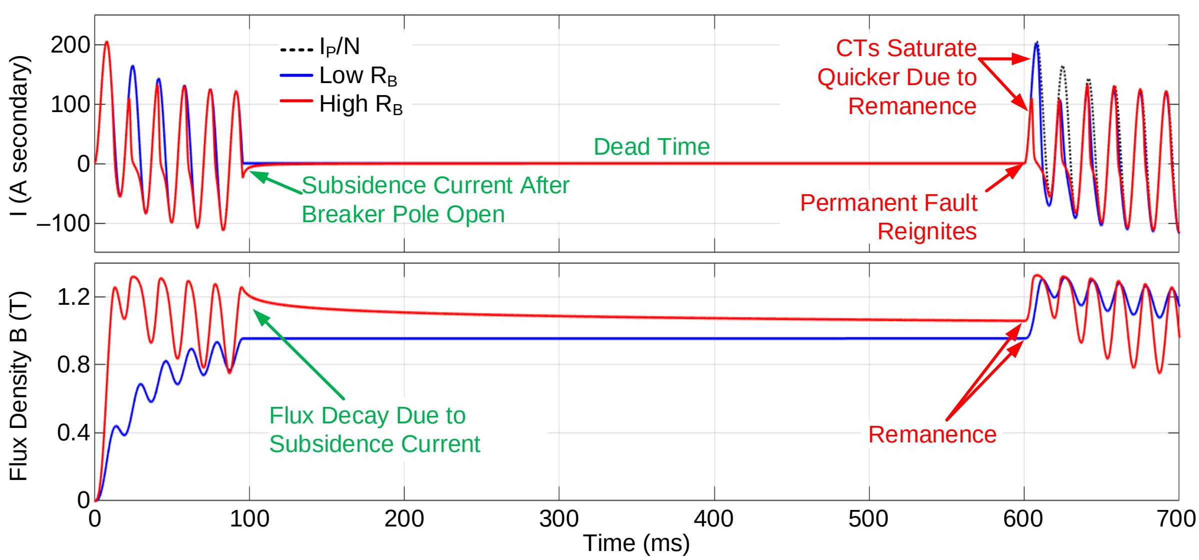
Remanent Flux Survey on 230 kV System

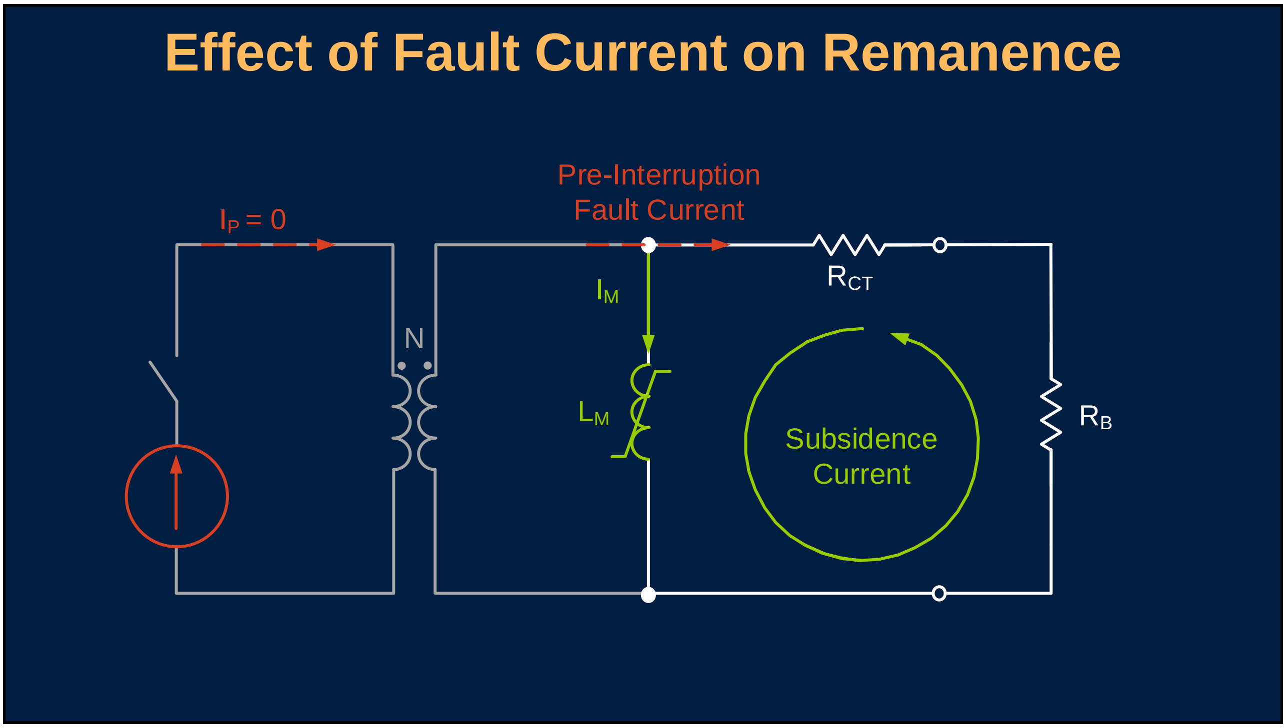
IEC

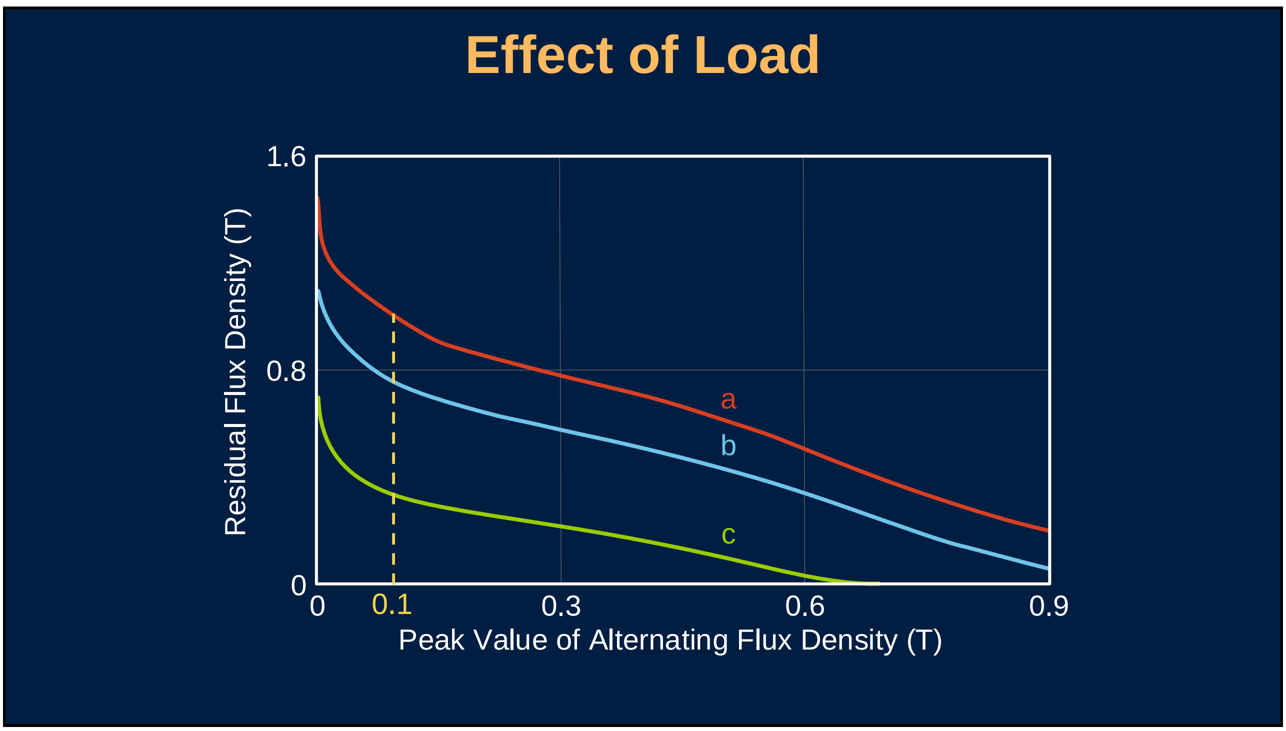
	Old CT Cores	New CT Cores
Theoretical Remanence	75–77%	88–95%
Measured Remanence	70–75%	85–87%

Theoretical and Measured Remanence

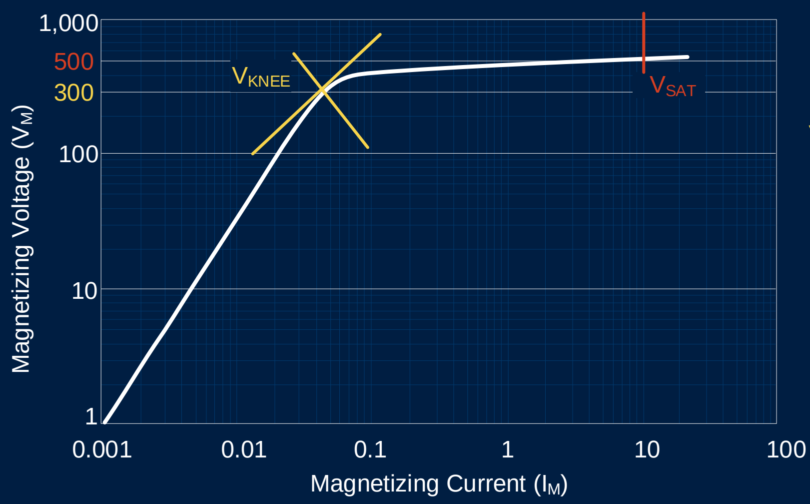
Effect of Faults on Remanence



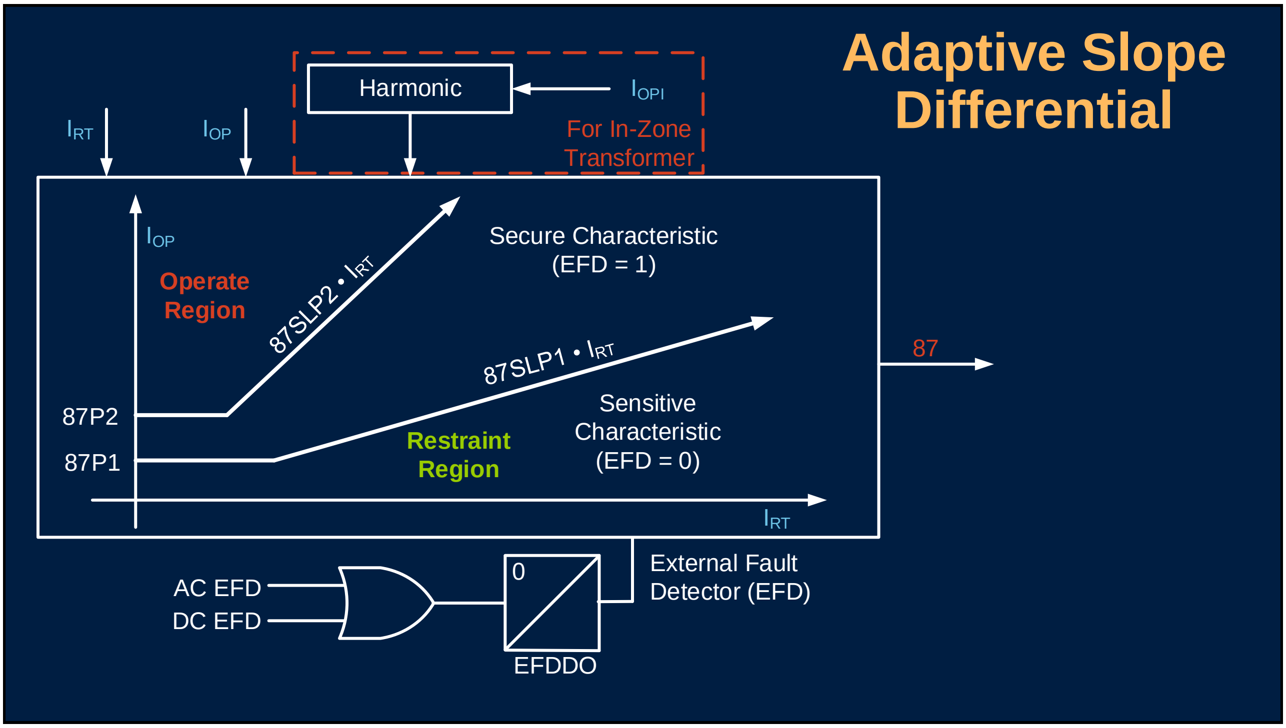

Effect of Fault Current on Remanence
Pre-Interruption
Fault Current
IP = 0
N
IM
LM
RCT
RB
Subsidence
Current


Effect of Load
1.6
0.8
0
Residual Flux Density (T)
0
0.1
0.3
0.6
0.9
Peak Value of Alternating Flux Density (T)
a
b
c

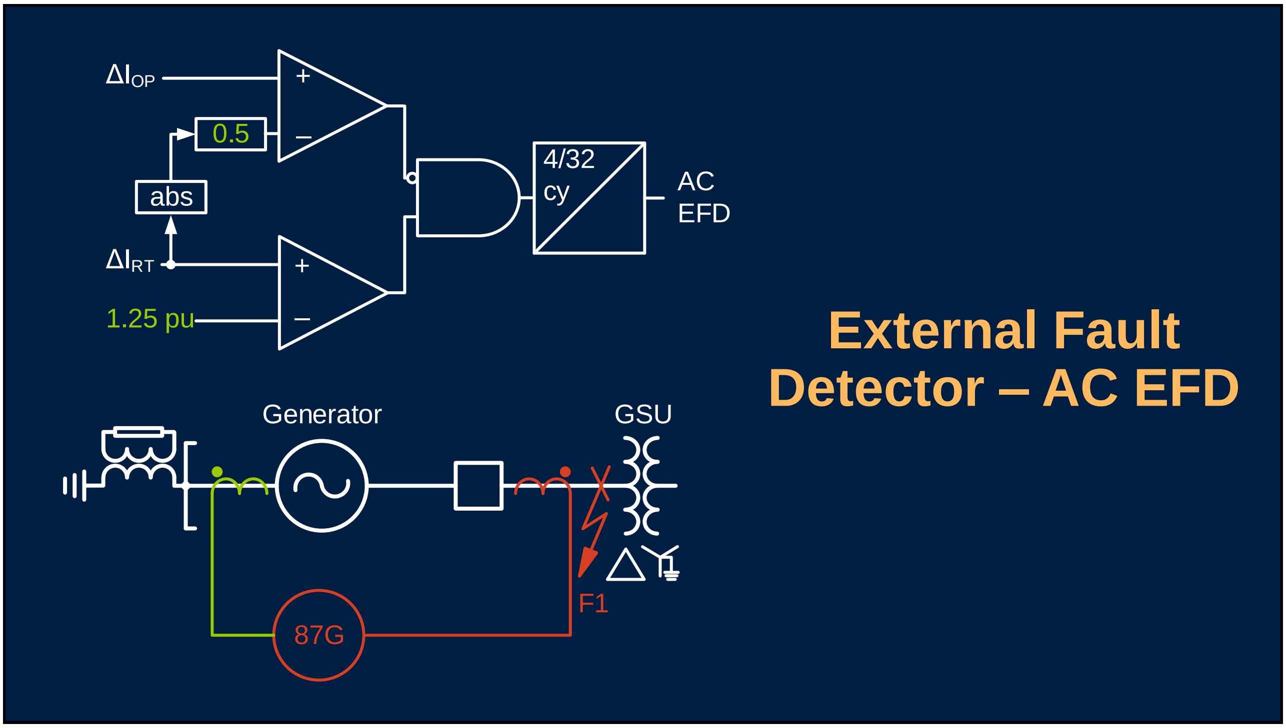
Load and Excitation Curve



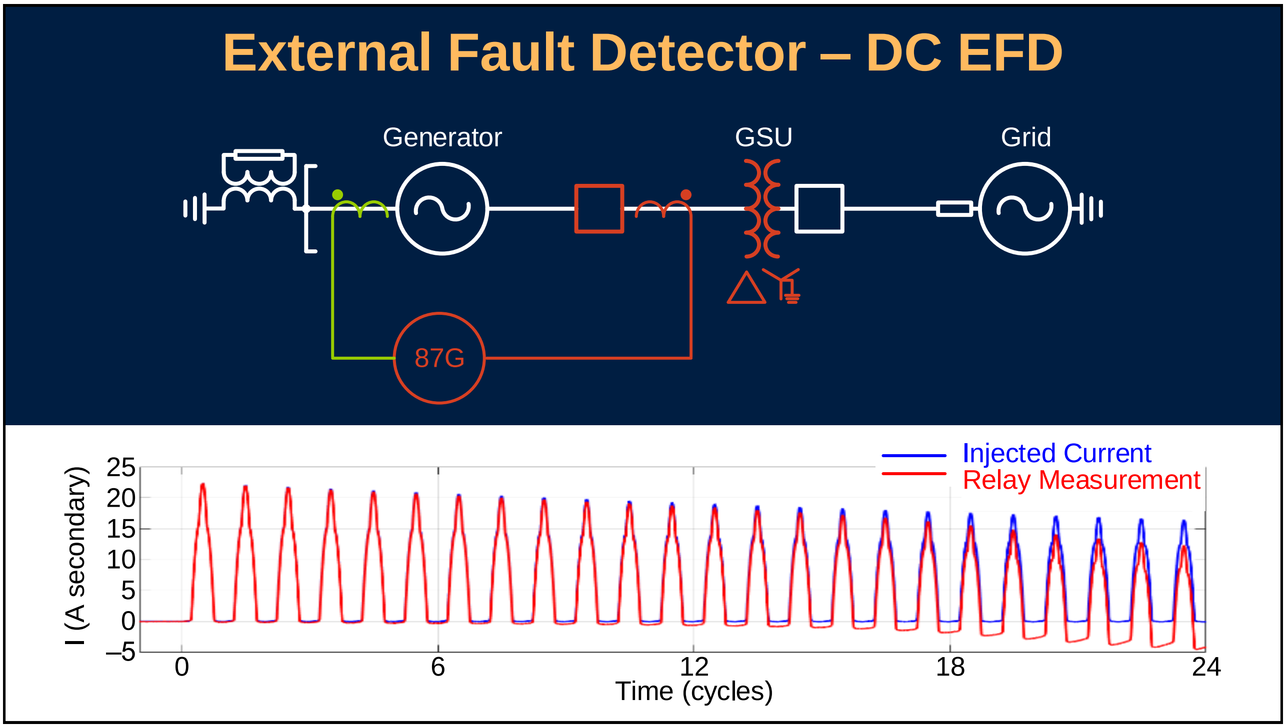
Protective Relay Scheme

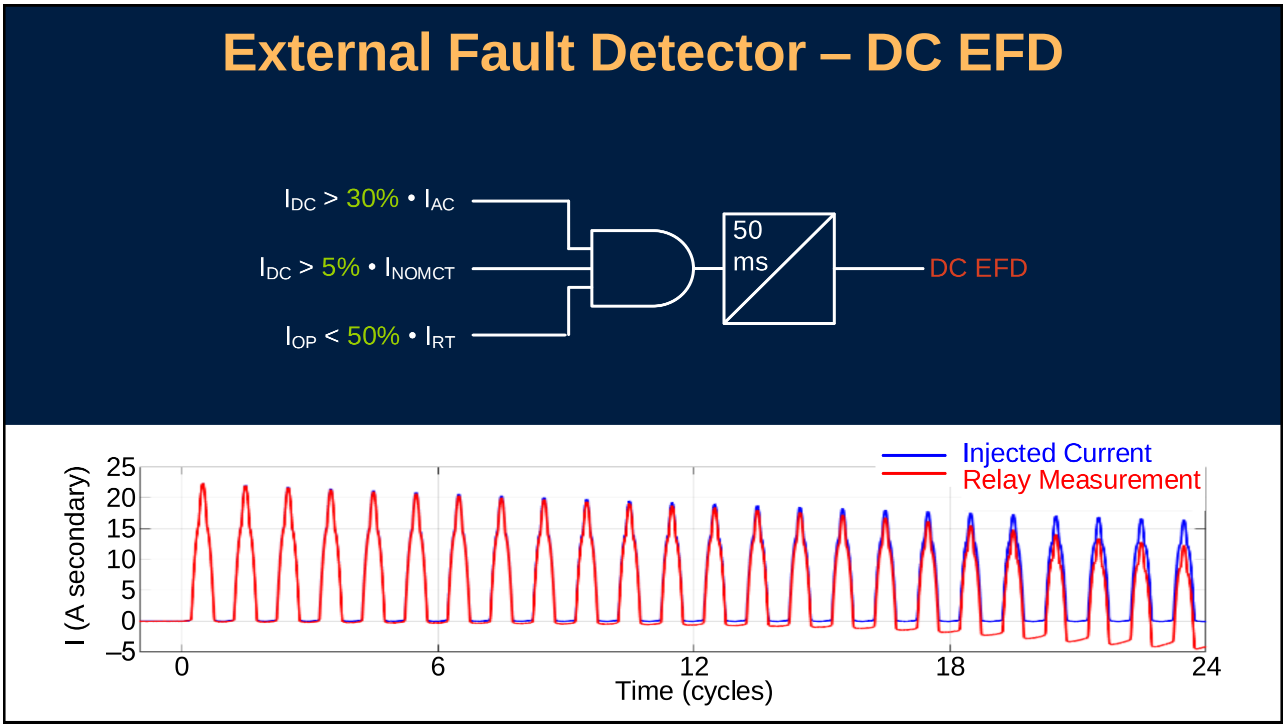


Adaptive Slope Differential
Harmonic
I_{OPI}
For In-Zone Transformer
I_{RT}
I_{OP}
I_{OP}
Operate Region
87SLP2 • I_{RT}
Secure Characteristic (EFD = 1)
87SLP1 • I_{RT}
87
87P2
87P1
Restraint Region
Sensitive Characteristic (EFD = 0)
I_{RT}
AC EFD
DC EFD
0
EFDDO
External Fault Detector (EFD)



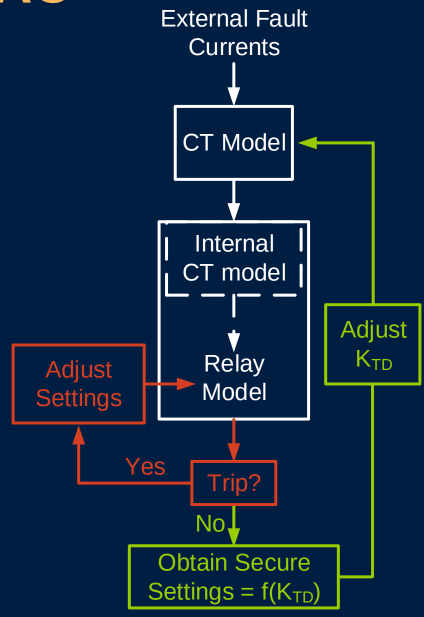
ΔI_{OP}
0.5
abs
ΔI_{RT}
1.25 pu
4/32 cy
AC EFD
External Fault Detector – AC EFD
Generator
GSU
F1
87G


External Fault Detector – DC EFD
Generator
GSU
Grid
87G
Injected Current
Relay Measurement
I (A secondary)
25
20
15
10
5
0
–5
0
6
12
18
24
Time (cycles)


External Fault Detector – DC EFD
I_DC > 30% • I_AC
I_DC > 5% • I_NOMCT
I_OP < 50% • I_RT
50 ms
DC EFD
Injected Current
Relay Measurement
I (A secondary)
25
20
15
10
5
0
–5
0
6
12
18
24
Time (cycles)

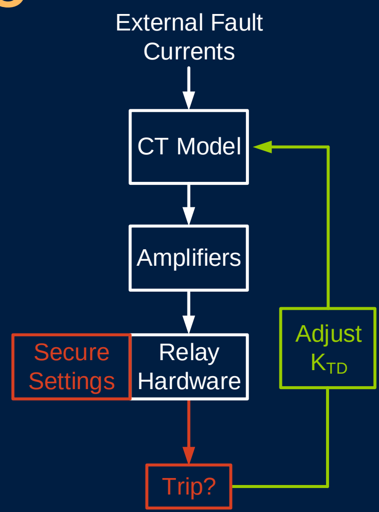
Test Method – AC

- Point on wave (0 to 360)
- X/R: up to 100
- Both ground and phase
- One saturated CT, other not
- 87P1 and 87SLP1 set low
- Simulations with 5% margin

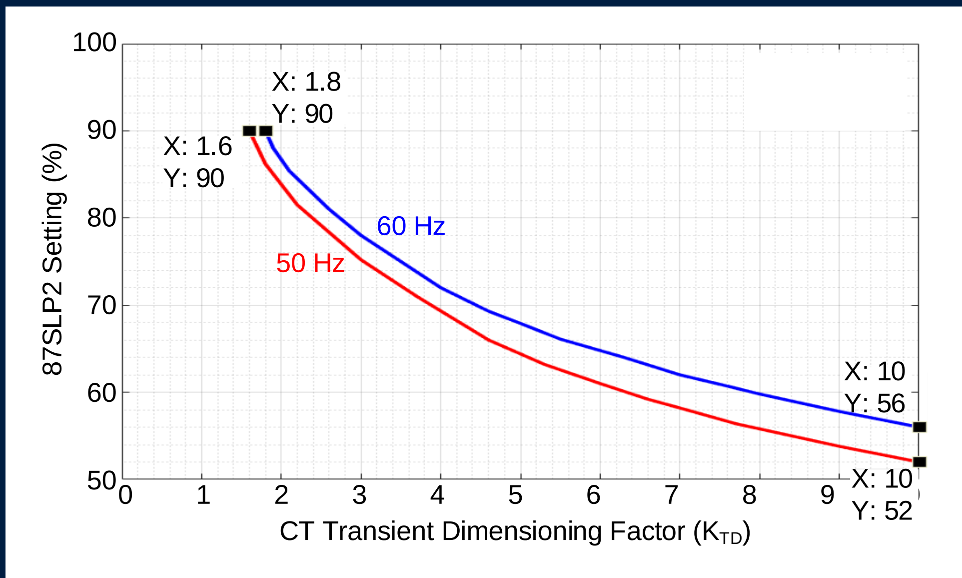


Test Method – AC

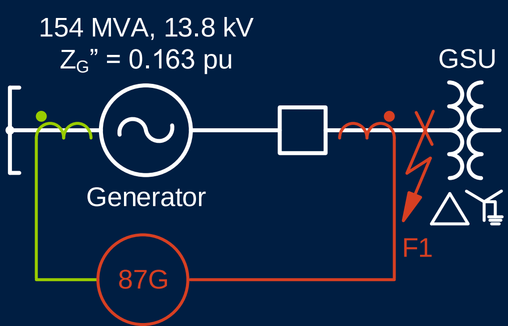
- Point on wave (0 to 360)
- X/R: up to 100
- Both ground and phase
- One saturated CT, other not
- 87P1 and 87SLP1 set low
- Simulations with 5% margin
- Hardware-in-the-loop verification



CT Sizing Requirements and Relay Setting



CT Sizing Requirement



$$V_{ANSI} = K_{REM} \bullet K_{S\_MIN} \bullet \left(\frac{I_F}{N}\right) \bullet R_B$$

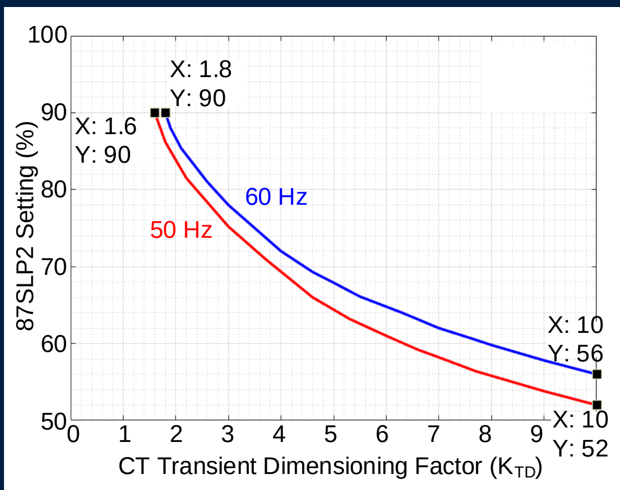
$$V_{ANSI} = 3 \bullet 1.8 \bullet \left(\frac{39{,}530\ \text{A}}{2{,}000}\right) \bullet 0.372\ \Omega = 39.7\ \text{V}$$

$$V_{SAT} = 3 \bullet 1.8 \bullet \left(\frac{39{,}530\ \text{A}}{2{,}000}\right) \bullet (0.372\ \Omega + 5\ \Omega)$$

$$= 573.3\ \text{V}$$

$$V_{SAT\_CT} = 100\ \text{V} + 20 \bullet 5\ \text{A} \bullet 5\ \Omega = 600\ \text{V}$$

CT Sizing Requirements and Relay Setting



$$V_{ANSI} = K_{REM} \cdot K_{S\_MIN} \cdot \left(\frac{I_F}{N}\right) \cdot R_B$$

$$V_{ANSI} = 3 \cdot 1.8 \cdot \left(\frac{39{,}530\ \text{A}}{2{,}000}\right) \cdot 0.372\ \Omega = 39.7\ \text{V}$$

$$V_{SAT} = 3 \cdot 1.8 \cdot \left(\frac{39{,}530\ \text{A}}{2{,}000}\right) \cdot (0.372\ \Omega + 5\ \Omega)$$

$$= 573.3\ \text{V}$$

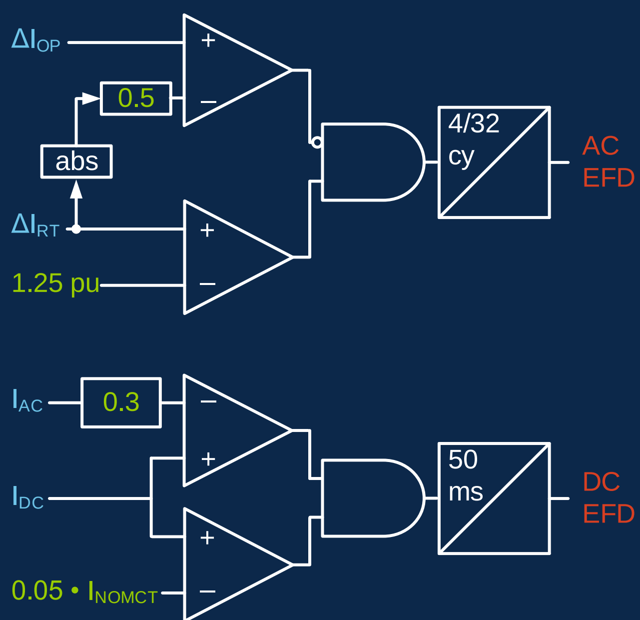
$$V_{SAT\_CT} = 400\ \text{V} + 20 \cdot 5\ \text{A} \cdot 5\ \Omega = 900\ \text{V}$$

$$K_{TD} = \left(\frac{900\ \text{V}}{573.3\ \text{V}}\right) \cdot 1.8 = 2.83$$

87SLP2 = 79%

Test Method and Results – DC

- Down to a K_S of 1
- Lower inrush
  - AC EFD drops out, but dc EFD does not
    87P2 = 0.50 pu
  - DC EFD drops out
    87P1 = 0.15 pu • I_{nom}/TAP
    ~ 0.25 pu



CT Requirements Summary

CT Size and Relay Setting

Before → After

$$V_{SAT} = \left(1 + \frac{X}{R}\right) \cdot I_S \cdot (R_B + R_{CT})$$

$$V_{SAT} = 100 \cdot \frac{39{,}530\ A}{2{,}000} \cdot 5.372\ \Omega = 1{,}062\ V$$

$$V_{ANSI} = C800 + (20 \cdot 5\ A \cdot 5\ \Omega) = 1{,}300\ V$$

$$SLP2 = SLP1 = 10\%?$$

Remanence?

$$V_{SAT} = (K_{REM} \cdot K_{TD}) \cdot I_S \cdot (R_B + R_{CT})$$

$$V_{SAT} = (3 \cdot 1.8) \cdot \frac{39{,}530\ A}{2{,}000} \cdot 5.372\ \Omega = 573.3\ V$$

$$V_{ANSI} = C100 + (20 \cdot 5\ A \cdot 5\ \Omega) = 600\ V$$

$$SLP2 = 90\%$$

CT Size and Relay Setting

Before → After

Before

$$V_{SAT} = \left(1 + \frac{X}{R}\right) \bullet I_S \bullet (R_B + R_{CT})$$

$$V_{SAT} = 100 \bullet \frac{39{,}530\ \text{A}}{2{,}000} \bullet 5.372\ \Omega = 1{,}062\ \text{V}$$

$$V_{ANSI} = \text{C800} + (20 \bullet 5\ \text{A} \bullet 5\ \Omega) = 1{,}300\ \text{V}$$

$$\text{SLP2} = \text{SLP1} = 10\%?$$

Remanence?

After

$$V_{SAT} = (K_{REM} \bullet K_{TD}) \bullet I_S \bullet (R_B + R_{CT})$$

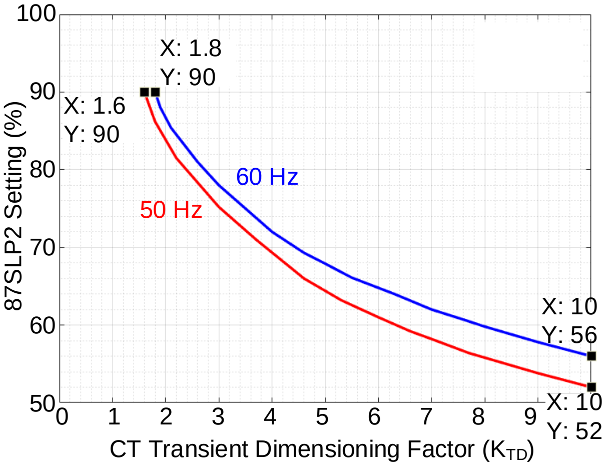
$$V_{SAT} = (3 \bullet 1.8) \bullet \frac{39{,}530\ \text{A}}{2{,}000} \bullet 5.372\ \Omega = 573.3\ \text{V}$$

$$V_{ANSI} = \text{C400} + (20 \bullet 5\ \text{A} \bullet 5\ \Omega) = 900\ \text{V}$$

$$\text{SLP2} = 79\%$$

Conclusion

- Both IEEE and IEC consider dc offset and remanence
- Use of CT models is neither ideal nor required
- Modern differential relay schemes can drastically reduce CT requirements
- Unambiguous application guidance results in precise
  - CT sizing
  - Relay settings


100
90
80
70
60
50
0 1 2 3 4 5 6 7 8 9
X: 1.8
Y: 90
X: 1.6
Y: 90
60 Hz
50 Hz
X: 10
Y: 56
X: 10
Y: 52
87SLP2 Setting (%)
CT Transient Dimensioning Factor (K_{TD})

Questions?