Bus Differential Protection and Simulation

EE 4223/5223

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Based on Team ITC 2005/2006 Senior Design Project

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Sponsor

- International Transmission Company
  - Novi, MI
  - 2700 miles of transmission lines in 13 counties in southeastern MI
  - www.itctransco.com

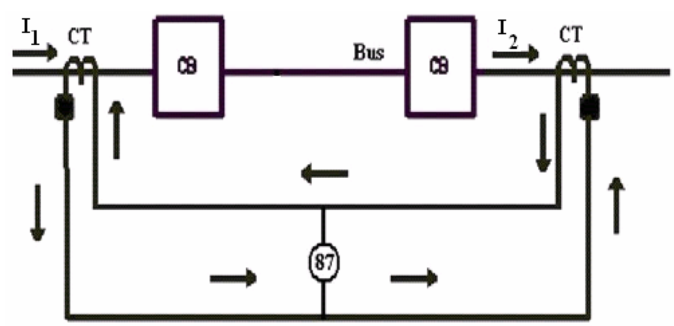
Dependability and Security

- Reliability – tripping breakers to protect from a fault
- Security – tripping only the necessary breakers
- Relay protection is finding a balance

Differential Relay Protection

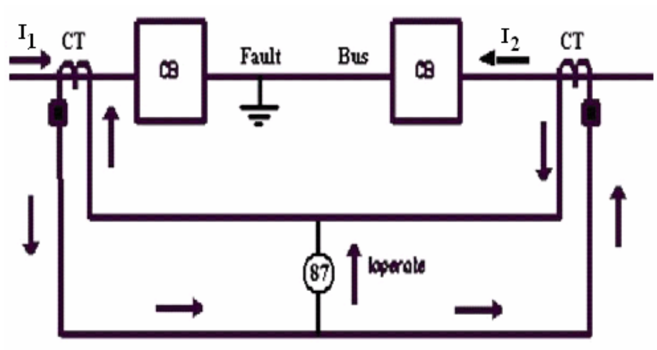
- Relay trips by the difference between the current (measured by CTs) going into and out of the zone of protection

Differential Relay Protection



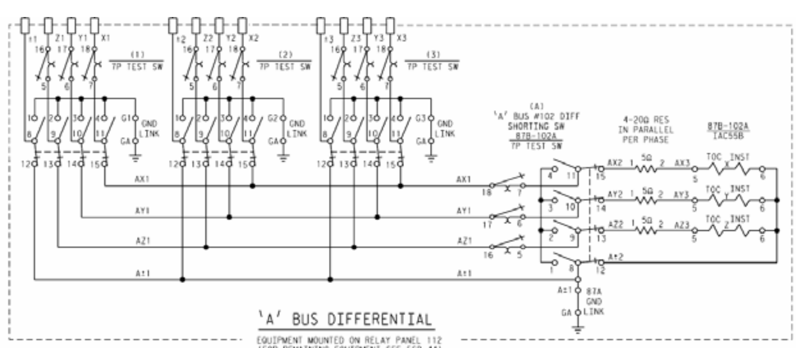
One-line Current Path under Normal Operation (I1=I2)

Differential Relay Protection



One-line Current Path under Fault Conditions (I1≠I2)

Existing Protection Scheme



IAC 55B

- General Electric electromechanical relay
  - Instantaneous time-overcurrent relay
  - Used by ITC to trip relay when differential current exceeds maximum value

SEL Relays

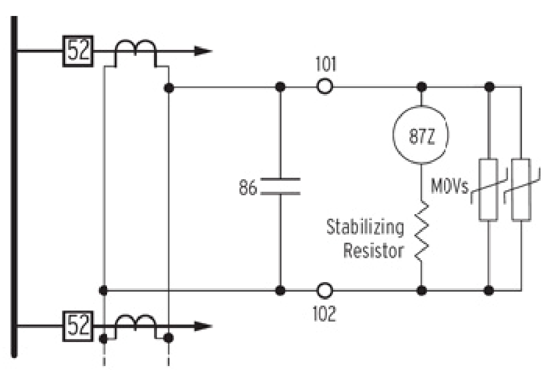
SEL-551C Overcurrent Relay

SEL-587Z High Impedance Differential Relay

Relay Characteristics

- SEL-551C
  - Near direct replacement for existing IAC55B relays
  - Less expensive than the SEL-587Z
  - Can be used with auxiliary CTs
  - Significantly slower trip time under some circumstances
- SEL-587Z
  - Faster fault detection & trip time
  - Provides greater degree of protection than overcurrent relays
  - High Impedance generates voltages up to 2kV (MOV)
  - Requires lock out relay protection
  - Requires dedicated main CTs

Relay Specifications



- Recommends lock out relay contacts in parallel with the 587Z CT inputs
  - Allows the relay to be shorted out on the circuit after fault is detected
- No more then 4 cycles (67ms) of fault current through the 587Z
- Breakers not relied on to interrupt the fault current coming into the relay

Settings Calculations

- Information provided by ITC for Bus 102 of the Milan substation
- SEL-551C
  - Instantaneous Current Setting
  - Time-Overcurrent Pickup and Time Dial
- SEL-587Z
  - Voltage setting

Settings Considerations

- Minimum Internal Fault
  - Single-line to ground
  - Relay must trip for internal faults
- Maximum External Fault
  - Fault outside zone of protection causes CT saturation
  - Differential current on secondary
  - Relay should not trip for external faults

CTs

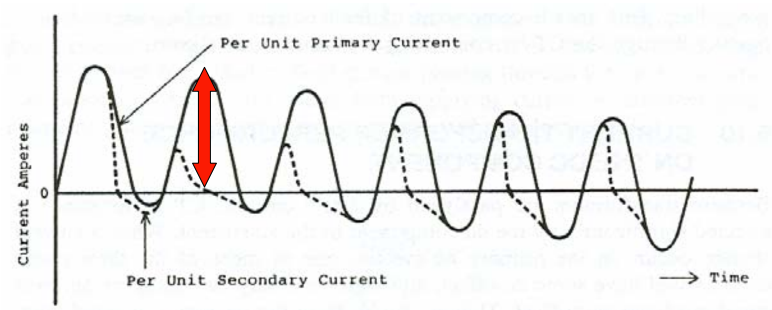
- Mistubishi Electric
- Mulit-ratio 3000:5
- C800 Accuracy

CT Saturation

- Causes of CT saturation
  - Primary winding of CT has a DC component
  - Primary winding's current is too high and core flux saturates
- Primary and secondary windings lose their linearity causing an error current

Current Transformer Saturation

Currents at the faulted CT

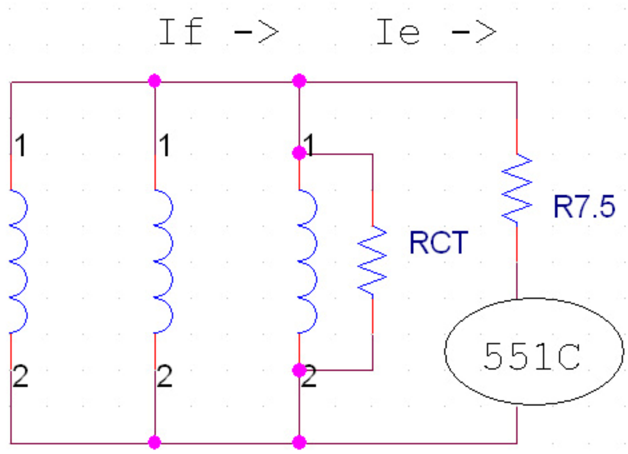


Saturation causes a large difference between induced CT current and the scaled line current

Parameters

- I_F = 17877 A (Maximum external fault current)
  - 19959 A (Maximum internal fault current)
  - 4168 A (Minimum internal fault current)
- N = 3000:5 (CT ratio)
- R_{CT} = 2.0 Ω (CT secondary winding and lead resistance)
- R_{LEAD} = 0.5 Ω (Resistance of lead from junction to CT)
- n = 3 (Total number of circuits)
- K = 150 % (ITC's factor of safety)

SEL-551C Saturated Circuit



Calculate Instantaneous Setting

- The current through the relay is:

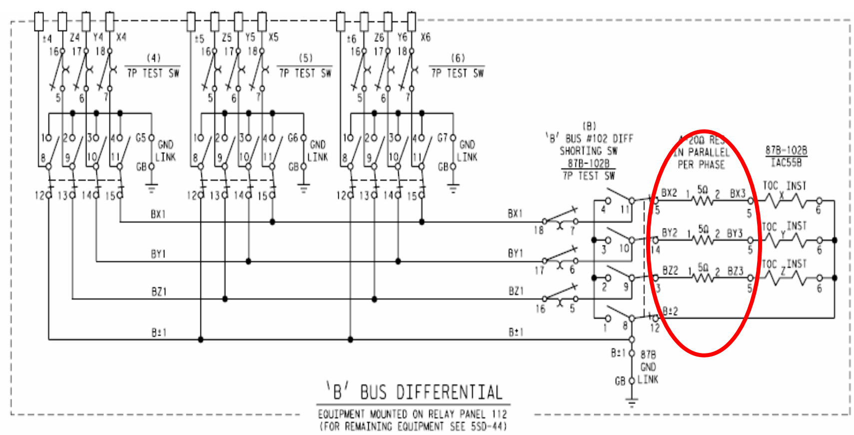
$$I_E = (\frac{R_{CT}}{R_{CT} + R_{7.5}}) \cdot \frac{I_F}{N}$$

$$I_E = (\frac{2.0\Omega}{2.0\Omega + 7.5\Omega}) \cdot \frac{17877A}{600}$$ = 6.27A

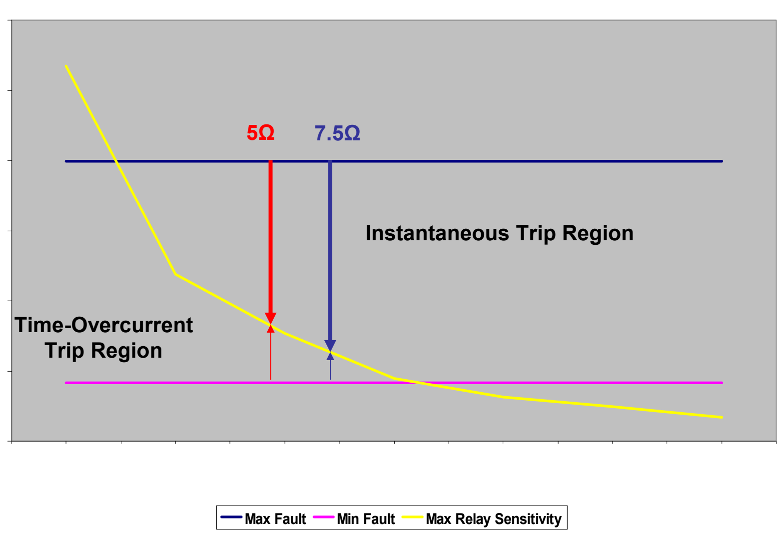
$$I_s = K \cdot I_E$$ = 10 A

$$I_{\min} = N \cdot I_S = 600 \cdot 10$$ = 6000 A

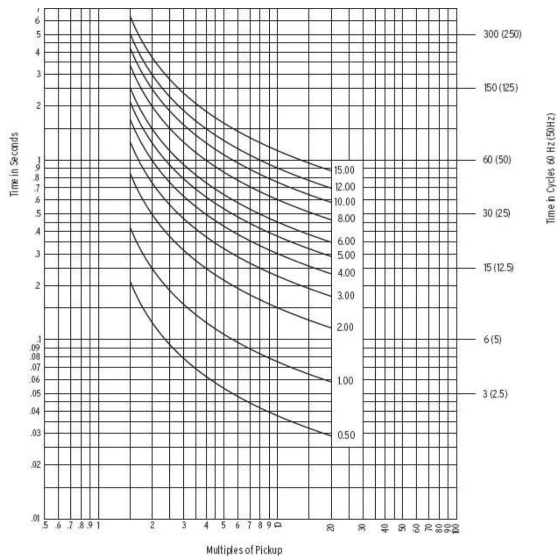
Series Resistance Placement



Relay Sensitivity Due to Series Resistance



TOC Curve



Time-Overcurrent Pickup

- Using ITC's standards, time-overcurrent pickup is set at 10% of the maximum external fault

$$PU = 10\% \cdot I_F$$

$$PU = 10\% \cdot 17877A \approx 1800A$$

Time Dial Calculation

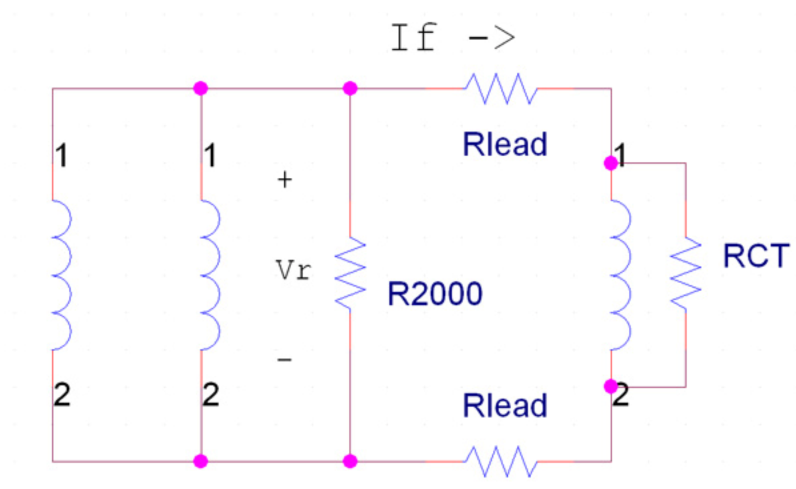
$$t_p = TD \cdot (0.00262 + \frac{0.00342}{M^{0.02} - 1})$$

- TD = Time dial setting
- tp = Trip time at multiple of pick-up (12 cycles = 0.2 secs)
- M = Multiple of pick-up (3600/1800 = 2)

$$0.2 = TD \cdot (0.00262 + \frac{0.00342}{2^{0.02} - 1})$$

TD = 0.8

SEL-587Z Saturated Circuit



Calculation of the Voltage Setting

- The relay voltage across the impedance element is:

$$V_r = (R_{CT} + 2 \times R_{LEAD}) \times \frac{I_F}{N}$$

$$V_r = (2.0\Omega + 2 \cdot 0.5\Omega) \cdot \frac{17877A}{600}$$ = 74.5 V

$$V_s = K \times V_r = 1.5 \times 74.5$$ = 112 V

Minimum Primary Current

Find minimum primary differential current by:

$$I_{\min} = (nI_e + I_r + I_m) \times N$$

$I_{\min} =$ minimum current

$n =$ # of CTs in parallel

$I_e =$ excitation current

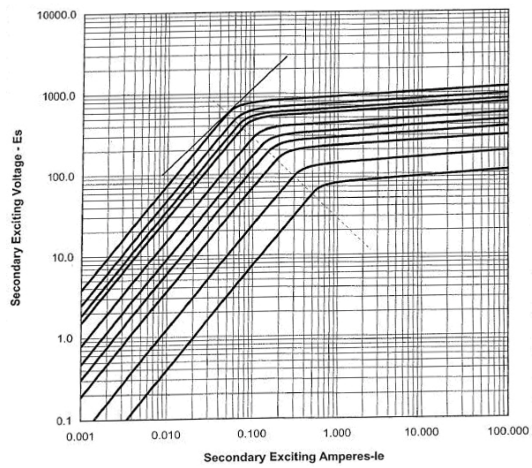
$I_r =$ current through relay

$I_m =$ current through MOV

Excitation Current

- Using the graph for the CT the value of the excitation current (I_e) can be found given V_s = 112 V

$$I_e = 0.015A$$



Current Through the SEL-587Z

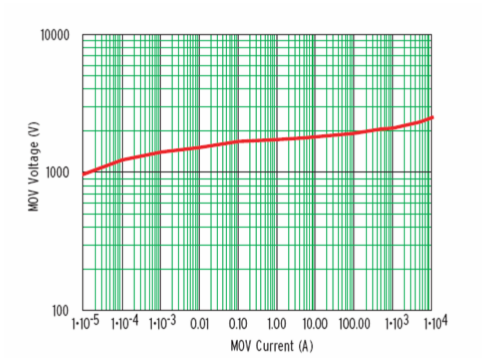
- The current through the relay (I_r) can be found by:

$$I_r = \frac{V_s}{R}$$

$$I_r = \frac{112V}{2000\,\Omega}$$

$$I_r = 0.056\text{ A}$$

Current Through the MOV



When V_{mov} < 1000 V the current through the MOV (I_m) is 0 A

Minimum Current

- Using the determined values, the minimum primary differential current (I_{min}) is:

$$I_{\min} = (nI_e + I_r + I_m) \times N$$

$$I_{\min} = (3 \times 0.015 + 0.056 + 0) \times 600$$

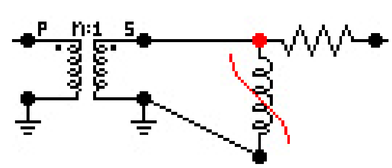
$$I_{\min} = 61 \text{ A}$$

- Minimum Internal Fault = 4168 A

ATP Simulation

- Use ATP to simulate CTs
- Determine voltage ‘seen’ by the relay for internal fault conditions
- Apply simulated waveforms to the relay for testing

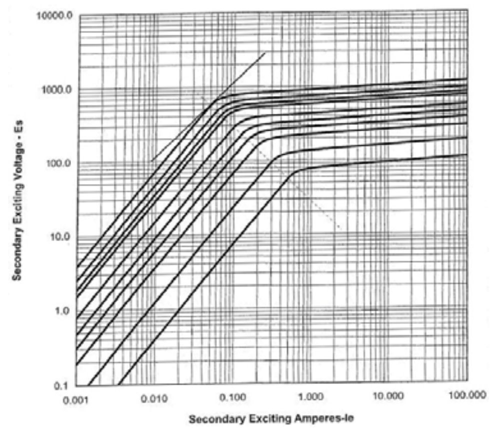
CT Simulation



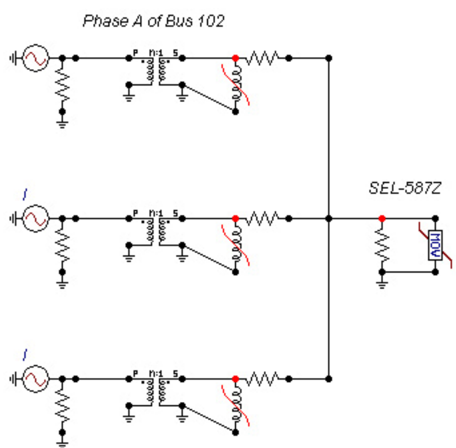
- Ideal transformer
- Type 93 non-linear inductor
- Series resistance

CT Characteristics

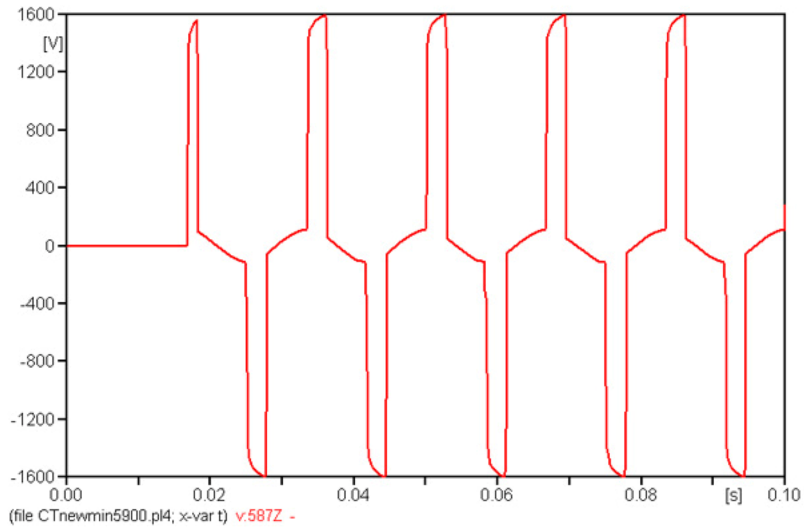
CT		Non-linear Inductance	
E (kV)	I (A RMS)	I (A PK)	λ (Wb-T PK)
0	0	0	0
0.116	0.014	0.02	0.435
0.232	0.024	0.032	0.87
0.54	0.05	0.069	2.026
0.96	10	17.581	3.601
1	20	54.241	3.751
1.2	100	208.373	4.502



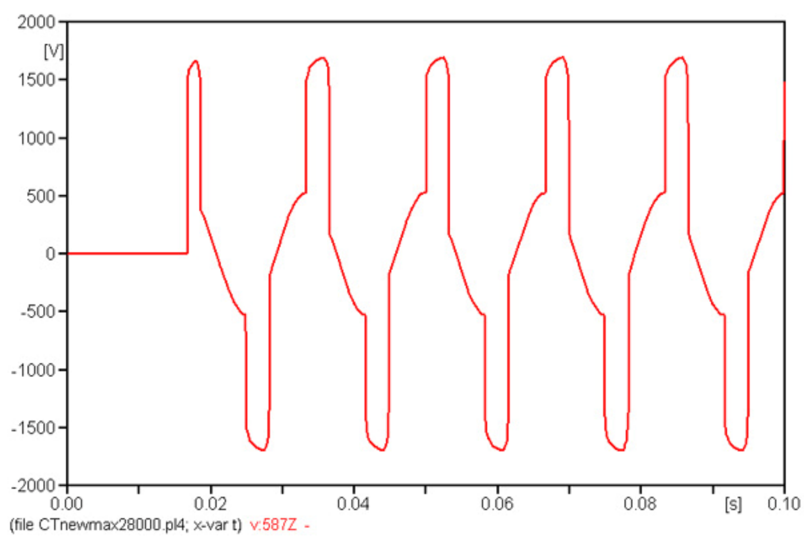
ATP Simulation



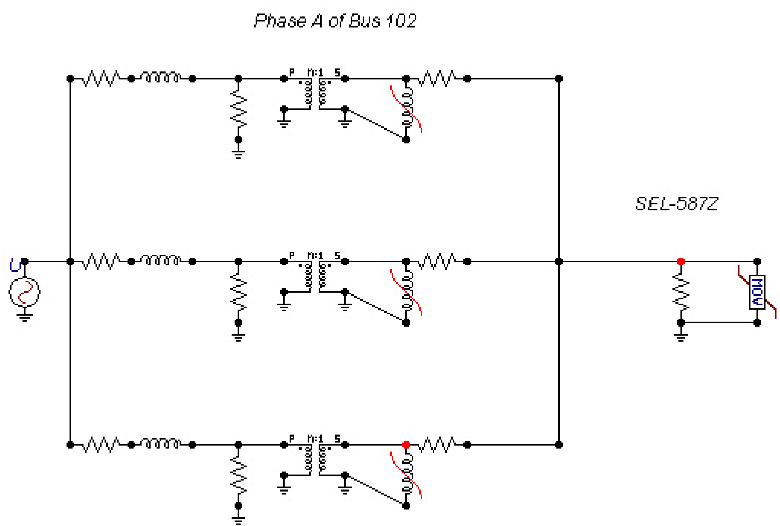
Minimum Internal Fault (4 kA)



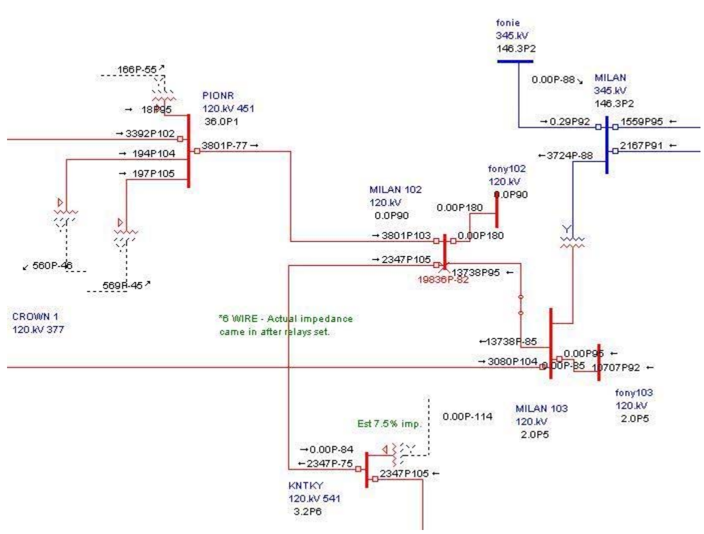
Maximum Internal Fault (20 kA)



Thevenin Equivalent



Fault Contributions



Line Impedances

Calculated Line Impedances at 120 kV

I (A)	Z (Ω)	R + jX (Ω)	X/R
3801 /_ -77	31.571 /_ 77	7.102 + j30.761	4.33
2347 /_ -75	51.129 /_ 75	13.233 + j49.387	3.73
13738 /_ -85	8.735 /_ 85	0.761 + j8.702	11.43

DC Offset

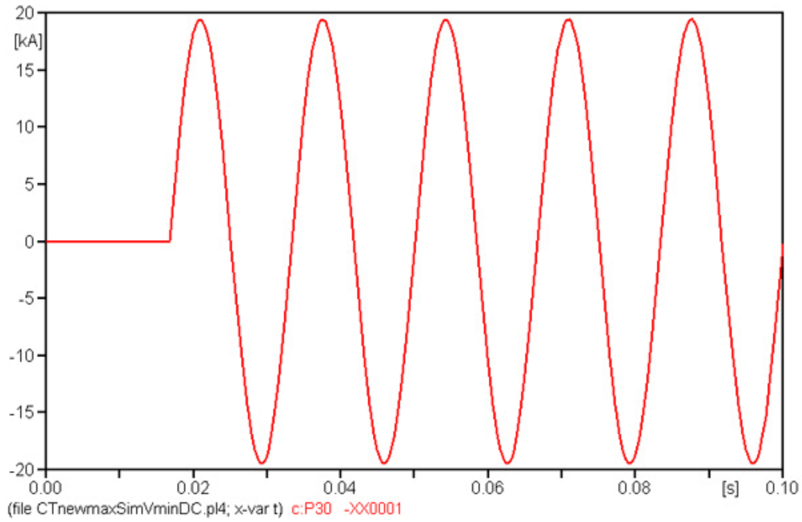
- DC offset determined by initial angle
- Use X/R ratio of line carrying most fault current

$$\alpha_{\min} = \theta - 90^\circ$$

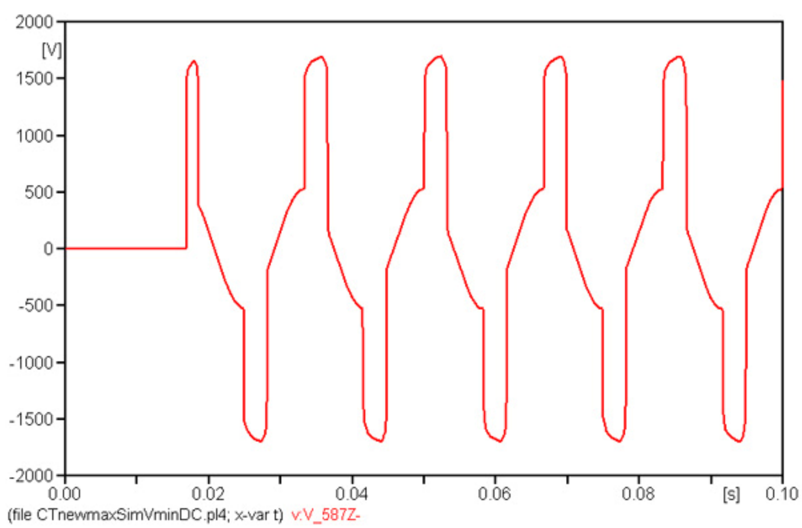
$$\alpha_{\max} = \theta - 180^\circ$$

$$\theta = \tan^{-1}\frac{X}{R}$$

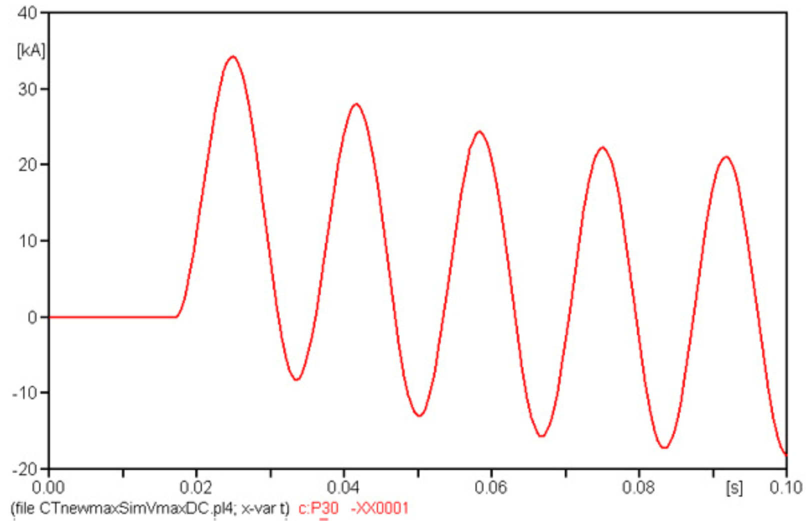
Minimum DC Offset



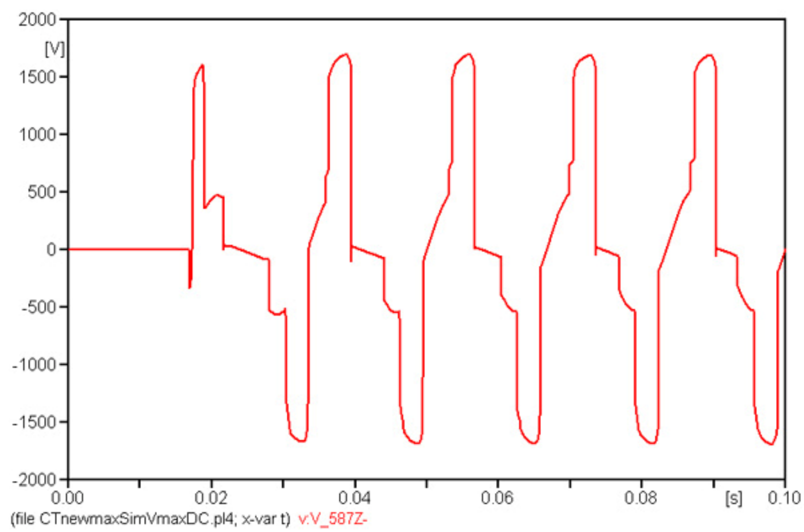
Minimum DC Offset



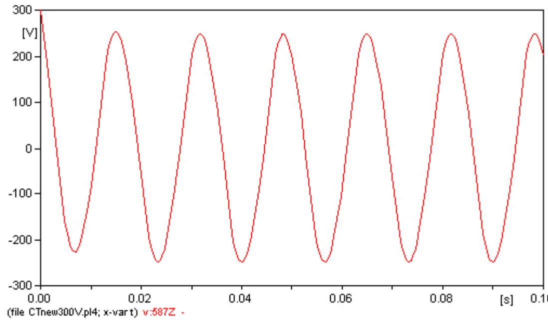
Maximum DC Offset



Maximum DC Offset



Doble Limitation



Relay Voltage

- Doble Simulator maximum output – 300 V
- Resulting wavform sinusoid with decaying DC offset
- Relay trips properly on slightly saturated waveform

Conclusion

- Differential schemes protect bus from internal faults
- Relay settings must balance reliability with security
- ATP can simulate CT saturation to understand fault conditions

References

- **[1]** Blackburn, J. Lewis. Protective Relaying: Principles and Applications. 2nd ed. New York: Marcel Dekker, Inc., 1998.
- **[2]** Dr. Mork, Bruce. Personal communication on substation layouts and relays. Michigan Technological University. Fall 2005.
- **[3]** General Electric. Short-Time Overcurrent Relays.
- **[4]** Mitsubishi Electric Power Products, Inc. Factory Test Report 120-SFMT-40J Gas Circuit Breaker. Oct 4, 2004.
- **[5]** Schweitzer Engineering Laboratories. SEL-587Z Instruction Manual
- [6] Schweitzer Engineering laboratories. SEL-551C Instruction Manual

Questions or Comments?