Performance of Time-Domain Line Protection Elements on Real-World Faults

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The Need for Speed

Safer • Less Damage • Improved Dynamics

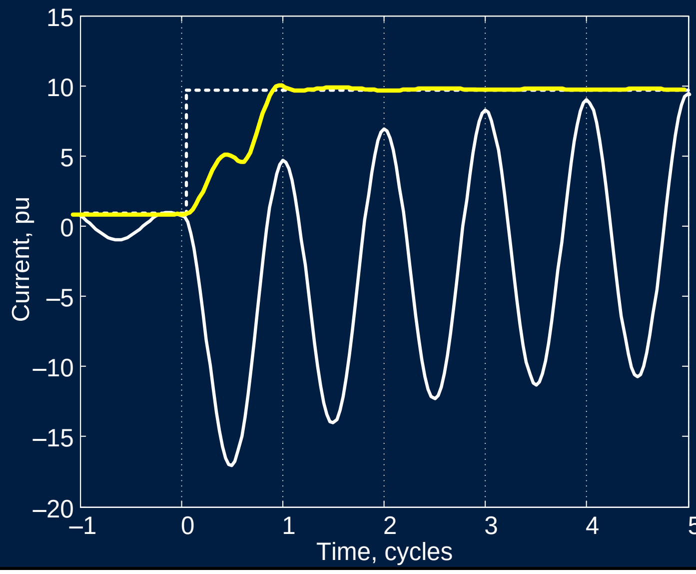
The Need for Ultra-Fast Fault Clearing

R. B. Eastvedt, BPA, 1976 WPRC

- Reduced damage to insulators, conductor and hardware from flashovers.
- Reduced safety hazards to substation personnel and linemen from step and touch potentials.
- Reduced mechanical stress in major substation equipment, generators and turbines.
- Also, faster reclosure may be possible because of reduced ionization resulting from the arc.

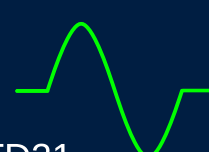
Speed of Phasor-Based Relays

Determining *Steady State* Takes Time

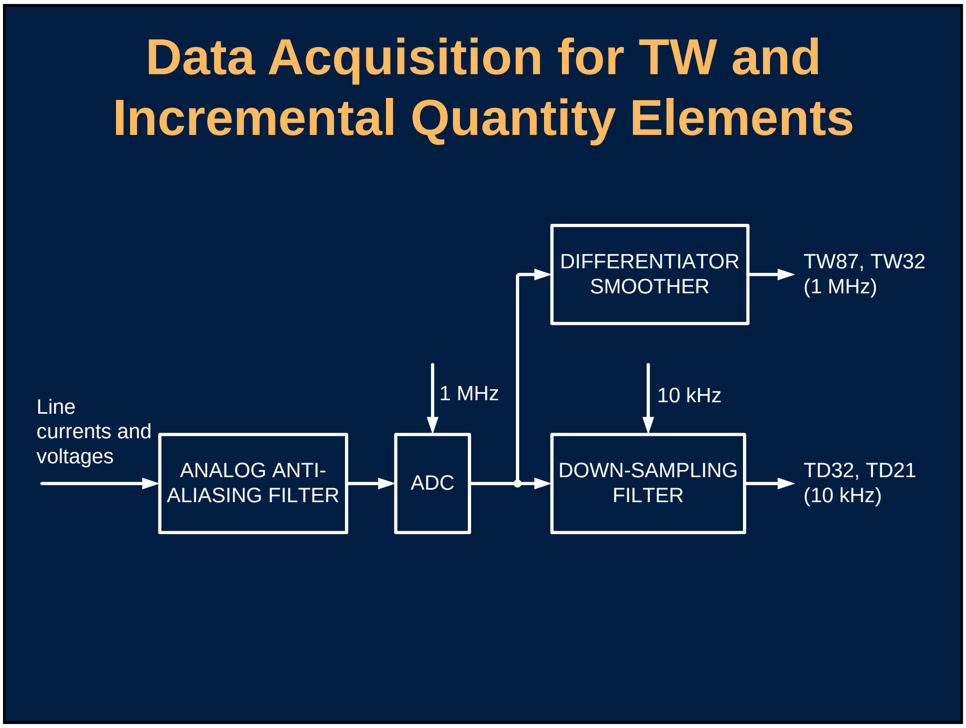


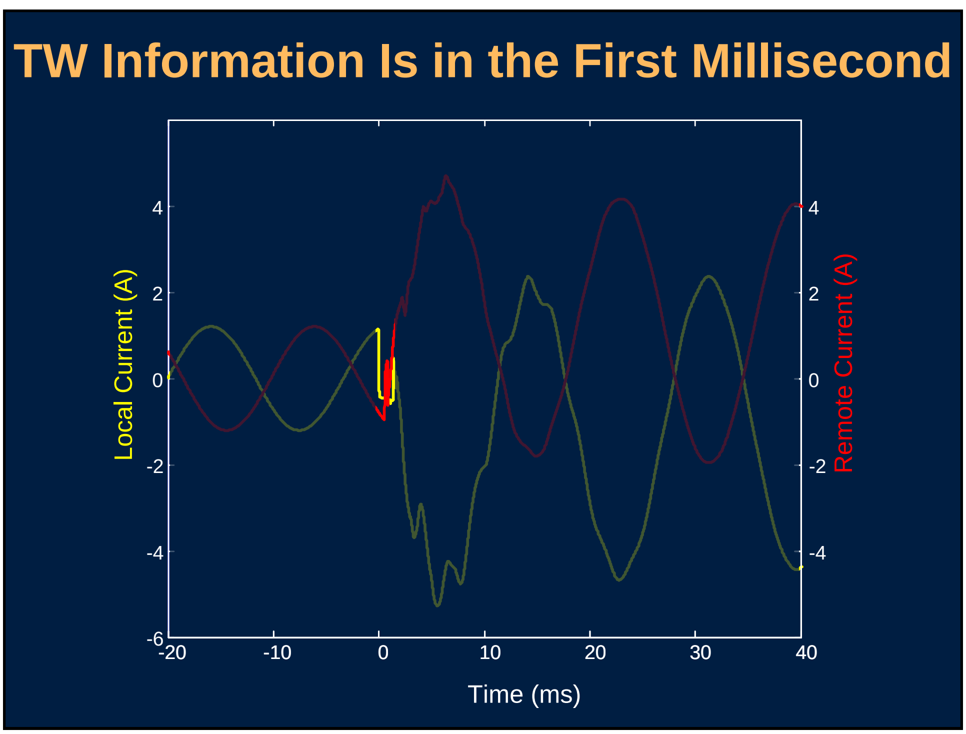
Time-Domain Elements Provide Speed With Security

- Based on traveling waves
  - Differential element, TW87
  - Directional element, TW32

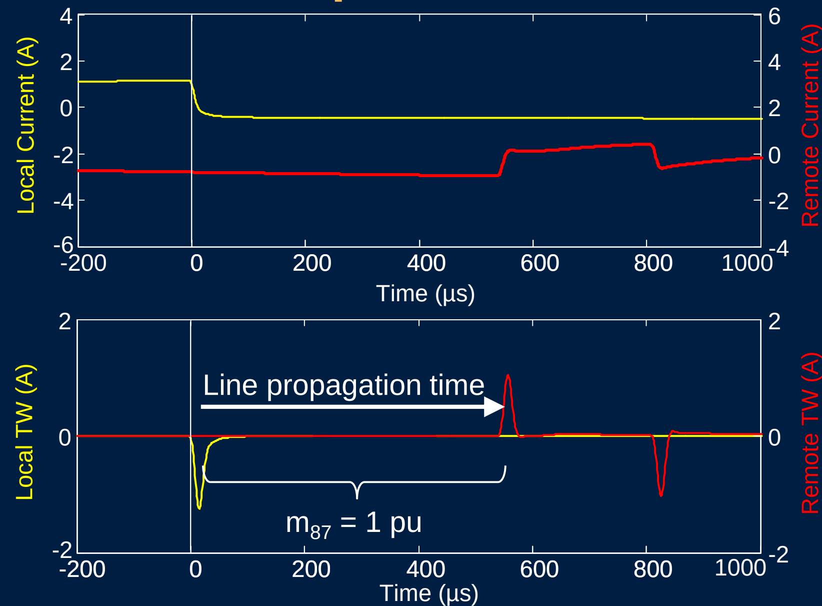


- Based on incremental quantities
  - Under-reaching element, Zone 1, TD21
  - Directional element, TD32


Data Acquisition for TW and Incremental Quantity Elements
Line currents and voltages
ANALOG ANTI-ALIASING FILTER
1 MHz
ADC
DIFFERENTIATOR SMOOTHER
TW87, TW32 (1 MHz)
10 kHz
DOWN-SAMPLING FILTER
TD32, TD21 (10 kHz)


TW Information Is in the First Millisecond
Local Current (A)
Remote Current (A)
Time (ms)
4
2
0
-2
-4
-6
-20
-10
0
10
20
30
40

TW87 Principle – External Fault

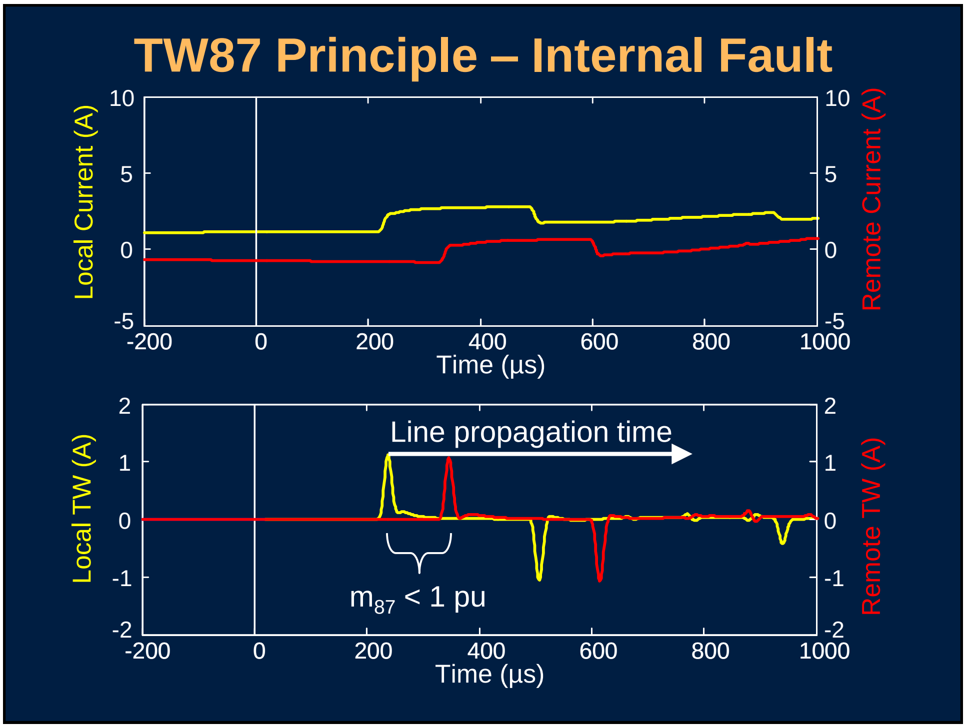


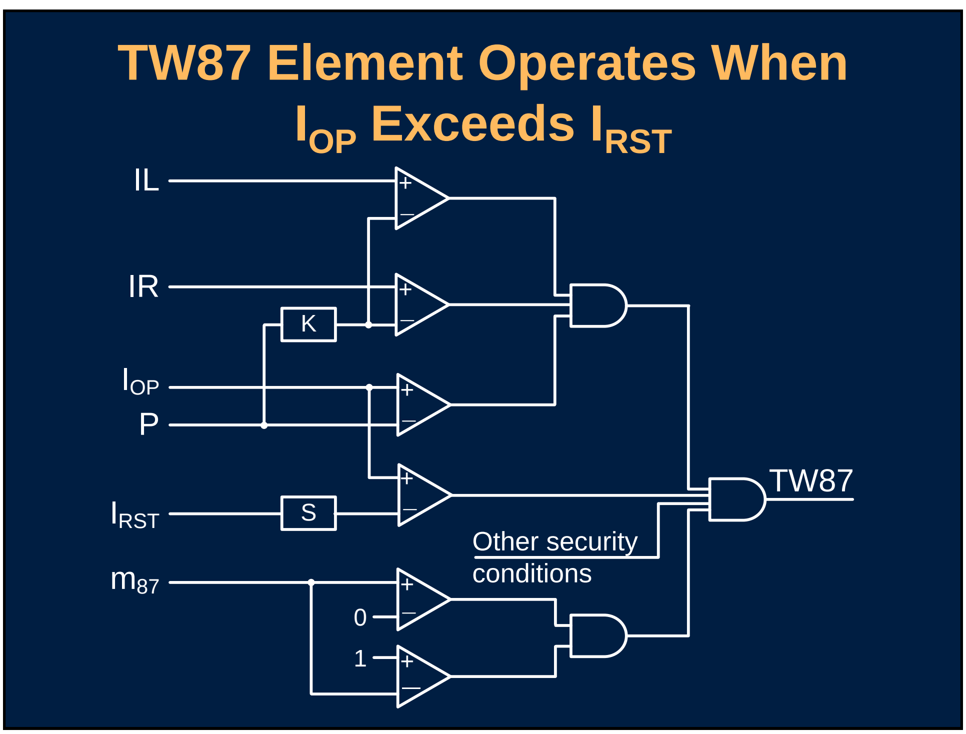
TW Differential Element Principle

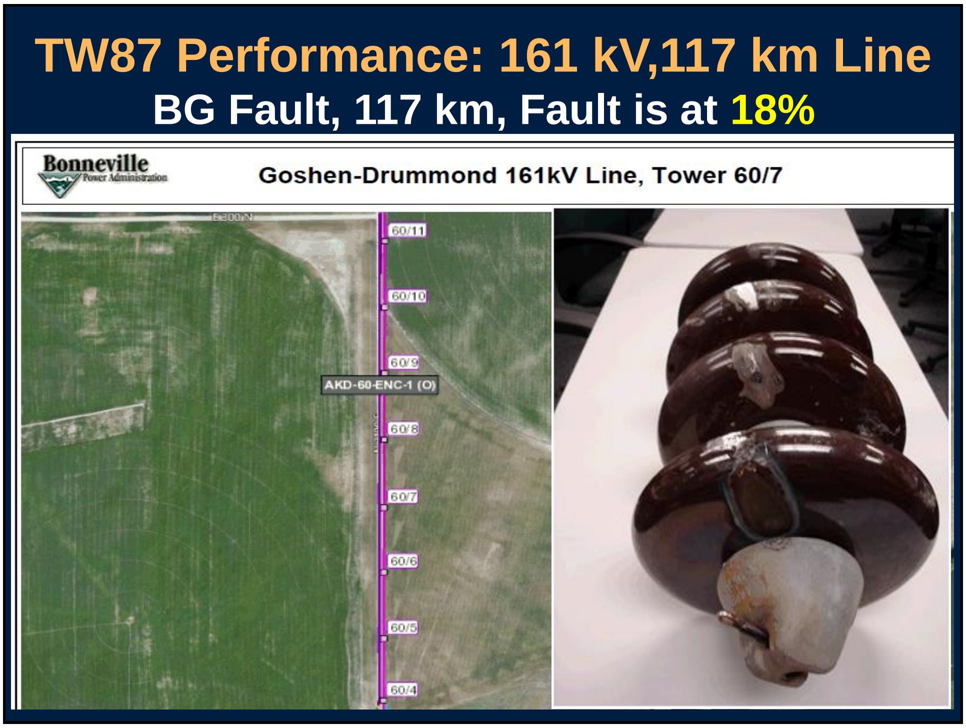
- External fault surges
  - Are of opposite polarity
  - Spaced one travel time, apart
- Internal fault surges: same polarity

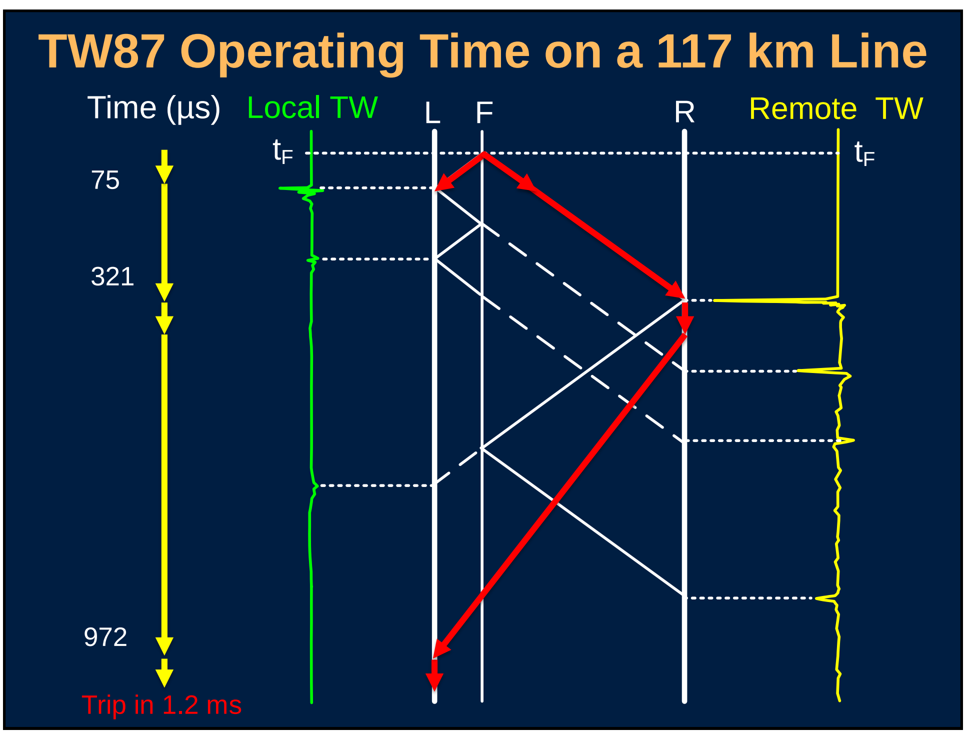
Σ of first surges = OPERATE

Δ of surges T apart = RESTRAIN

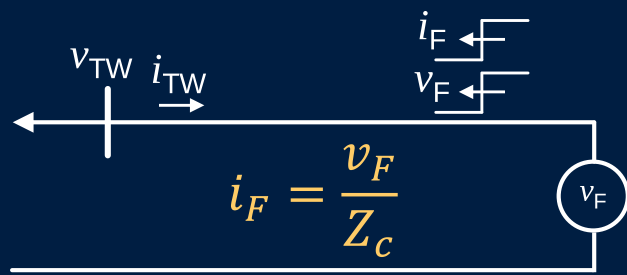

TW87 Principle – Internal Fault
Local Current (A)
Remote Current (A)
Time (µs)
Local TW (A)
Remote TW (A)
Line propagation time
m87 < 1 pu


TW87 Element Operates When
IOP Exceeds IRST
IL
IR
K
IOP
P
IRST
S
m87
TW87
Other security
conditions


TW87 Performance: 161 kV,117 km Line
BG Fault, 117 km, Fault is at 18%
Bonneville Power Administration
Goshen-Drummond 161kV Line, Tower 60/7
60/11
60/10
60/9
AKD-60-ENC-1 (O)
60/8
60/7
60/6
60/5
60/4


TW87 Operating Time on a 117 km Line
Time (µs)
Local TW
L
F
R
Remote TW
tF
tF
75
321
972
Trip in 1.2 ms

TW Directional Element Principle

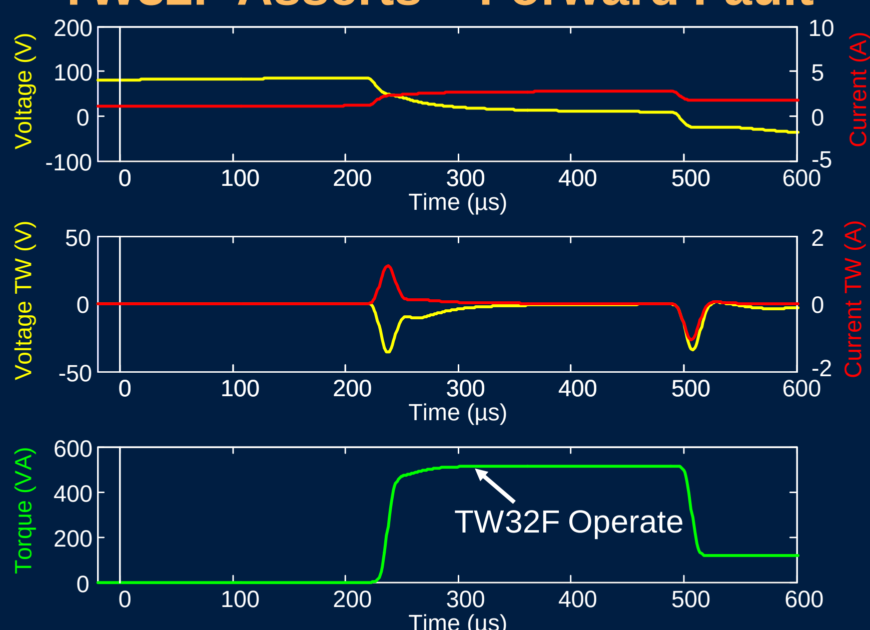


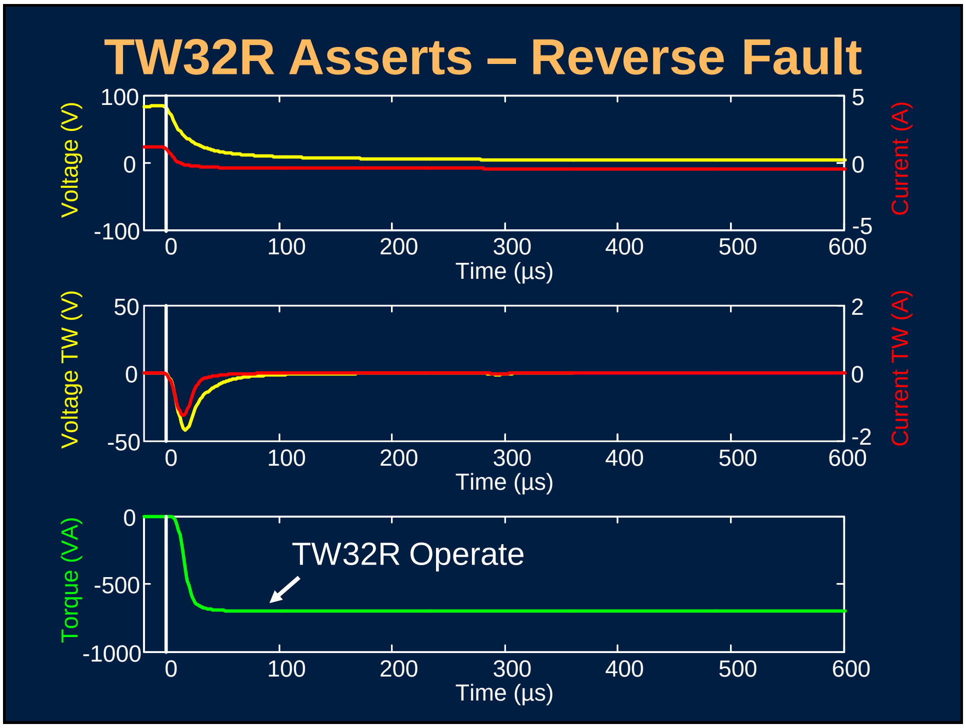
$$i_F = \frac{v_F}{Z_c}$$

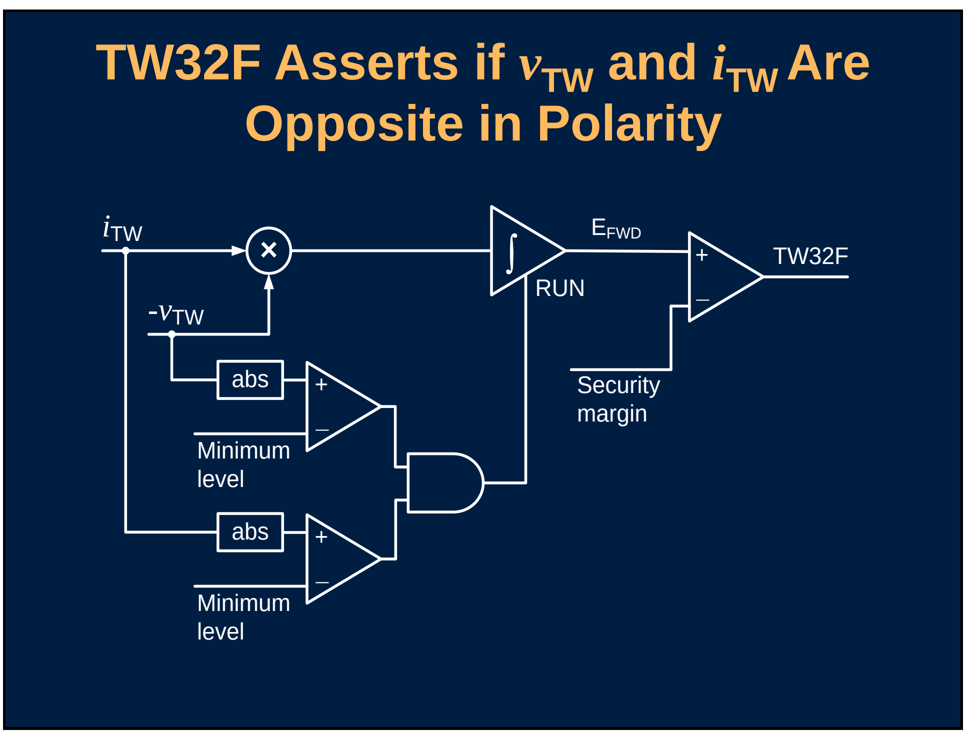
$Z_c = Characteristic\ Impedance$

v_{TW}	i_{TW}	
+ –	– +	Forward
+ –	+ –	Reverse

TW32F Asserts – Forward Fault

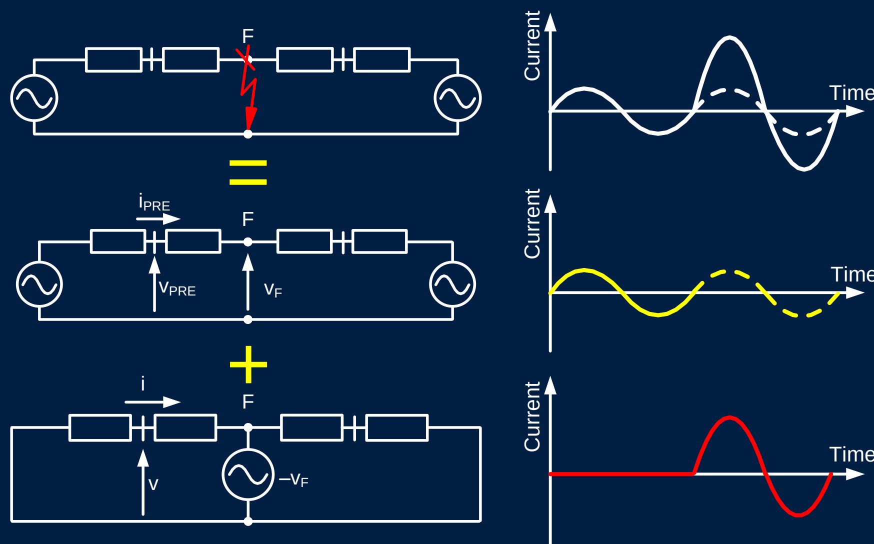



TW32R Asserts – Reverse Fault
Voltage (V)
Current (A)
100
0
-100
5
0
-5
0
100
200
300
400
500
600
Time (µs)
Voltage TW (V)
Current TW (A)
50
0
-50
2
0
-2
0
100
200
300
400
500
600
Time (µs)
Torque (VA)
0
-500
-1000
TW32R Operate
0
100
200
300
400
500
600
Time (µs)


TW32F Asserts if v_{TW} and i_{TW} Are Opposite in Polarity
i_{TW}
$-v_{TW}$
abs
abs
+
–
Minimum level
Minimum level
E_{FWD}
RUN
TW32F
Security margin

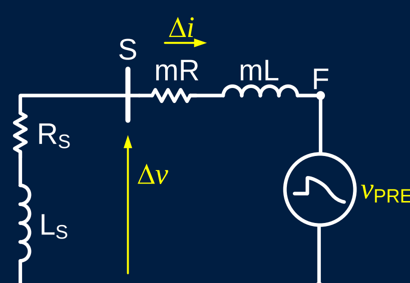
Time-Domain Directional Element (R-L)

Incremental Quantities



Replica Current Simplifies Pure Fault Network Representation

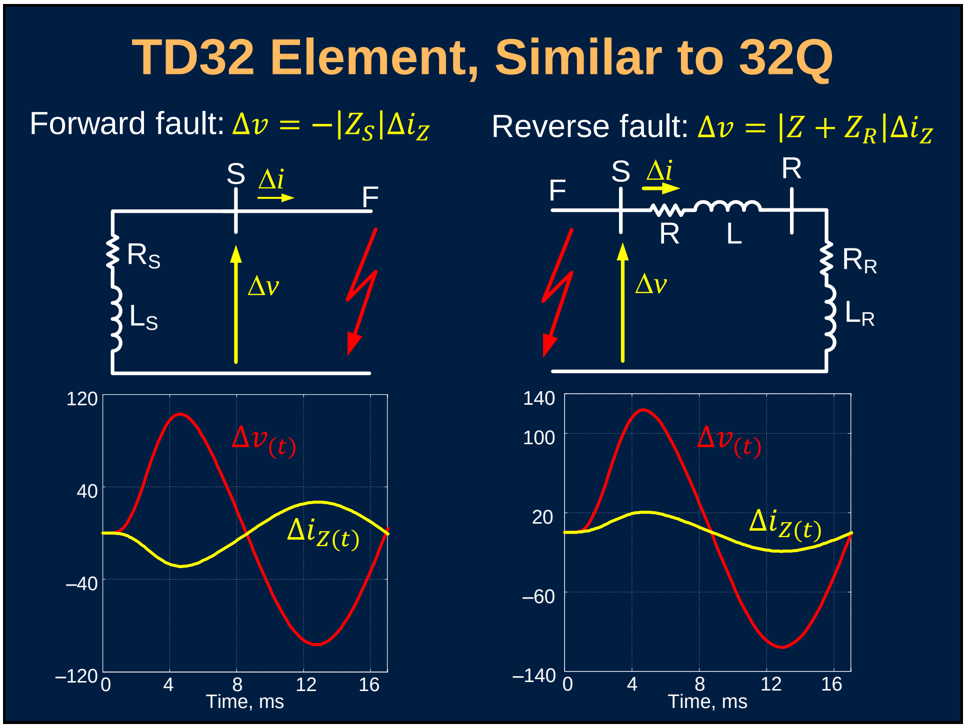
$$\Delta v + \left(R_S \Delta i + L_S \frac{d\Delta i}{dt} \right) = 0$$

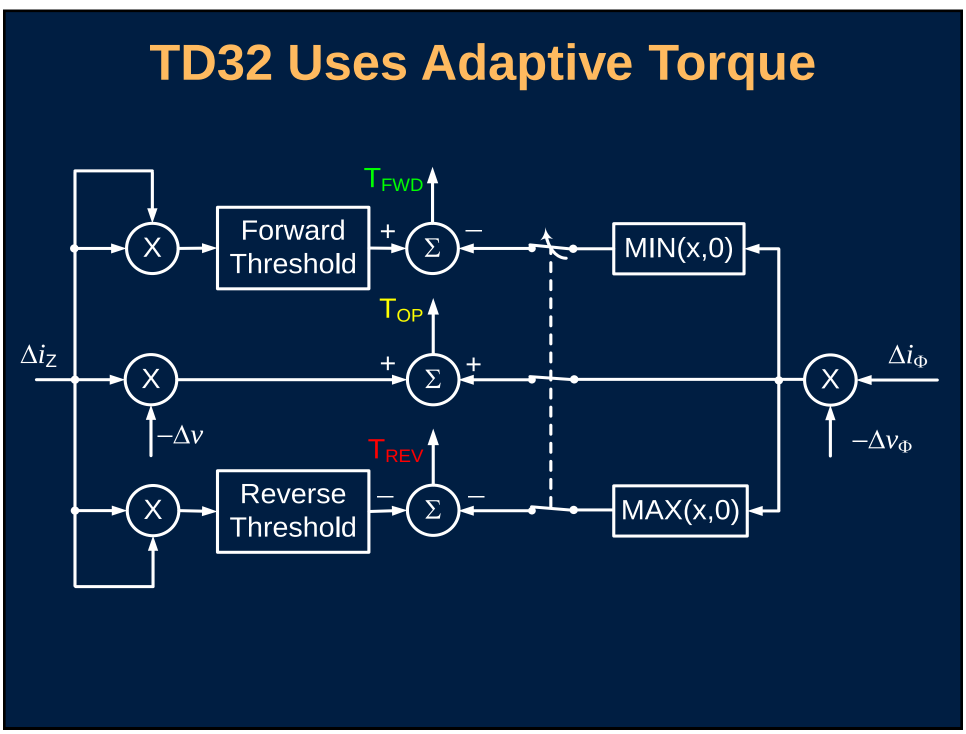


Replica current: $\Delta i_z = \frac{1}{|Z|} \left(R \Delta i + L \frac{d\Delta i}{dt} \right)$

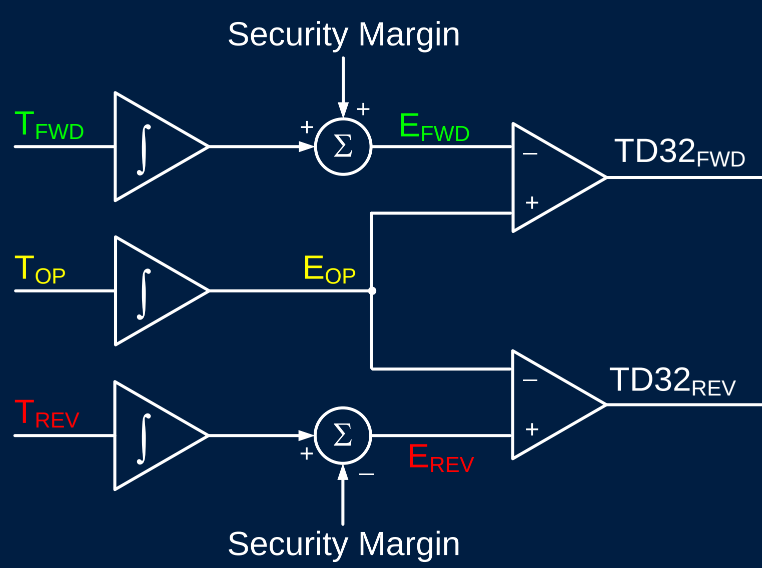
Even simpler equations…

$$\Delta v + |Z_S| \Delta i_Z = 0 \qquad \Delta v - m|Z| \Delta i_Z = v_{PRE}$$


TD32 Element, Similar to 32Q
Forward fault: $\Delta v = -|Z_S|\Delta i_Z$
Reverse fault: $\Delta v = |Z + Z_R|\Delta i_Z$
S
Δi
F
R_S
L_S
Δv
R
L
R_R
L_R
$\Delta v_{(t)}$
$\Delta i_{Z(t)}$
Time, ms

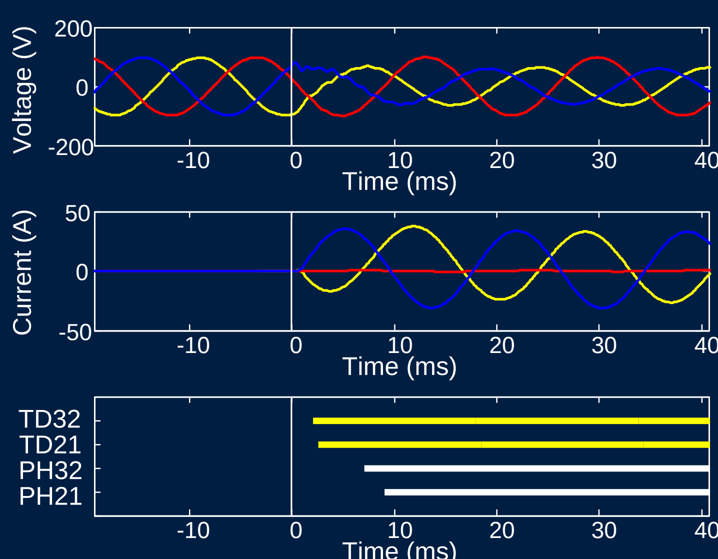

TD32 Uses Adaptive Torque
T_{FWD}
T_{OP}
T_{REV}
Forward Threshold
Reverse Threshold
MIN(x,0)
MAX(x,0)
Δi_Z
$-\Delta v$
Δi_Φ
$-\Delta v_\Phi$

TD32 Element Is Fast and Secure

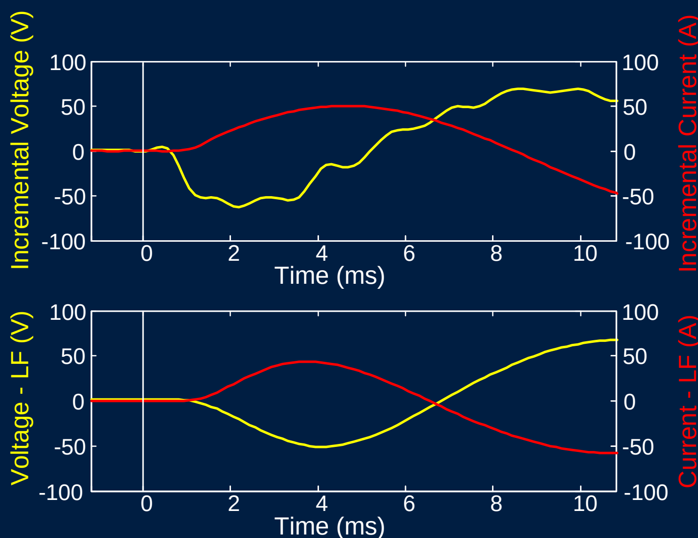


TD32 Operated 3x Faster

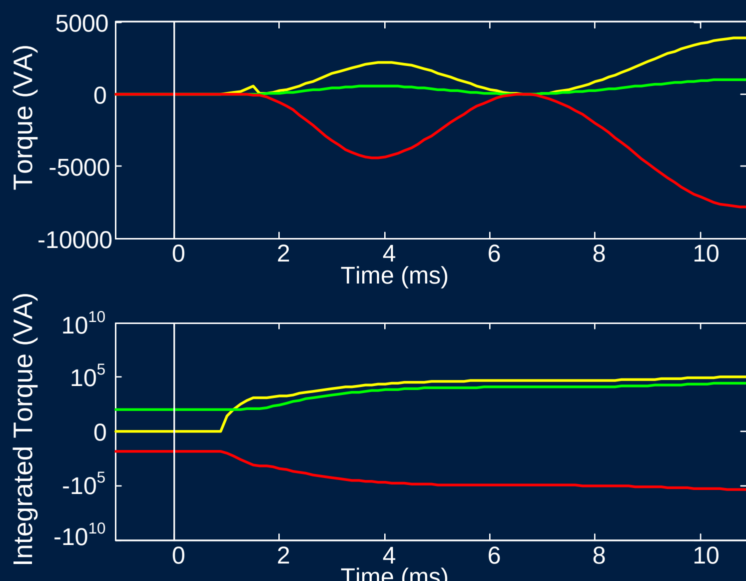
230 kV, 159 km, Fault Is at 18% of the Line



Δv and Δi Are of Opposite Polarities for Forward Faults

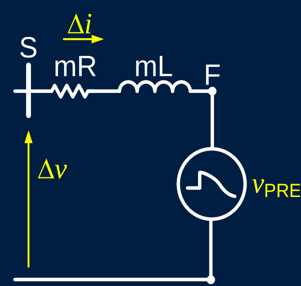


TD32 Asserts in 2.3 ms



Time-Domain Distance Element Principle

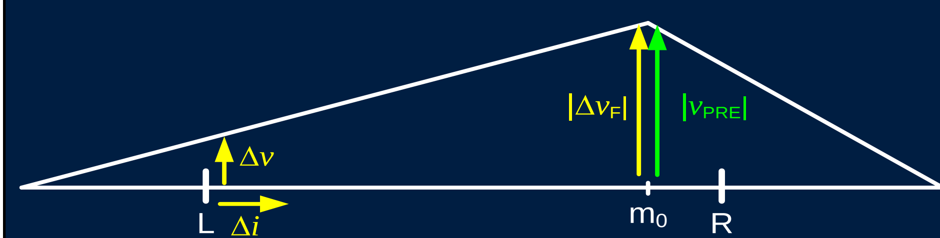
$$\Delta v - m|Z|\Delta i_Z = v_{PRE}$$

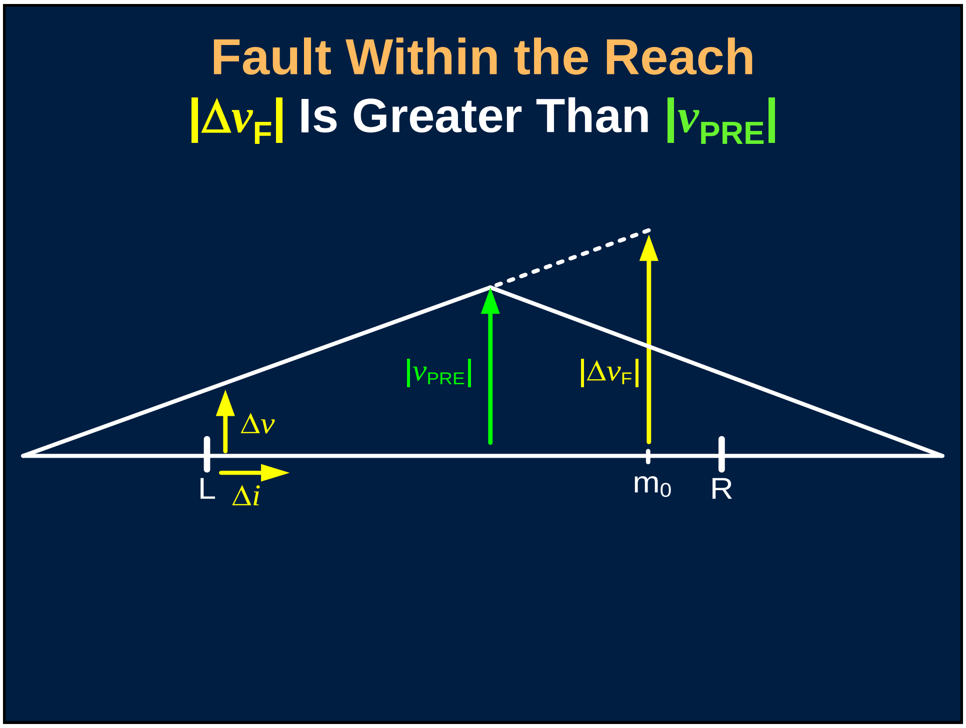


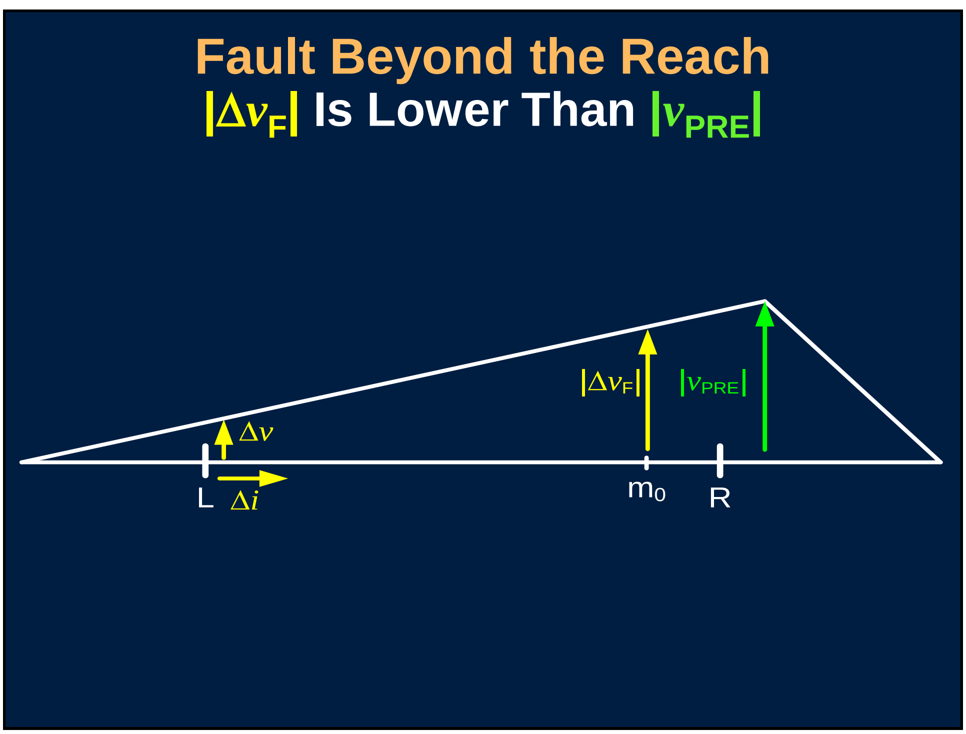
Define: $\Delta v_F = \Delta v - m|Z|\Delta i_Z$

Therefore, at location m: $|\Delta v_F| = |v_{PRE}|$

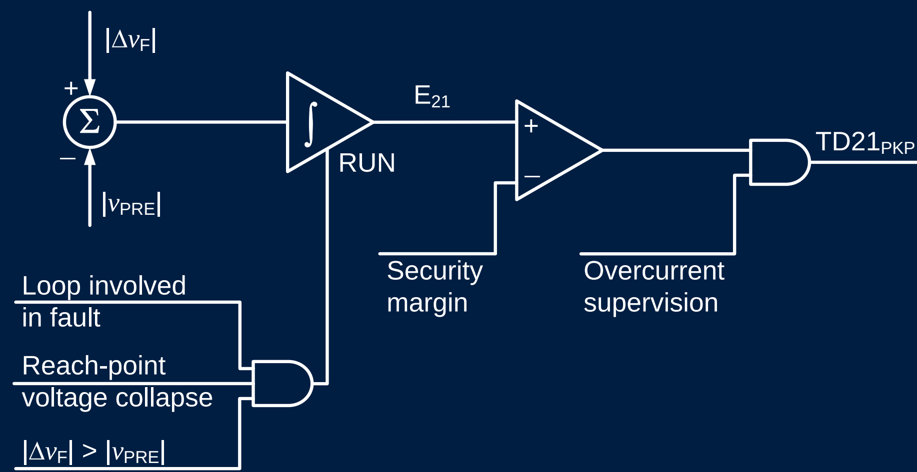
Fault at the Reach
$|\Delta v_F|$ Is Equal to $|v_{PRE}|$




Fault Within the Reach
|ΔvF| Is Greater Than |vPRE|
|vPRE|
|ΔvF|
Δv
L
Δi
m0
R

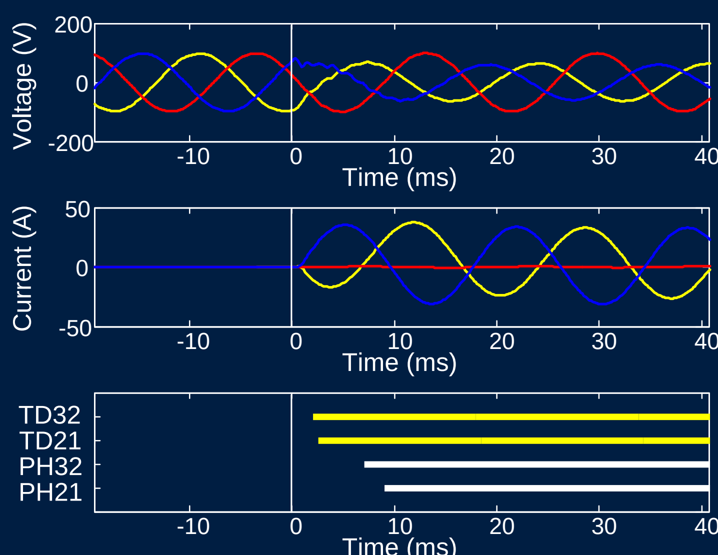

Fault Beyond the Reach
|ΔvF| Is Lower Than |vPRE|
|ΔvF|
|vPRE|
Δv
L
Δi
m0
R

TD21 Integrates Only if Voltage Has Collapsed

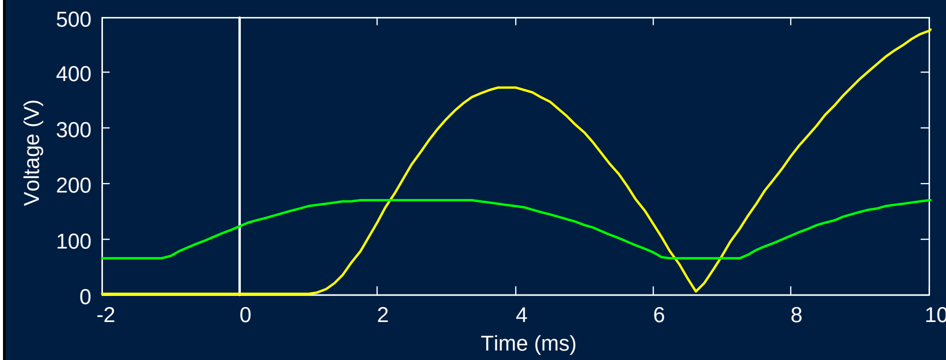


TD21 Operates 3x Faster

230 kV, 159 km, Fault Is at 18% of the Line

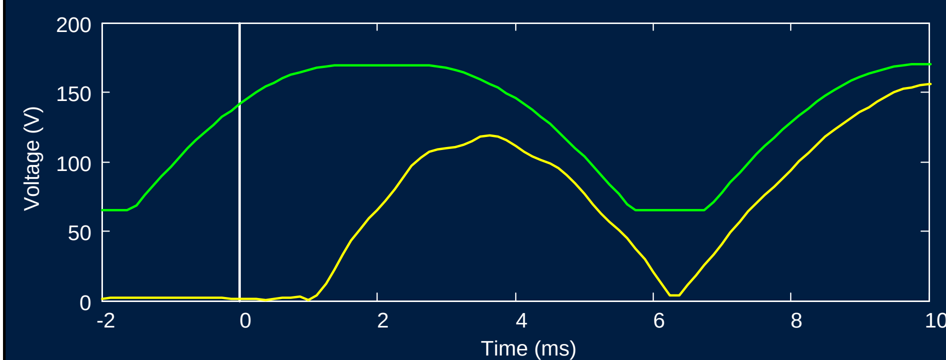


TD21 Asserts in 2.8 ms



TD21 Restrains for Out-of-Zone Faults

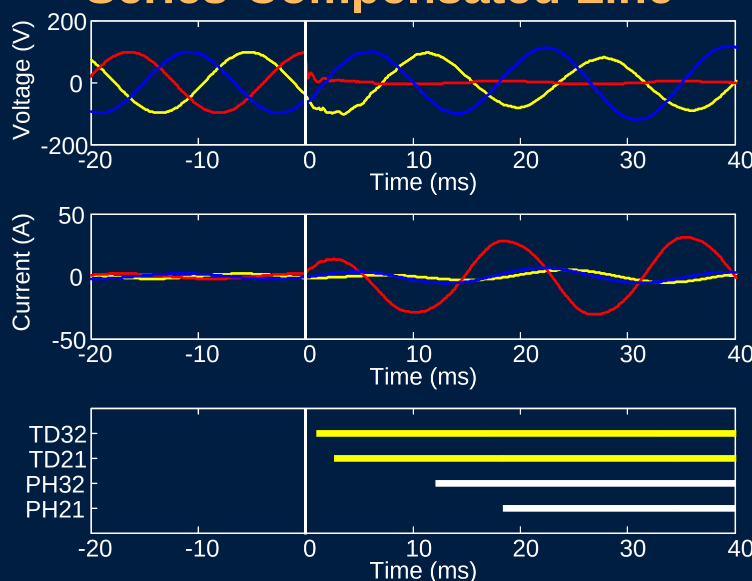
Fault Is at 82% of the Line



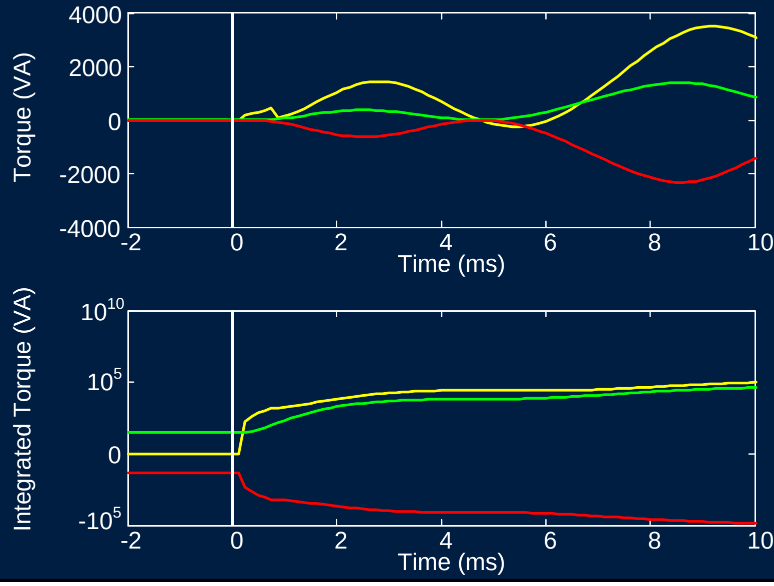
Performance Evaluated With Field-Captured Data

- Event reports captured by line relays
- Line lengths from 56 to 252 km
- System voltages from 161 to 500 kV
- Variety of fault types and locations
- Variety of CCVTs

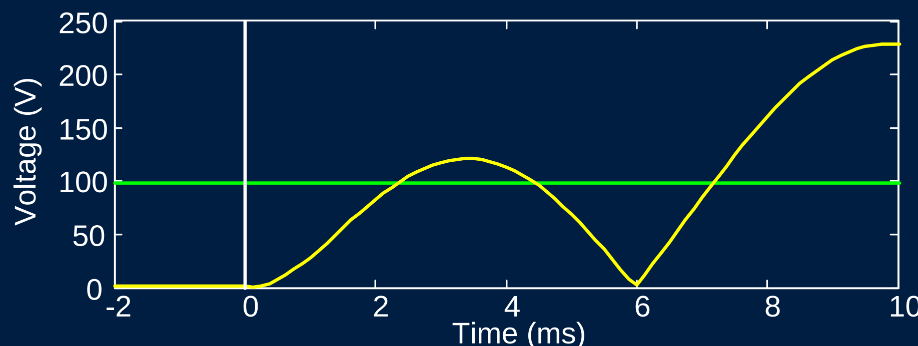
TD21 and TD32 Performance on Series-Compensated Line

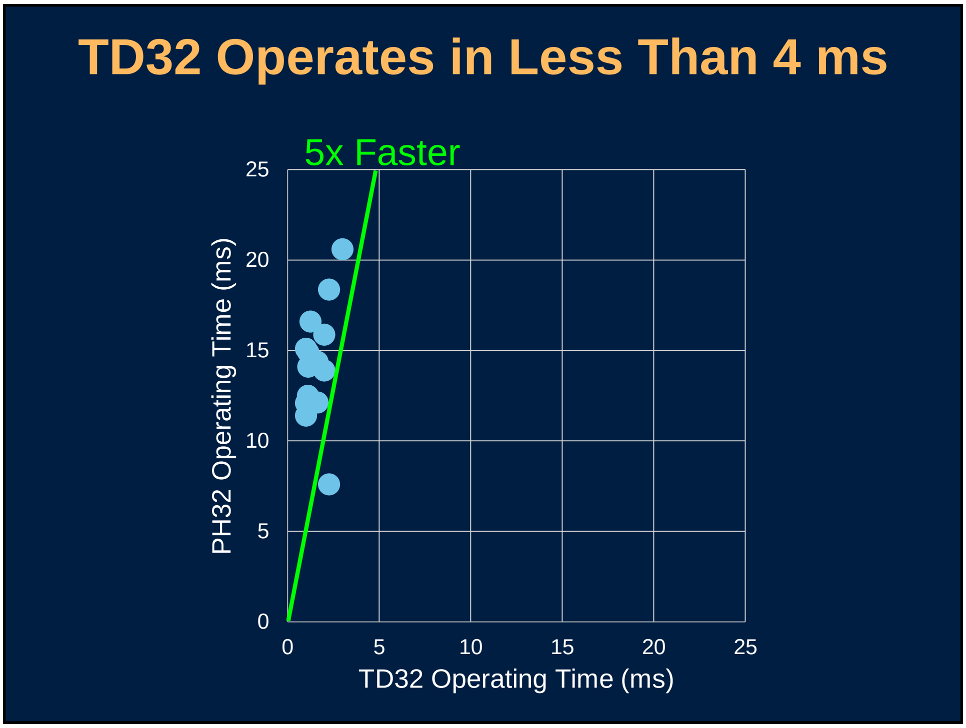


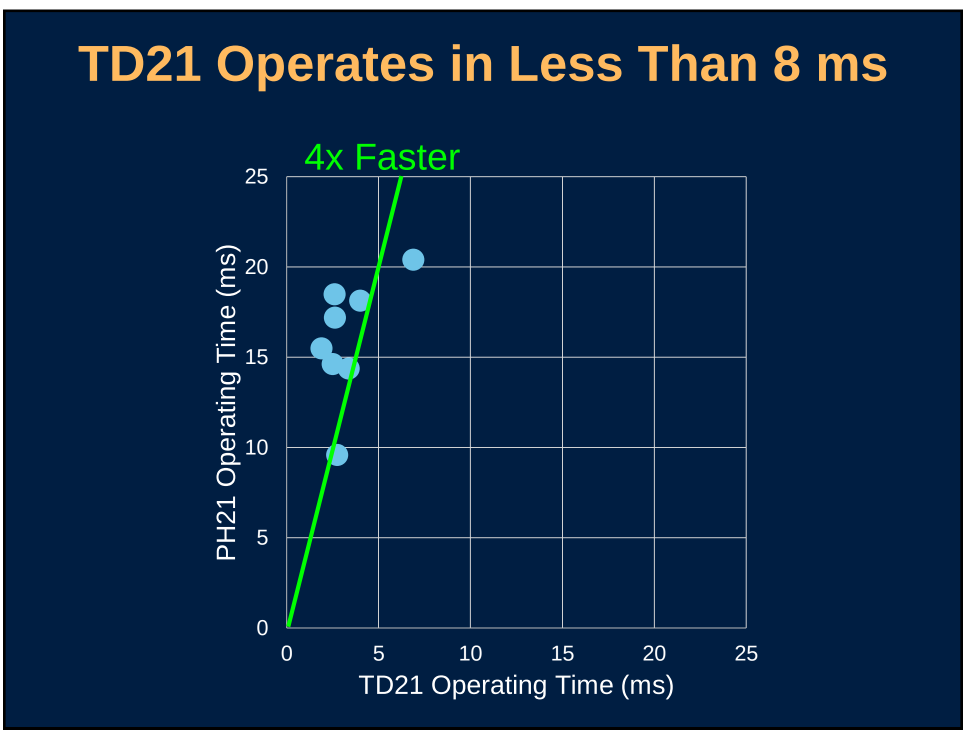
TD32 Operates in 1 ms With Excellent Security and Dependability Margins



Conservative TD21 Restraint for Series-Compensated Lines



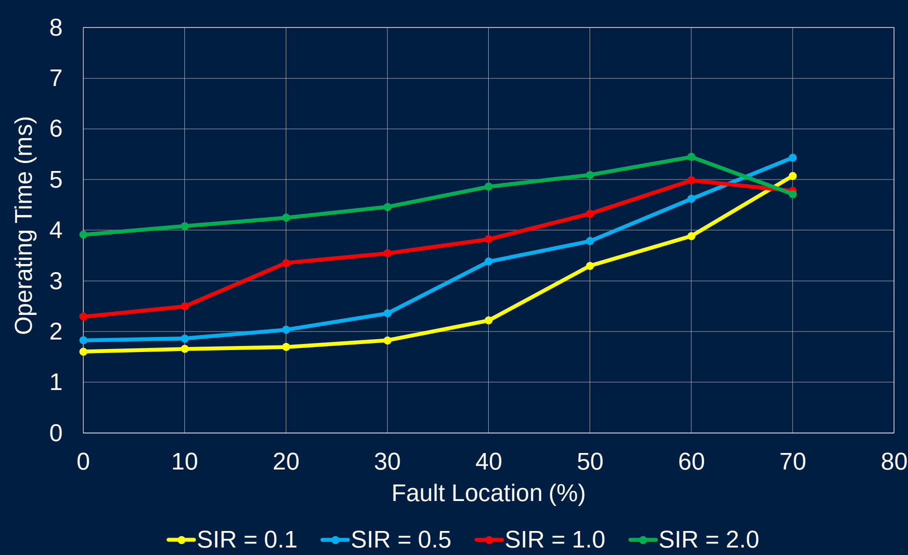

TD32 Operates in Less Than 4 ms
5x Faster
PH32 Operating Time (ms)
TD32 Operating Time (ms)
0
5
10
15
20
25

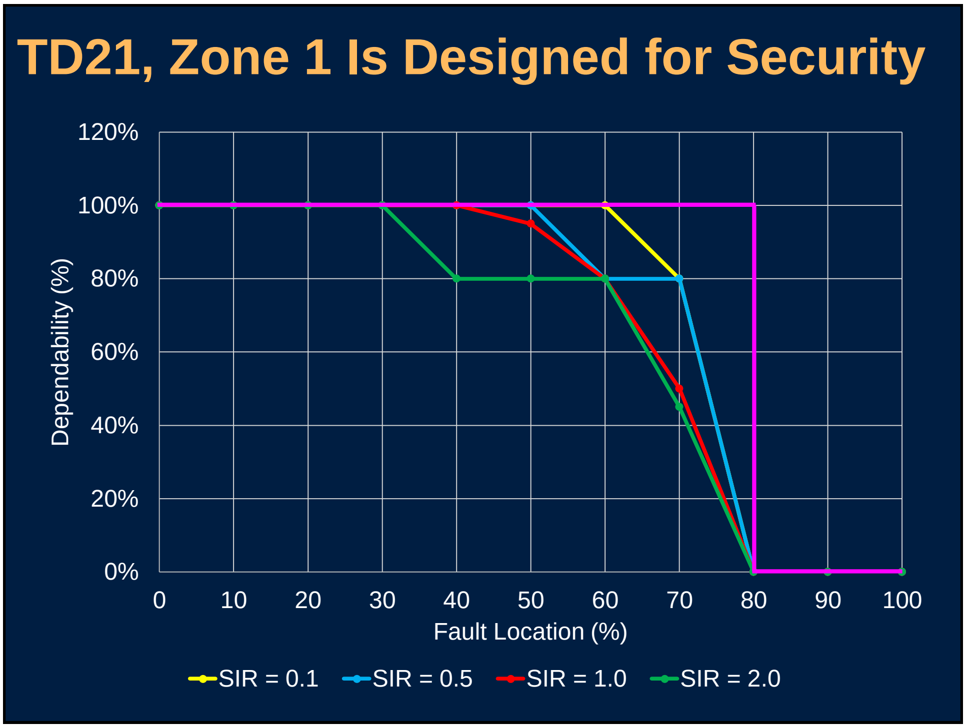

TD21 Operates in Less Than 8 ms
4x Faster
PH21 Operating Time (ms)
TD21 Operating Time (ms)
0
5
10
15
20
25

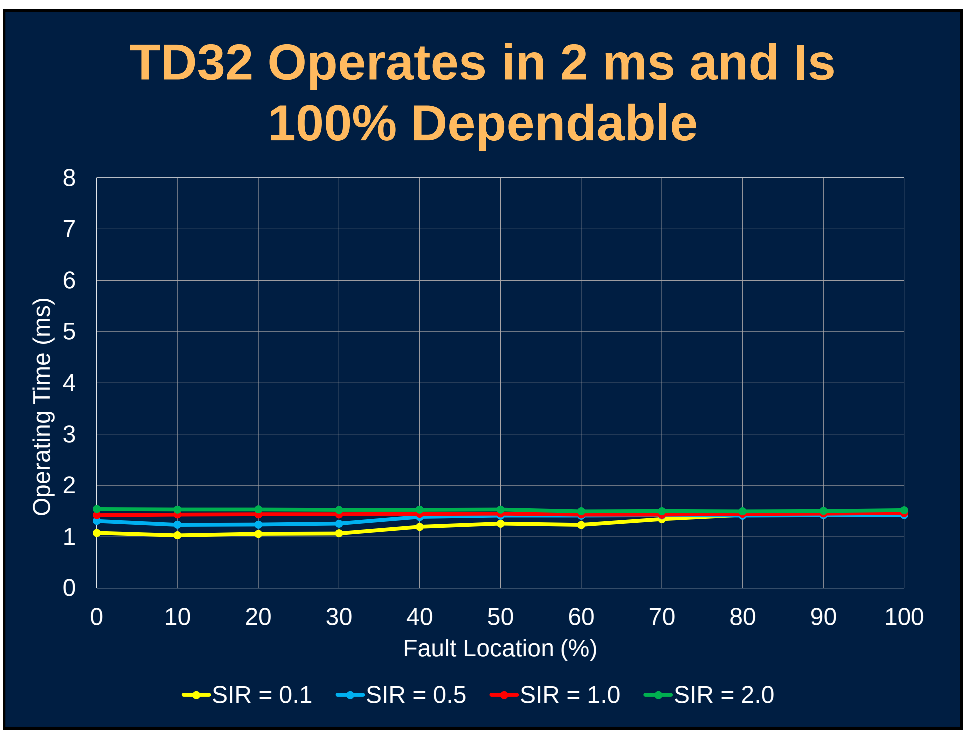
Testing With Controlled Test Parameters Using EMTP

- Fault type and location
- Point on wave
- Fault resistance
- SIR
- Line length

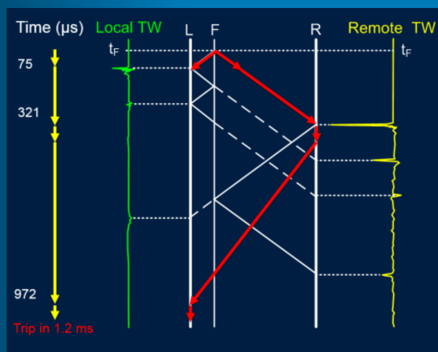
TD21, Zone 1 Operates in 3–5 ms for Midline Faults

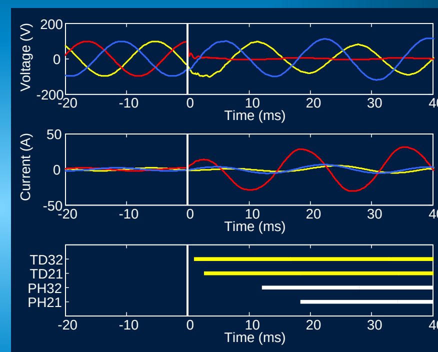



TD21, Zone 1 Is Designed for Security
120%
100%
80%
60%
40%
20%
0%
Dependability (%)
0
10
20
30
40
50
60
70
80
90
100
Fault Location (%)
SIR = 0.1
SIR = 0.5
SIR = 1.0
SIR = 2.0


TD32 Operates in 2 ms and Is 100% Dependable
8
7
6
5
4
3
2
1
0
Operating Time (ms)
0
10
20
30
40
50
60
70
80
90
100
Fault Location (%)
SIR = 0.1
SIR = 0.5
SIR = 1.0
SIR = 2.0

Time-Domain Line Protection Principles Are Fast and Secure





Work with traditional CTs and CCVTs