Line Protection: From Phasors to Traveling Waves

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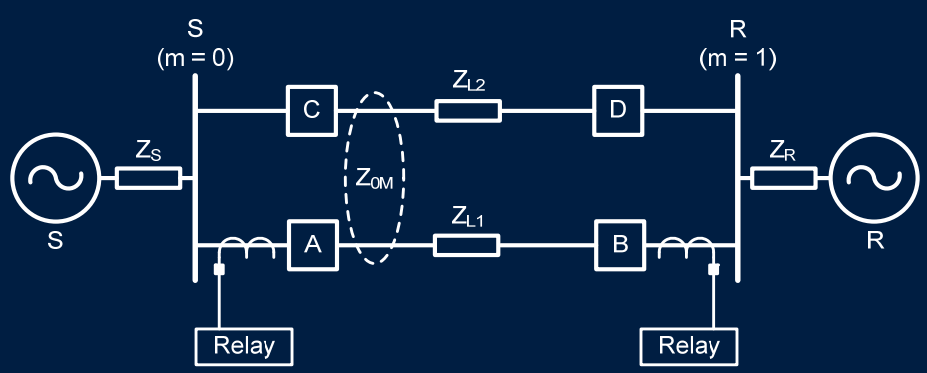
Example 100 Mile Transmission Line



$Z_{1S} = 2\ \Omega\ \angle 88°$
$Z_{0S} = 2\ \Omega\ \angle 88°$

$Z_{1L1} = Z_{1L2} = 8\ \Omega\ \angle 84°$
$Z_{0L1} = Z_{0L2} = 24\ \Omega\ \angle 80°$
$Z_{0M} = 16\ \Omega\ \angle 78°$

$Z_{1R} = 2\ \Omega\ \angle 88°$
$Z_{0R} = 2\ \Omega\ \angle 88°$

Focus for Today

- Benefits of faster line protection
- Limitations of present-day phasor-based protection
- Principles of time-domain protection
- New Time-Domain Line Protection Relay

Already Pretty Fast – Why Faster?

- Higher power transfers (investment dollars saved)
- Reduced equipment wear (generators and transformers)
- Improved safety
- Reduced property damage
- Improved power quality

How Much Faster?

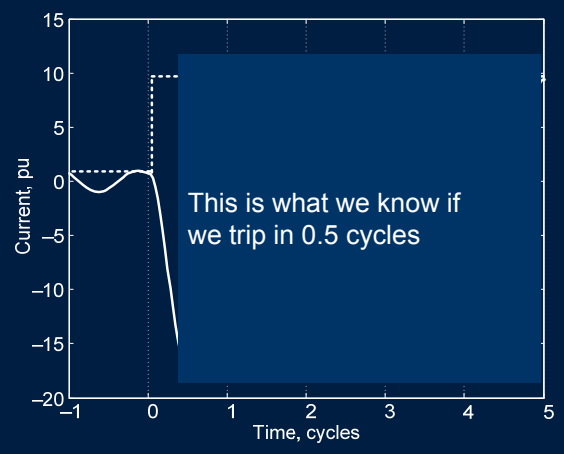
- Present-day relays
  - Based on phasors
  - Operate in 0.5–1.5 cycles
- Present-day breakers operate in 2 cycles
- Ultra-high-speed fault clearing
  - Consistent relay operating times
  - 2 ms (TW) to 4 ms (differential equations)
  - Subcycle times from future dc breakers

Phasor-Based Protection Makes Sense

- Power systems were traditionally designed and modeled for steady-state operation at system frequency
- “Forcing functions” are at system frequency
- Instrument transformers are rated at system frequency
- CCVTs are band-pass devices

Speed of Present-Day Relays

- Phasors represent steady state
- Determining steady state takes time



Speed of Present-Day Relays

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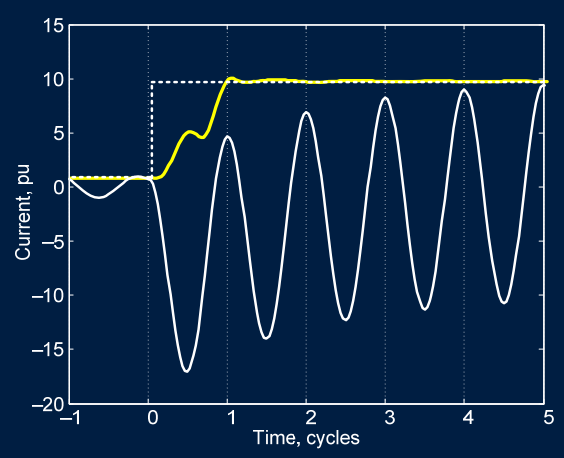
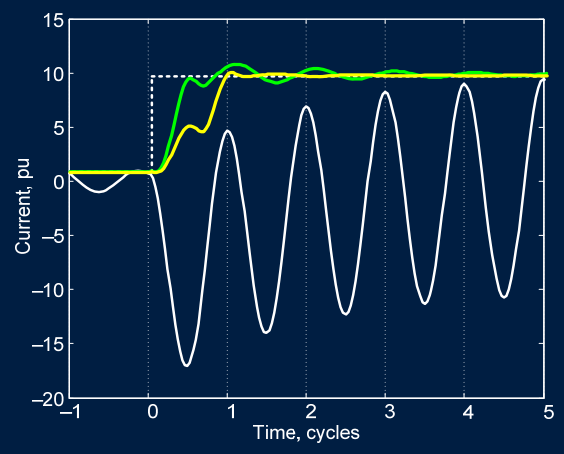
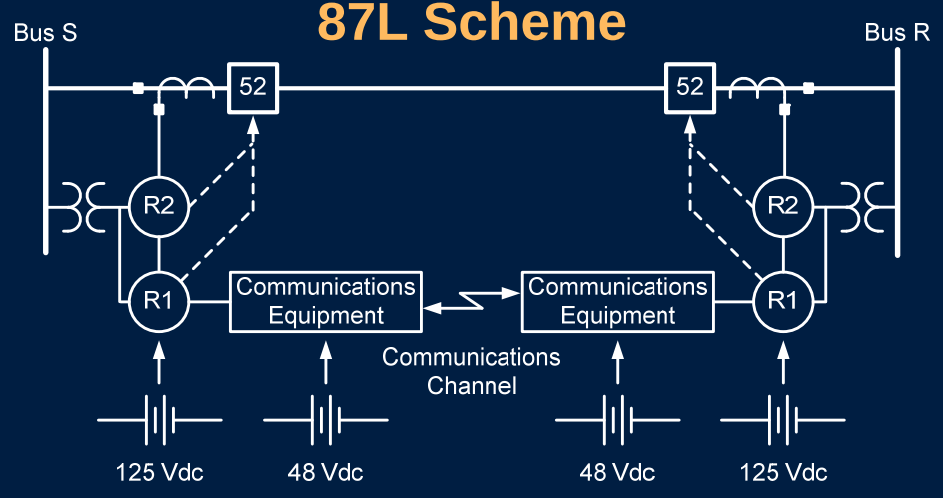


Speed of Present-Day Relays

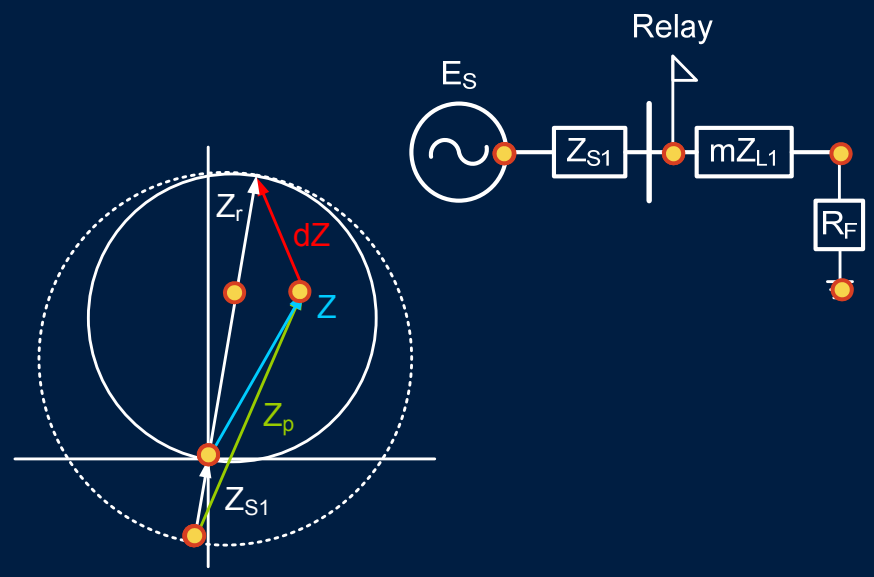
- Phasors represent steady state
- Determining steady state takes time
- Shorter windows are faster but less accurate



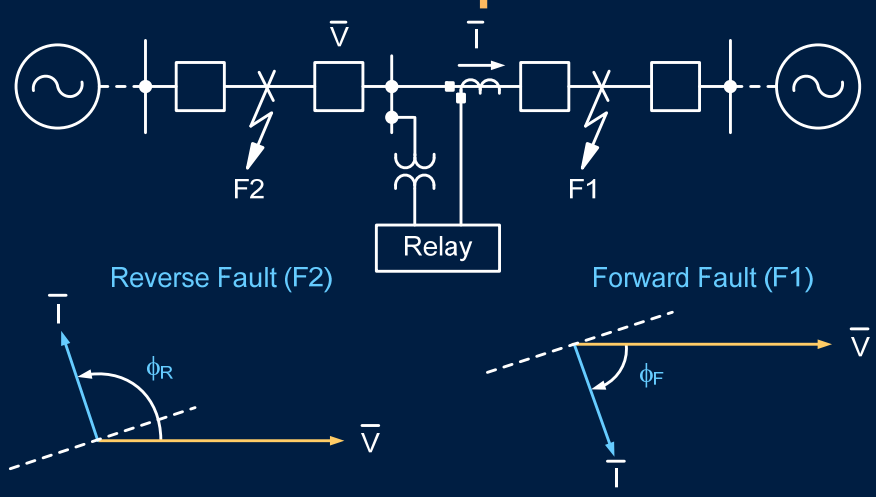
Line Protection Using POTT Scheme With 21/67 Elements or 87L Scheme



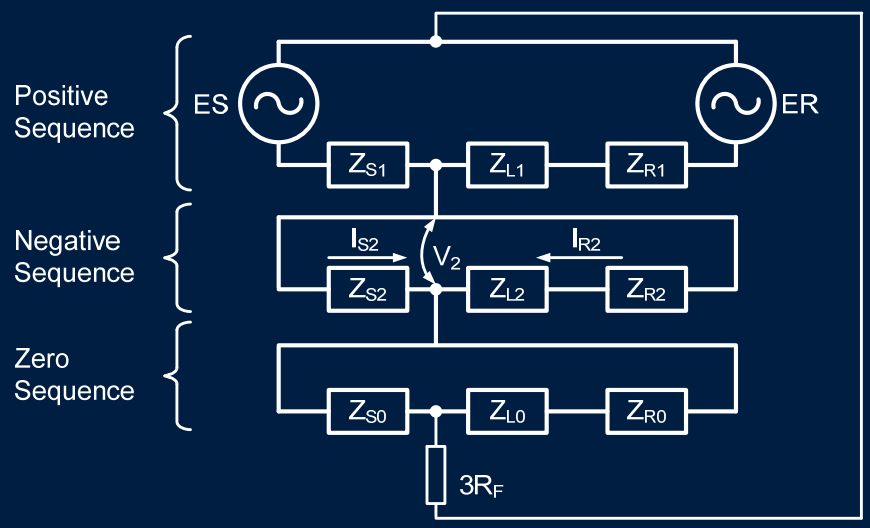
Dynamic Expansion



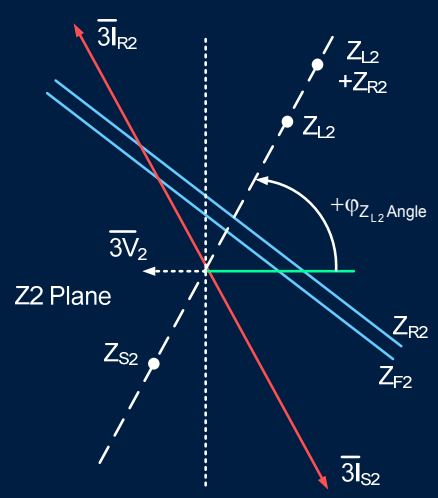
Basic Directional Element (32) Principle



Symmetrical Components for Single-Line-to-Ground Fault

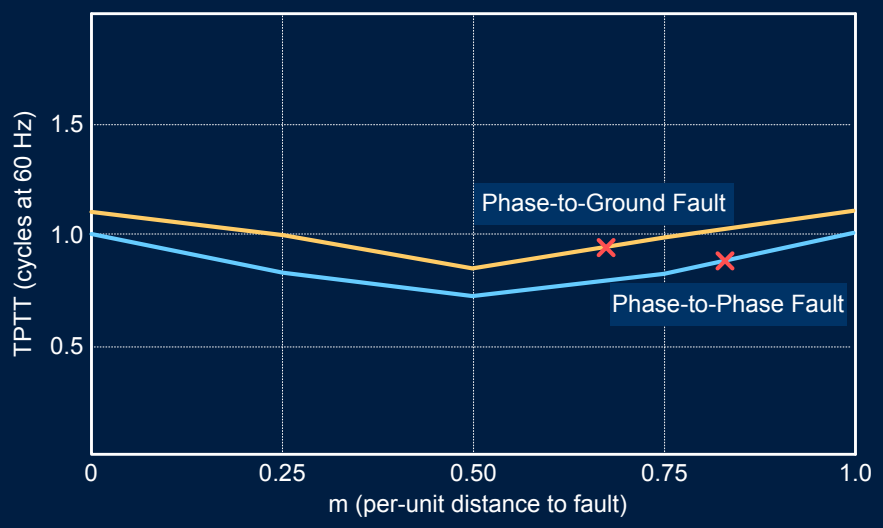


Negative-Sequence Impedance Used to Determine Fault Direction

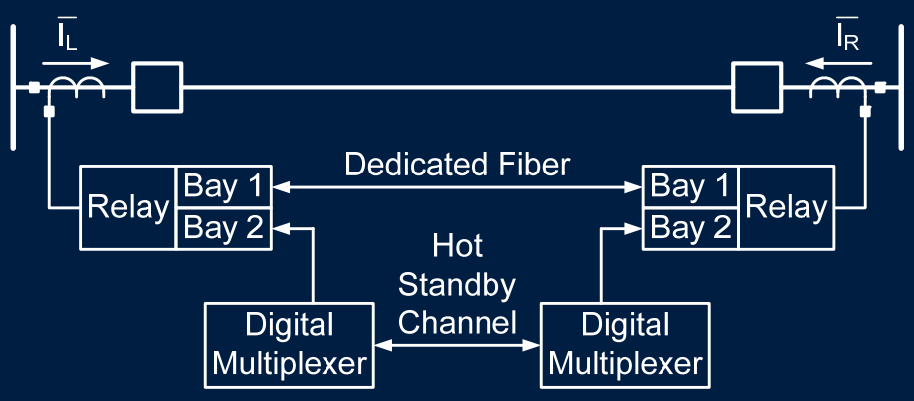


$$Z_{2measured} = \frac{\mathrm{Re}\left[V_2 \cdot \left(1\angle Z1ANG \cdot I_2\right)^*\right]}{\left|I_2\right|^2}$$

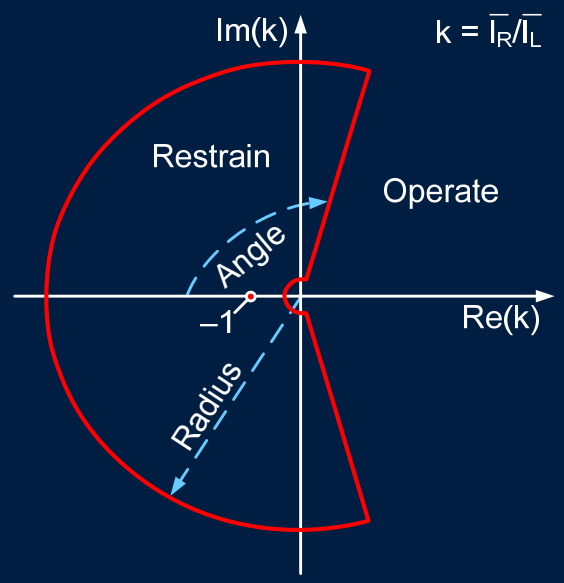
Protection Scheme Trip Time for Comm. Scheme Using 21/67



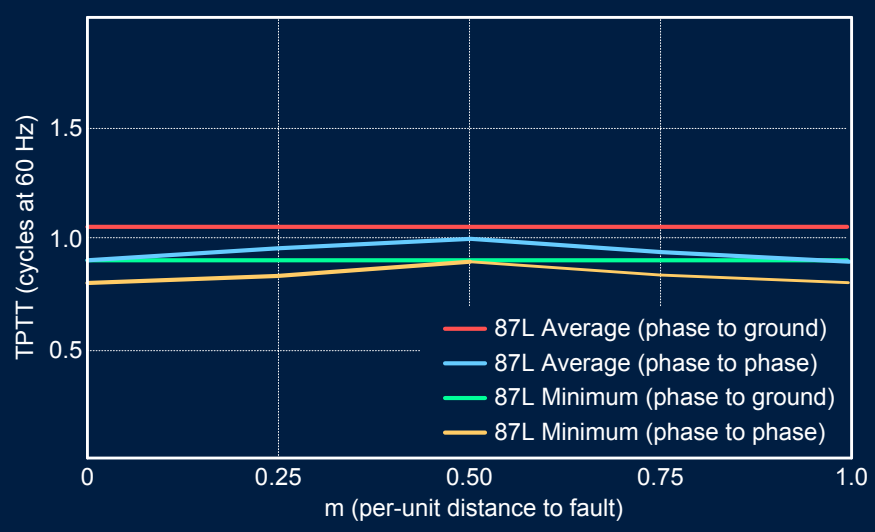
Two-Terminal Digital Line Current Differential (87L) Application



Alpha Plane Used for 87L Scheme

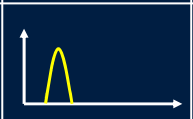
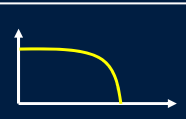


Protection Scheme Trip Time for 87L



Phasor and Time-Domain Principles

Similarities and Differences

Algorithm	Phasor-Based	Differential Equations	Traveling Waves
Spectrum	50 / 60 Hz	1 kHz	100 kHz
Filtering			
Sampling	16–32 s/c	10 kHz	1 MHz
Line theory	$V_F = V - ZI$	$v_F = v - \left(Ri + L\frac{di}{dt}\right)$	$i_{S(t)} \approx -i_{R(t-\tau)}$
Operating time	~ 1 cycle	A few milliseconds	1 ms
Requirements for CTs and PTs	Low	Moderate	High

Time Domain: Speed With Security

TD21

- Underreaching
- Communications-independent

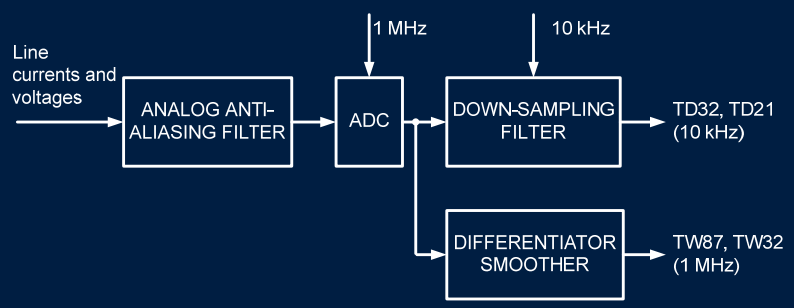
Comm-Based Scheme Using 32 (directional)

- TD32 and TW32 for direction
- Fast communications as a teleprotection channel

TW87

- Current-only
- Direct fiber as a channel (100 Mbps)
- GPS-independent

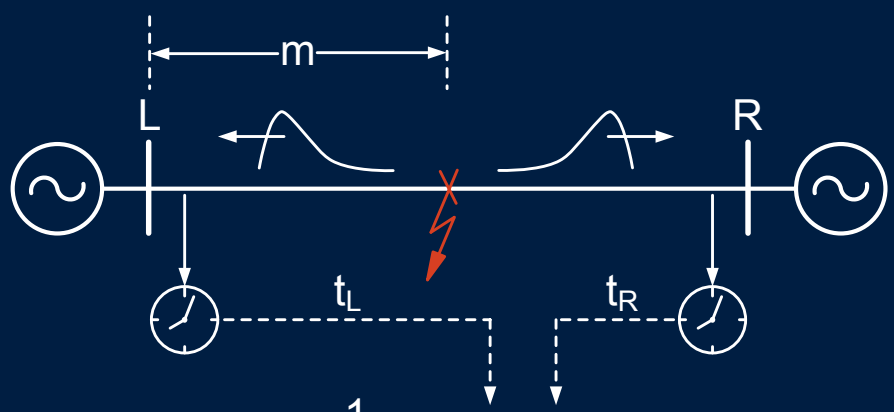
Time Domain Uses High-Speed Data



- Full-scale 1 MHz sampling
- TWs processed every microsecond
- Δ-quantities processed every 0.1 ms
- Protection logic runs every 0.1 ms

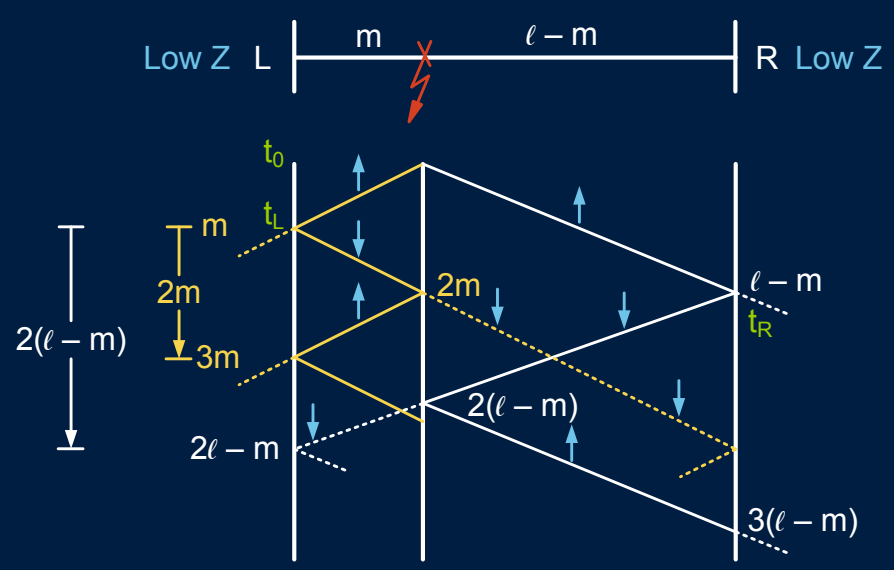
Traveling-Wave Principles

Lightning and Faults Launch Traveling Waves



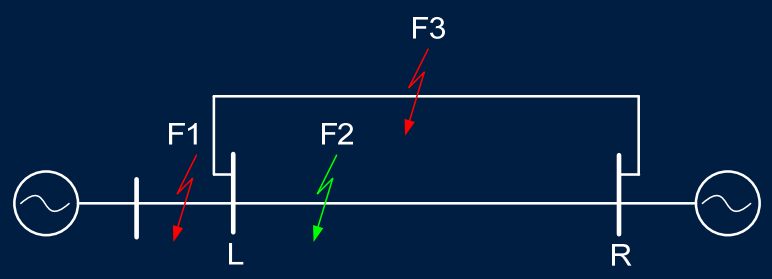
$$m = \frac{1}{2}\left[\ell + \left(t_L - t_R\right)v\right]$$

Polarity of Waves



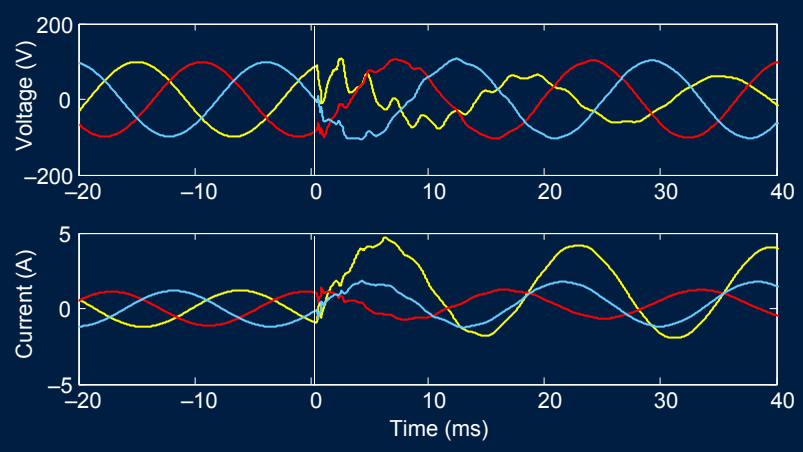
Deriving TW87 Operating Principles

Three Scenarios to Consider



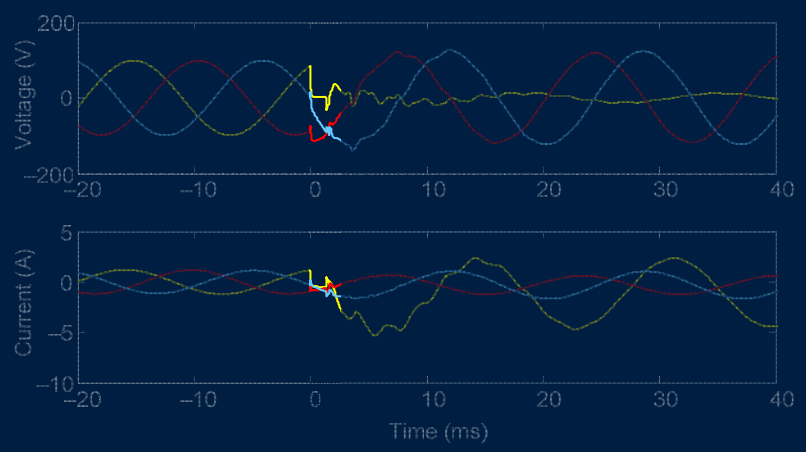
External Fault Behind Local Relay

Remote Terminal



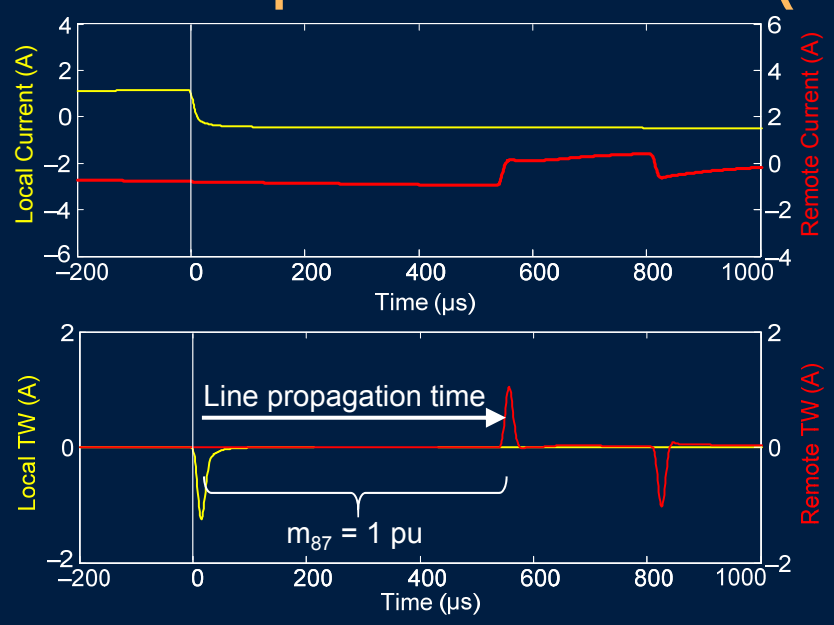
External Fault Behind Local Relay

Local Terminal



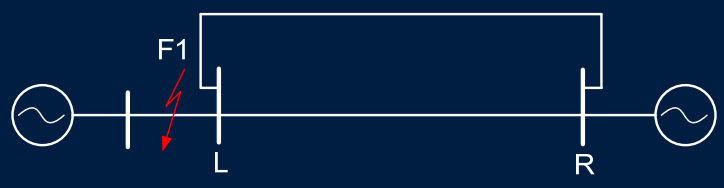
TW fault information is contained in the first 1–2 milliseconds of the fault

TW87 Principle – External Fault (F1)

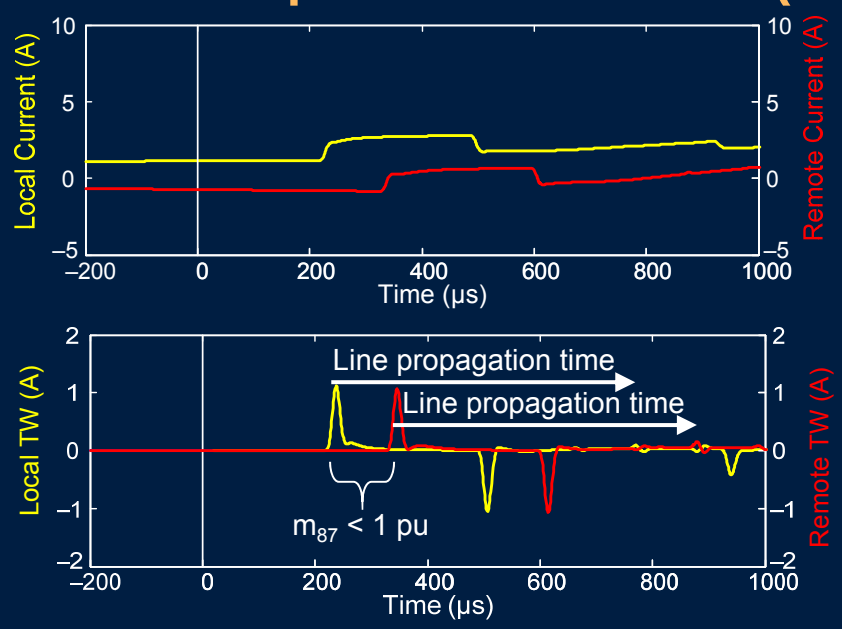


TW87 Is Secure for External Fault (F1)

	Φ	I_L (A)	I_R (A)	I_{DIF} (A)	I_{RST} (A)	m_{87} (pu)
F1	A	1.41	0.75	0.66	2.16	1.0
	B	0.40	0.40	0.01	0.80	1.0
	C	0.38	0.38	0.00	0.76	1.0

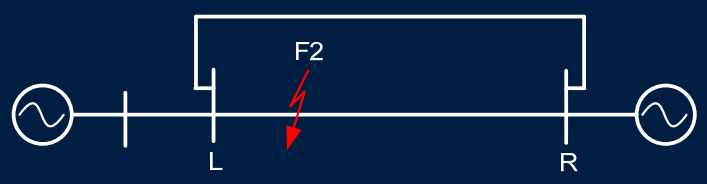


TW87 Principle – Internal Fault (F2)

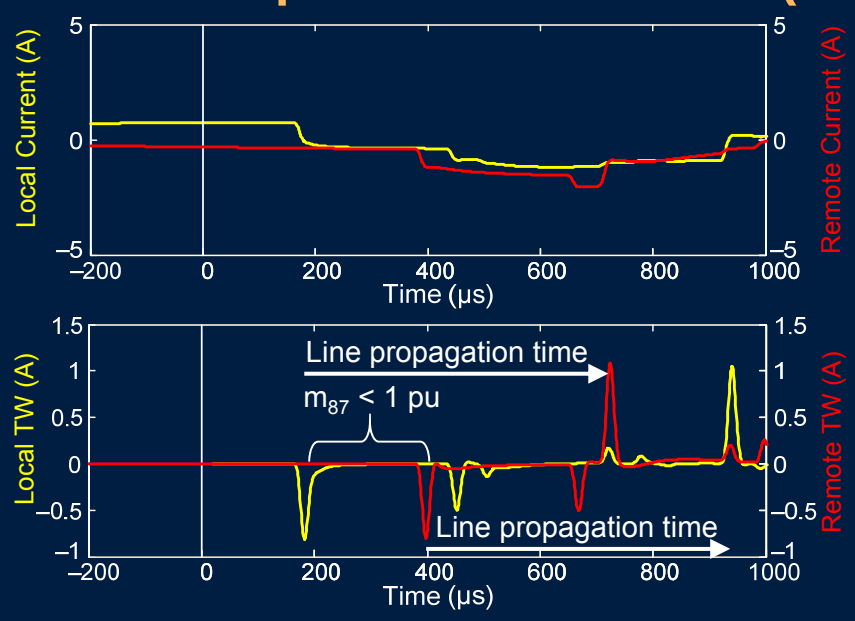


TW87 Operates in 1.5 ms

	Φ	I_L (A)	I_R (A)	I_{DIF} (A)	I_{RST} (A)	m_{87} (pu)
F2	A	1.22	0.76	1.98	1.22	0.4
	B	0.51	0.39	0.90	0.51	0.4
	C	0.54	0.38	0.92	0.54	0.4

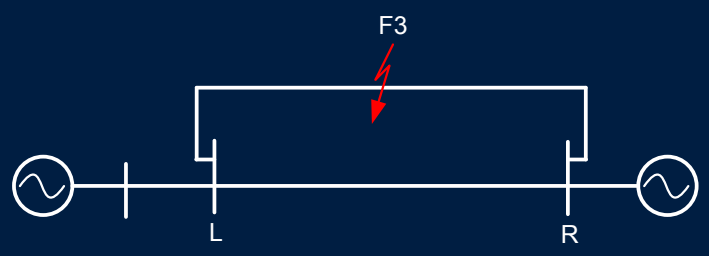


TW87 Principle – External Fault (F3)

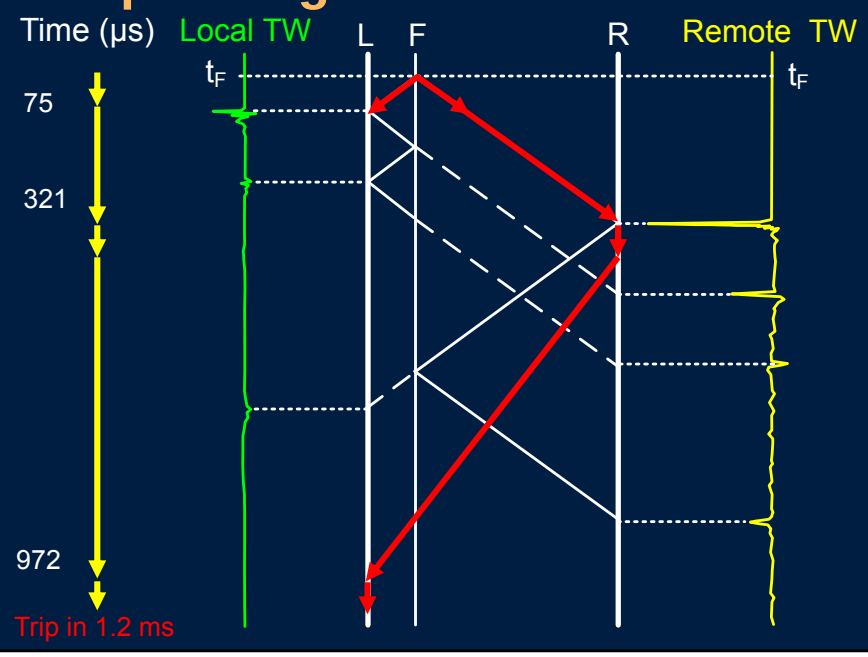


TW87 Is Secure for External Fault (F3)

	Φ	I_L (A)	I_R (A)	I_{DIF} (A)	I_{RST} (A)	m_{87} (pu)
F3	A	0.92	0.53	1.45	1.70	0.3
	B	0.31	0.27	0.58	0.74	0.3
	C	0.30	0.28	0.57	0.72	0.3

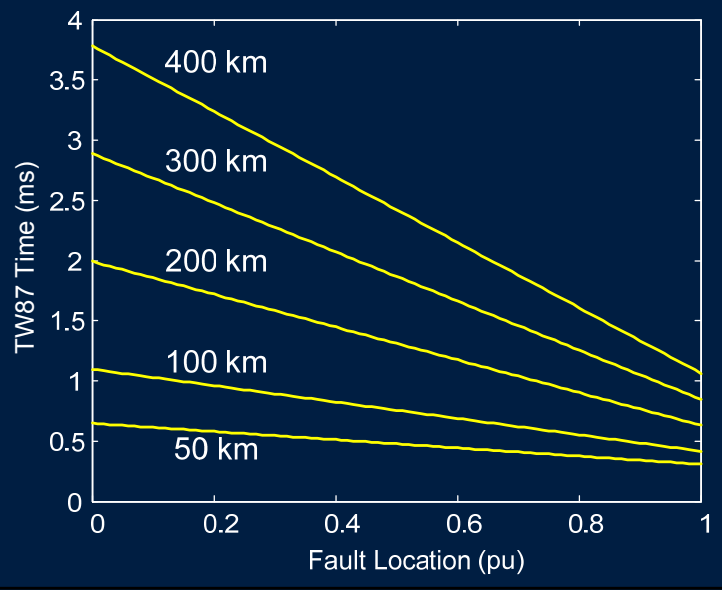


TW87 Operating Time on a 117 km Line



Processing Is Fast

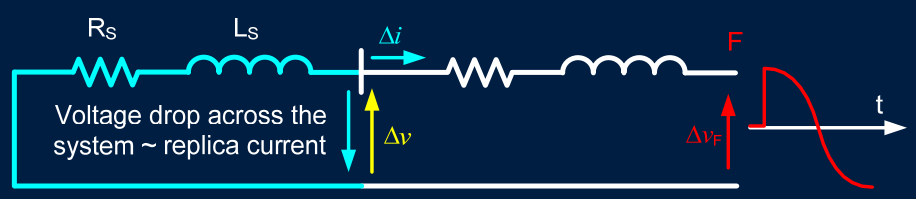
TW87 Speed Depends on Line Length



Incremental Quantity Directional Element (TD32)

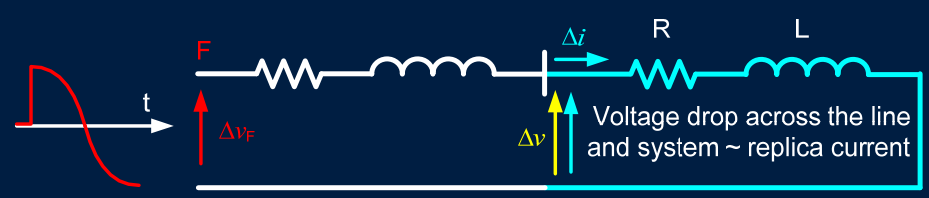
Forward Fault

Δv Is Opposite Polarity to Replica Current

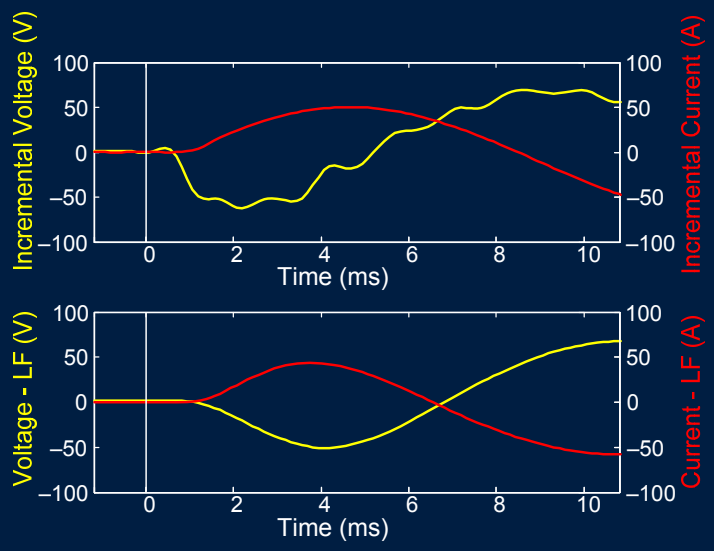


Reverse Fault

Δv Is Same Polarity as Replica Current



Δv and Δi Are of Opposite Polarities for Forward Faults



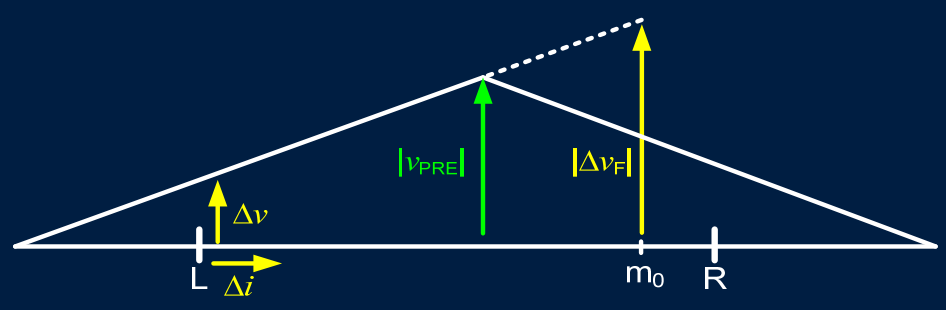
Incremental Quantity Distance Element (TD21)

Fault at the Reach

$|\Delta v_F|$ Is Equal to $|v_{PRE}|$

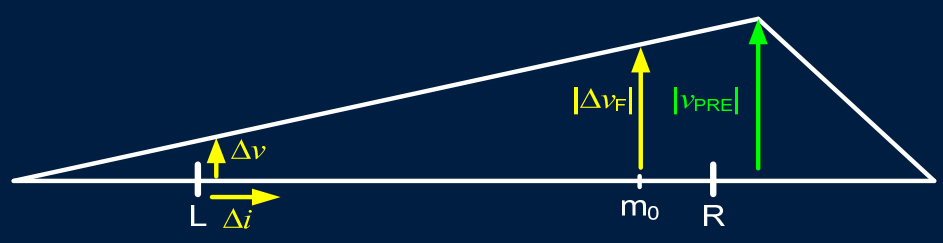
Fault Within the Reach

$|\Delta v_F|$ Is Greater Than $|v_{PRE}|$



Fault Beyond the Reach

$|\Delta v_F|$ Is Lower Than $|v_{PRE}|$

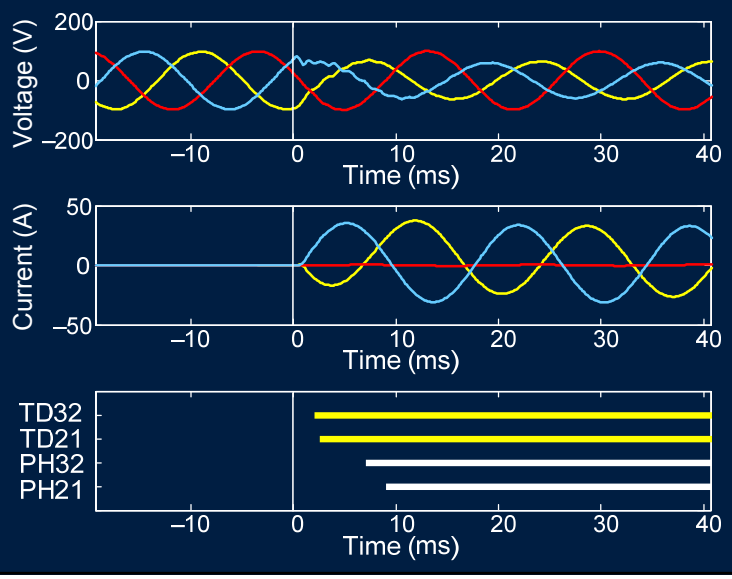


Competitive Testing

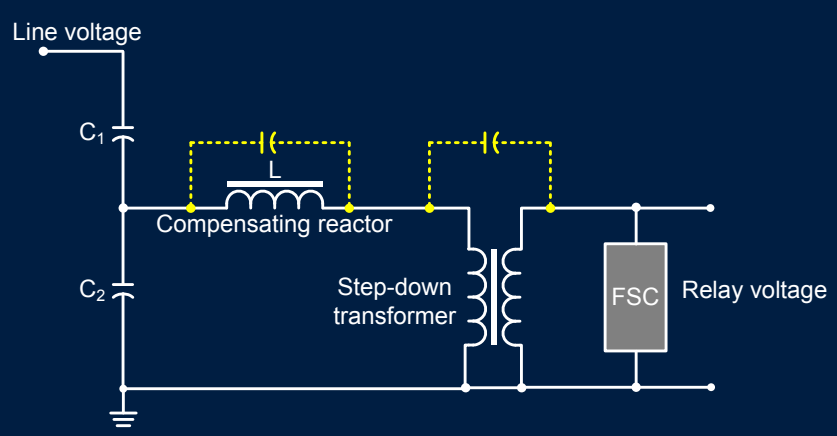
Time-Domain vs. Phasors

TD21 amd TD32 Operate Faster

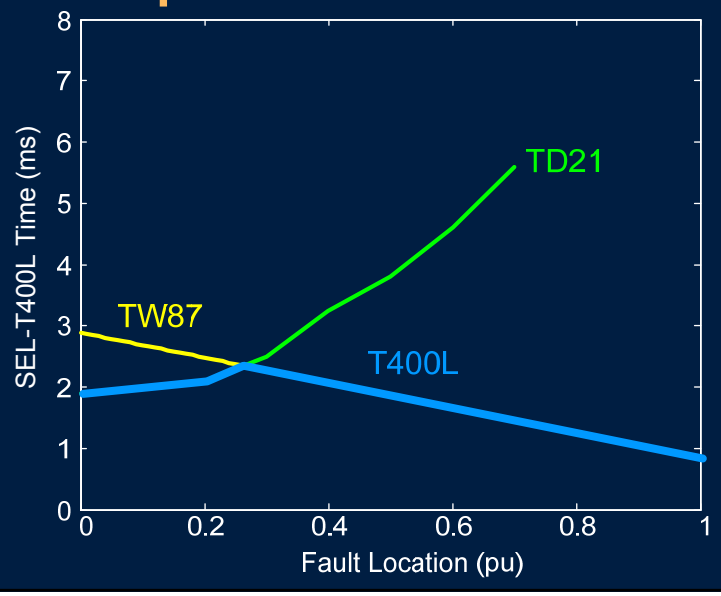
230 kV, 159 km, Fault at 18%



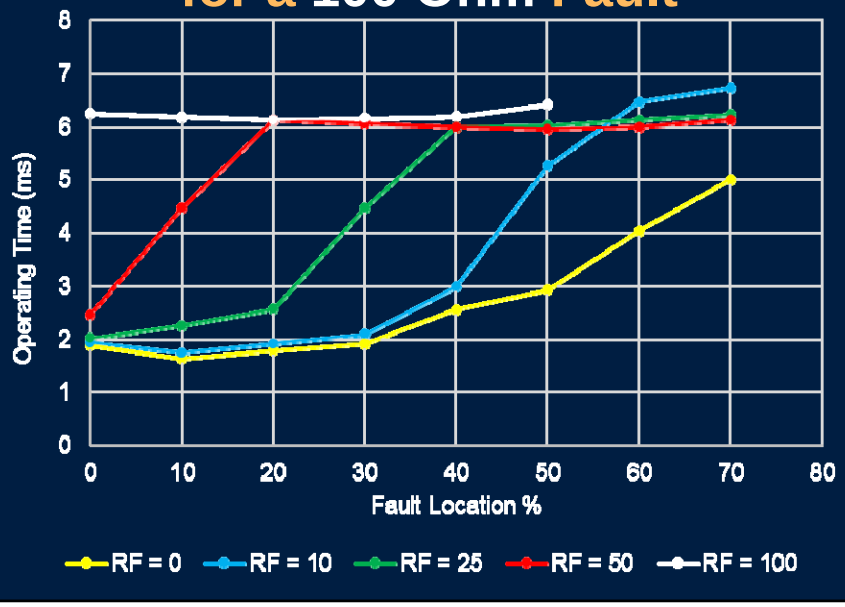
Extracting Polarity of the First Wave



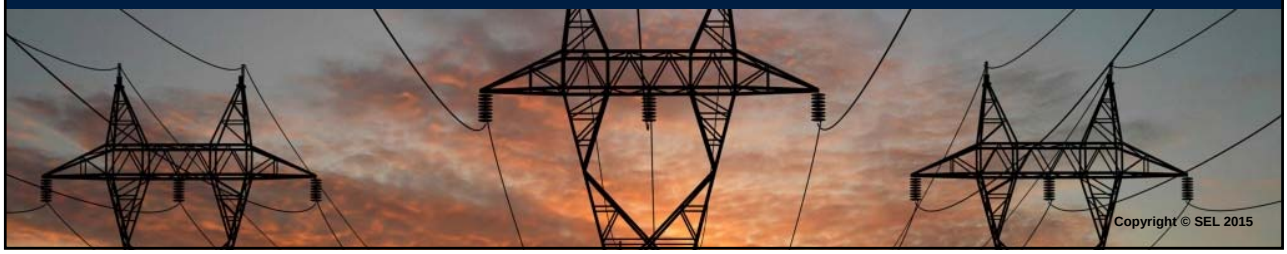
TD21 and TW87 Elements Complement One Another



TD21 Operates in Less Than 8 ms for a 100 Ohm Fault



Questions?



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