# Distance Protection: Why Have We Started With a Circle, Does It Matter, and What Else Is Out There?

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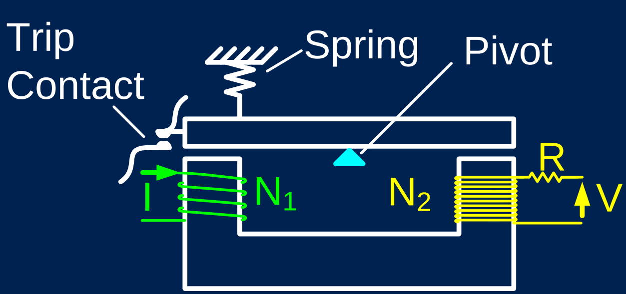
## What Is a Distance Protection Element?

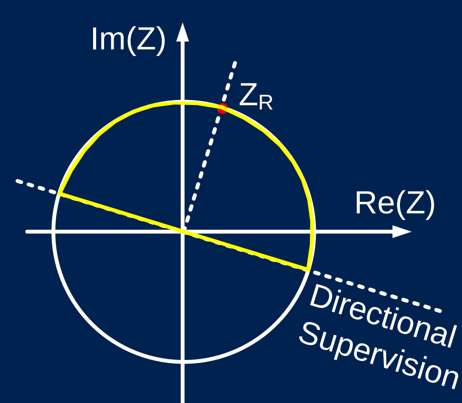

- Uses local voltage and current only
- Responds to faults within a predetermined reach
- Operates independently of fault current level, pre-fault load, fault type, or fault resistance

# Distance Element Applications

- Line protection without a pilot channel
  - Underreaching element (Zone 1)
  - Stepped distance (time coordinated)
- Directional comparison schemes
- Applications that require impedance elements
  - Out-of-step, power swing, loss of excitation

# Why Did We Start With a Circle?



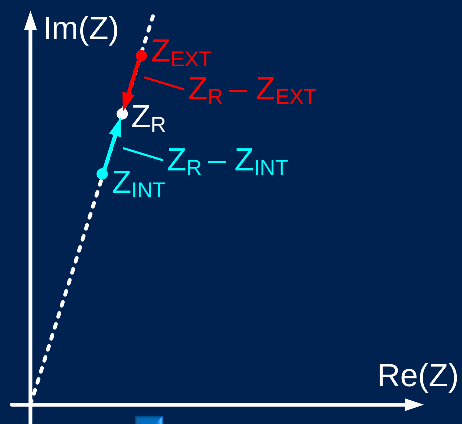



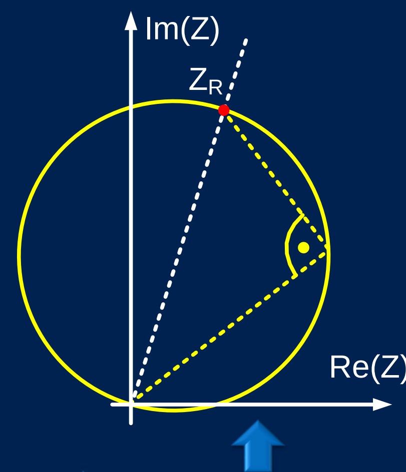

$$N_1 \cdot |I| > \frac{|V|}{R} \cdot N_2 \Rightarrow \frac{|V|}{|I|} < |Z_R|$$

$$|Z_R| = R \cdot \frac{N_1}{N_2}$$

# Innovation and Progress

## Directional Mho Characteristic




$Z_R - Z_{APP} \quad vs \quad Z_R \;\Rightarrow\; Z_R - \frac{V}{I} \quad vs \quad Z_R \;\Rightarrow\; I \cdot Z_R - V \quad vs \quad V$

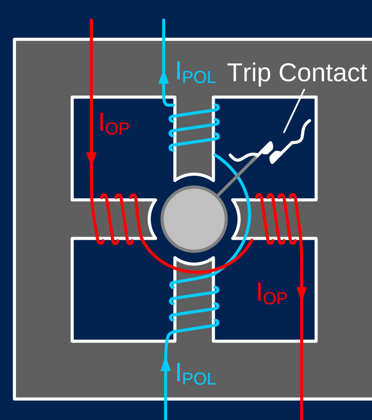
# Implementation With a Cylinder-Unit Relay

$\angle(S_{OP}, S_{POL}) < \pm 90°$

$S_{POL} = V$

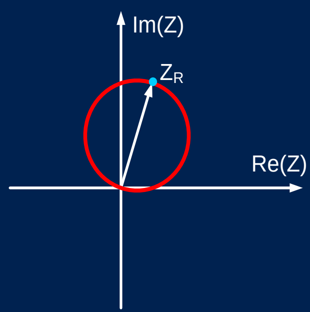
$S_{OP} = I \cdot Z_R - V$

Replica Current



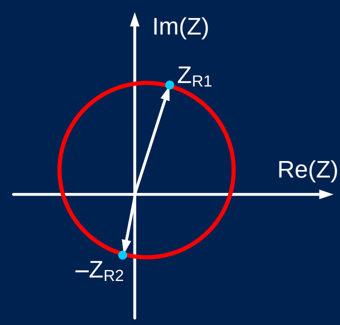
# Shaping Distance Characteristics Using Phase Comparators

### Directional Mho



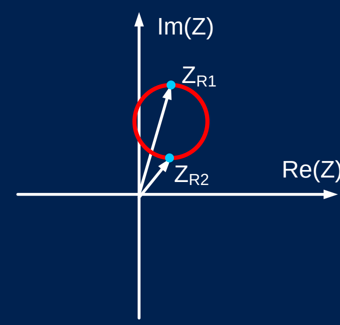

$S_{OP} = I \cdot Z_R - V$
$S_{POL} = V$

### Reverse Offset Mho




$S_{OP} = I \cdot Z_{R1} - V$
$S_{POL} = -(I \cdot Z_{R2} + V)$

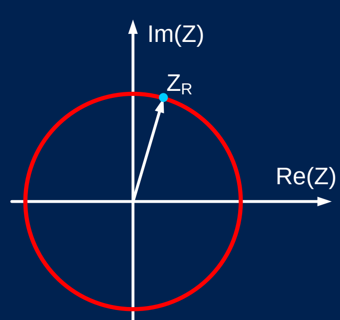
### Forward Offset Mho




$S_{OP} = I \cdot Z_{R1} - V$
$S_{POL} = I \cdot Z_{R2} - V$

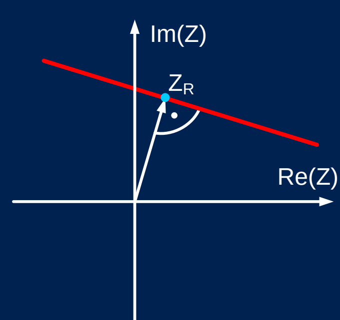
# Shaping Distance Characteristics Using Phase Comparators

### Nondirectional Mho



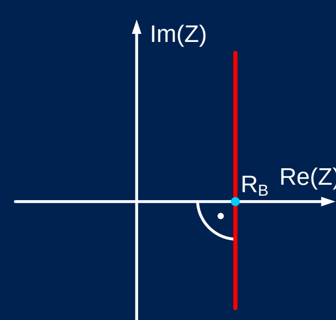

$S_{OP} = I \cdot Z_R - V$
$S_{POL} = -(I \cdot Z_R + V)$

### Reactance



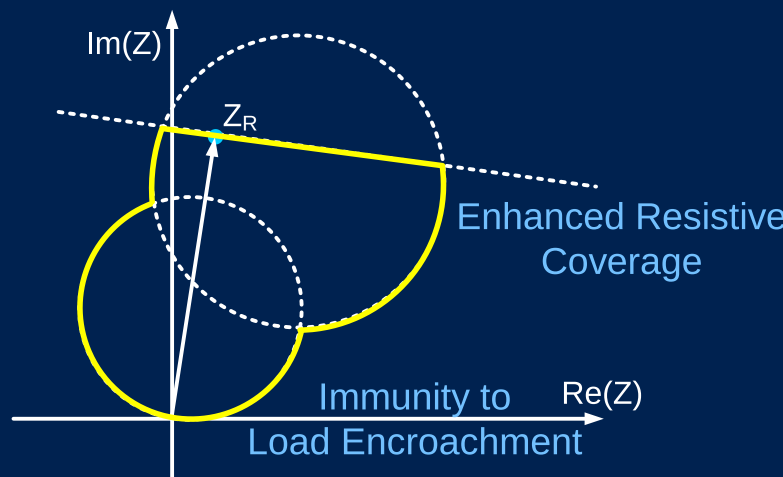

$S_{OP} = I \cdot Z_R - V$
$S_{POL} = I \cdot Z_R$

### Resistive Blinder




$S_{OP} = I \cdot R_B - V$
$S_{POL} = I \cdot R_B$

## Shaping Complex Characteristics




## Need for Speed, 1969

A.R. van C. Warrington
*Protective Relays Their Theory and Practice: Vol. 2*:

"Faults on E.H.V. links must be cleared as fast as possible to prevent instability on the H.V. system. Modern relays can trip in less than 1 cycle but half-cycle tripping time is the desirable goal, making an overall clearing time of 2½ cycles.

There is very little possibility of improvement in electromagnetic relays in these respects and this may be a reason for accelerating the acceptance of transistorized relays."

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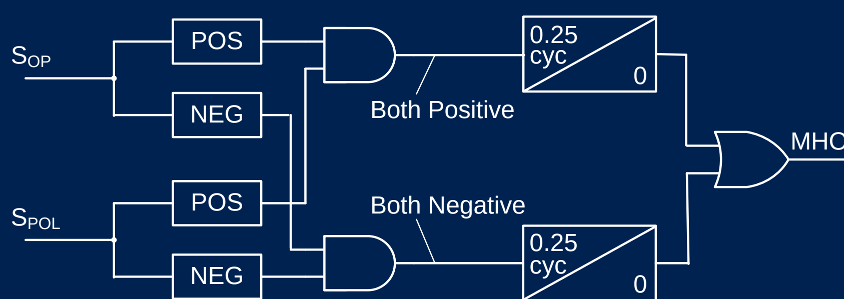
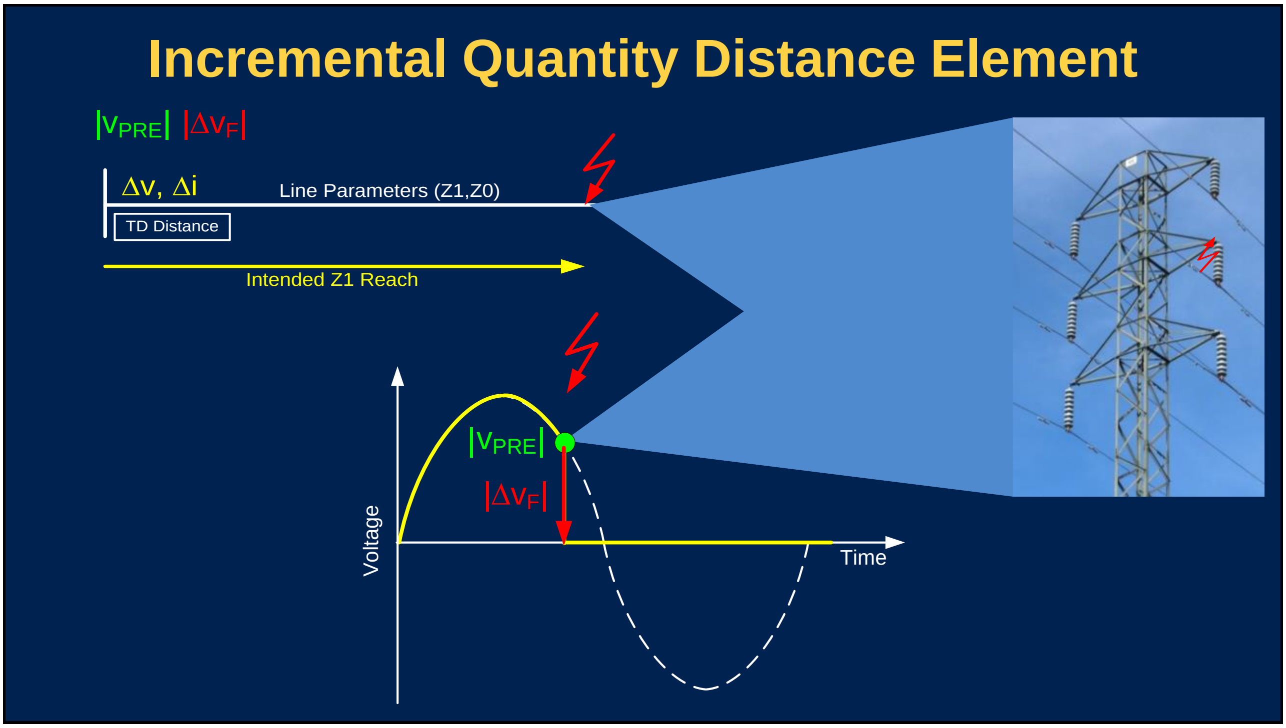
# Static Implementations

- "Analog machines" with electronics
- Speed vs security is a design choice (filtering)
- Coincidence timing as a phase comparator

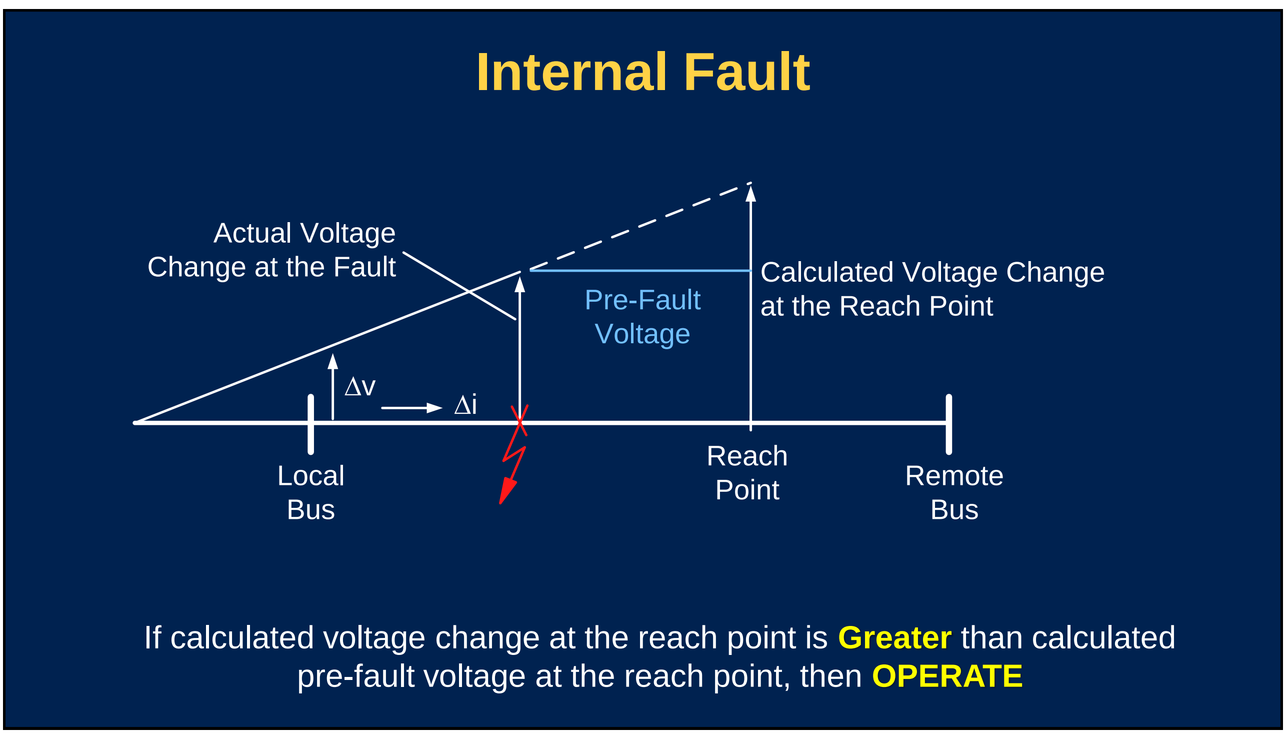



# Microprocessor-Based Implementations

- First µP-based relays sampled at low rates
- Phasors were the only practical solution
  - Cosine filter, or
  - Fourier with mimic prefiltering
- Full-cycle band-pass filtering set the speed vs security balance
- Operating characteristics through calculations on complex numbers, such as $\angle(I \cdot Z_R - V, V) < \pm 90°$

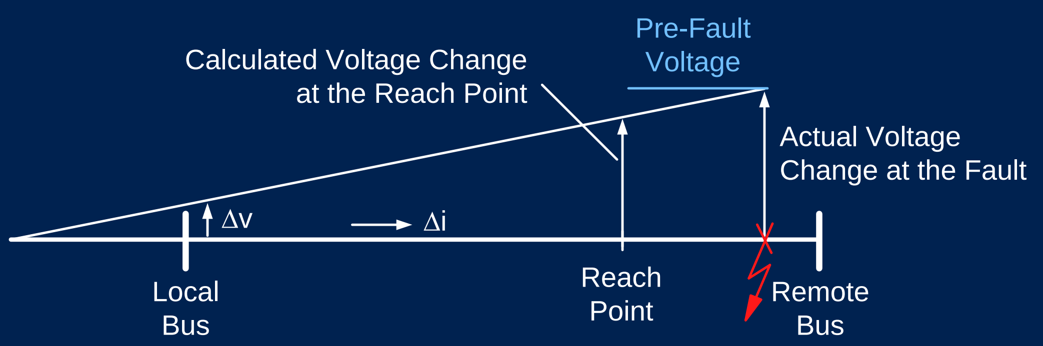


Incremental Quantity Distance Element
|VPRE| |ΔVF|
Δv, Δi
Line Parameters (Z1,Z0)
TD Distance
Intended Z1 Reach
|VPRE|
|ΔVF|
Voltage
Time

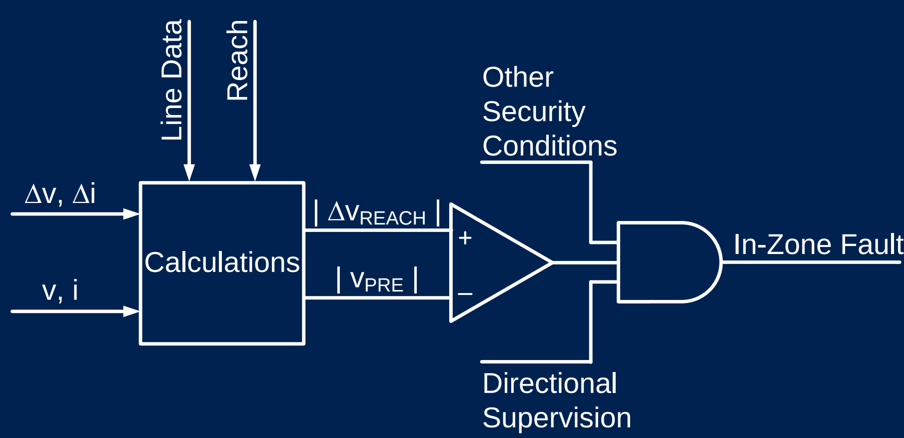
Internal Fault
Actual Voltage
Change at the Fault
Pre-Fault
Voltage
Calculated Voltage Change
at the Reach Point
Δv
Δi
Local
Bus
Reach
Point
Remote
Bus
If calculated voltage change at the reach point is Greater than calculated
pre-fault voltage at the reach point, then OPERATE

# External Fault



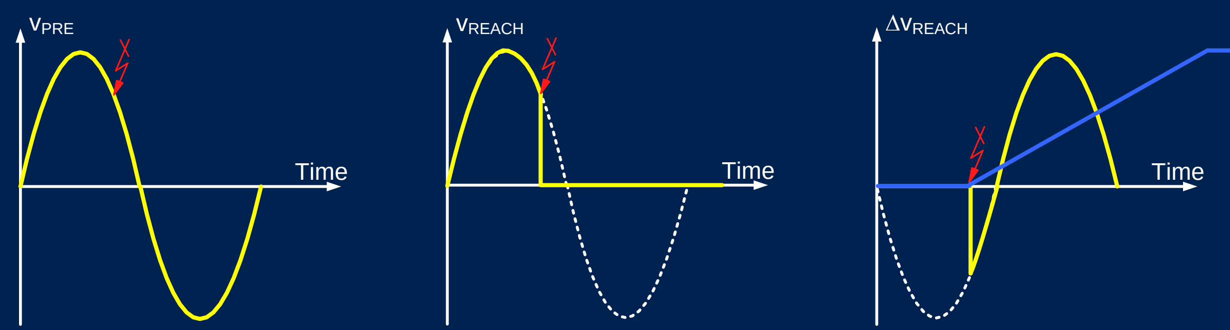

If calculated voltage change at the reach point is **Lower** than calculated pre-fault voltage at the reach point, then **RESTRAIN**

# General Implementation



# Implementation Considerations

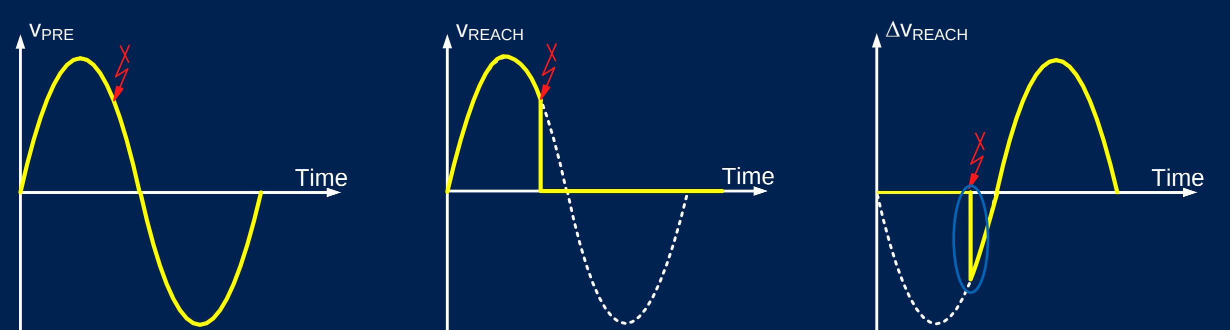
Pre-Fault Voltage | Reach Point Voltage | Change in Voltage




Calculated voltage change can be the magnitude of a phasor (hypothetical)

# Implementation Considerations

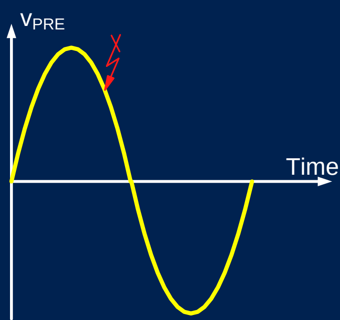
Pre-Fault Voltage | Reach Point Voltage | Change in Voltage



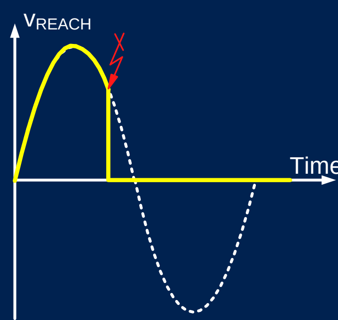

Calculated voltage change can be an edge or a step obtained with a high-pass filter (actual three-decade-old implementation)

# Implementation Considerations

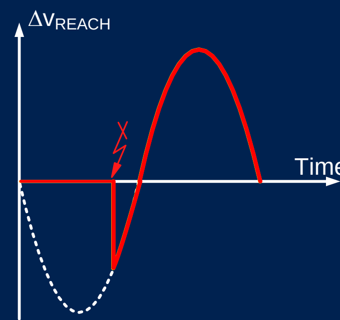
Pre-Fault Voltage




Reach Point Voltage

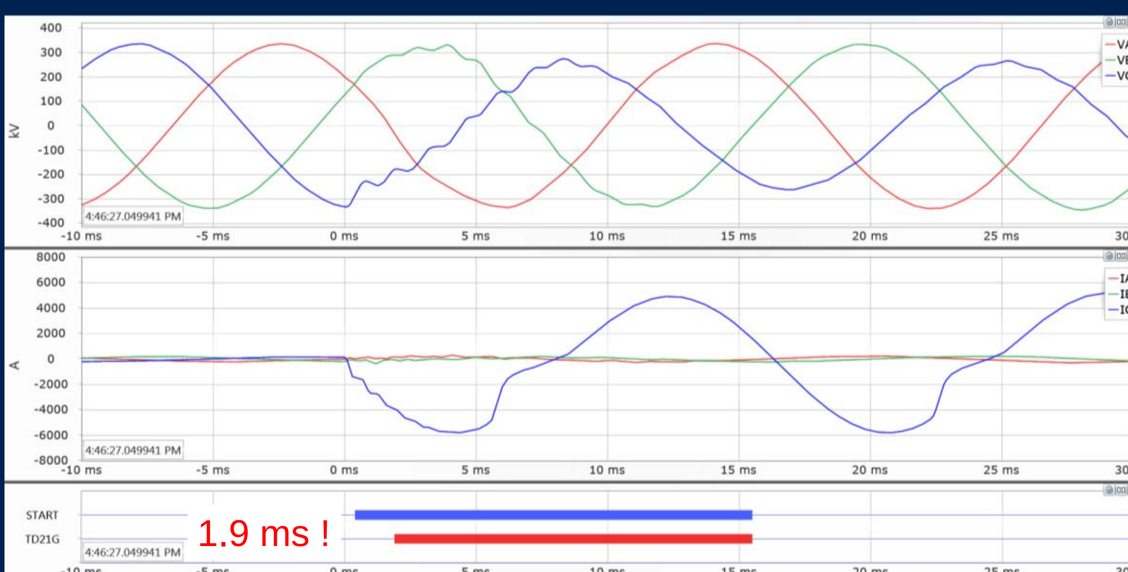



Change in Voltage

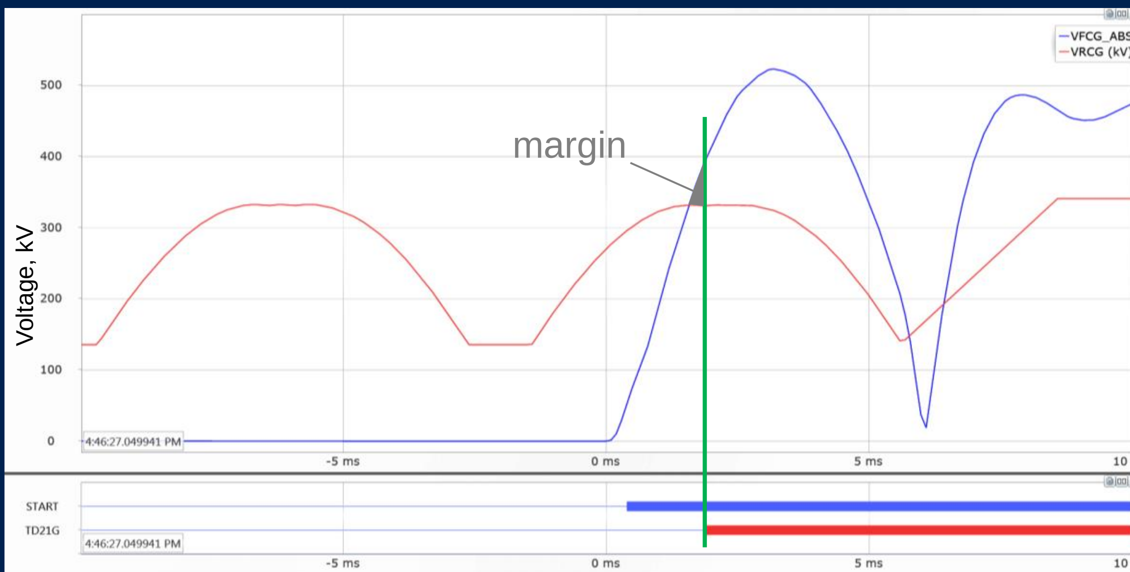



Calculated voltage change can be a time-domain value obtained via memory (actual modern implementation)

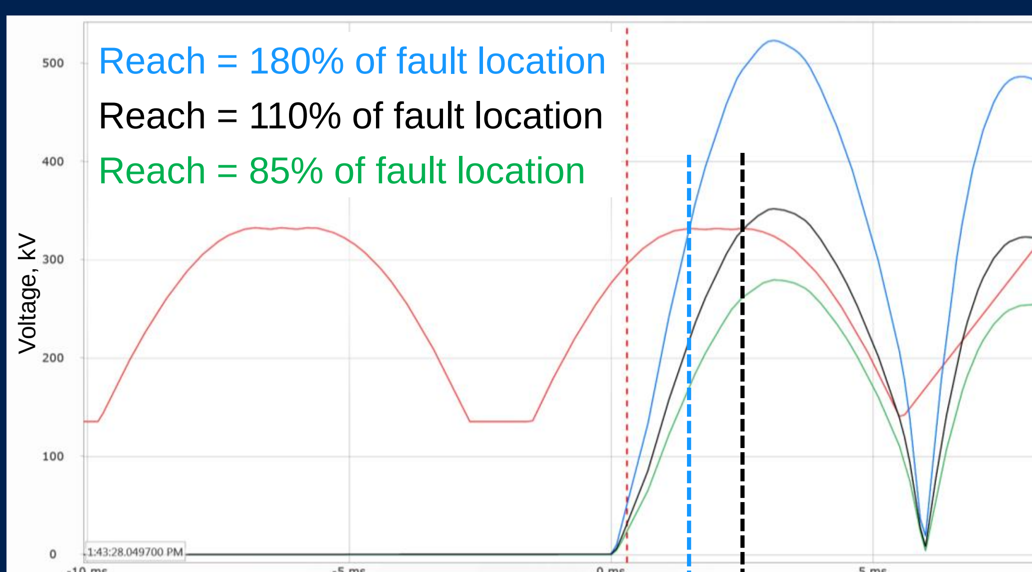
# CG Fault at 57% of Zone 1 on a 400 kV, 224 km Line



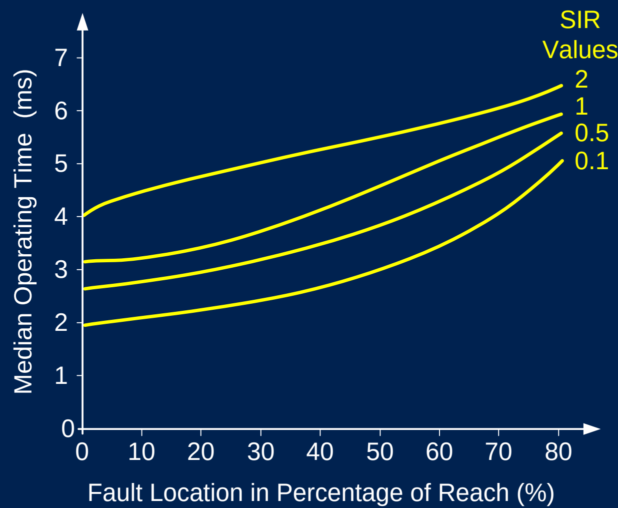
## CG Fault at 57% of Zone 1 on a 400 kV, 224 km Line




## CG Fault on a 400 kV, 224 km Line



## Need for Speed, 2017

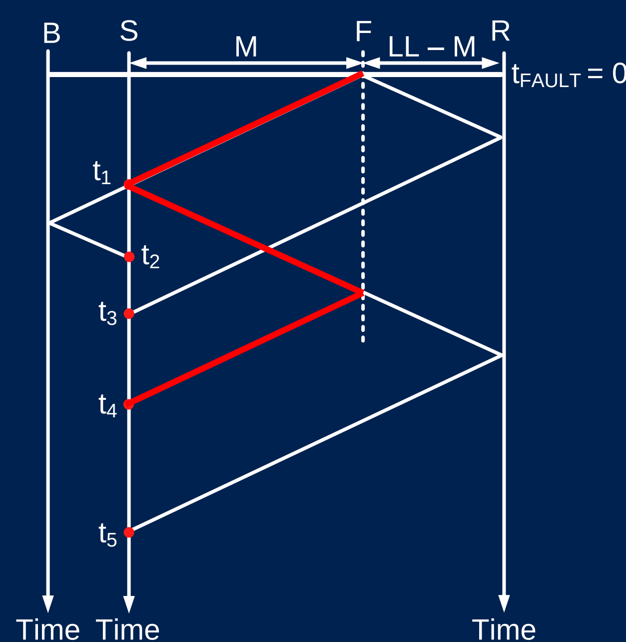



## Traveling-Wave Distance Zone 1

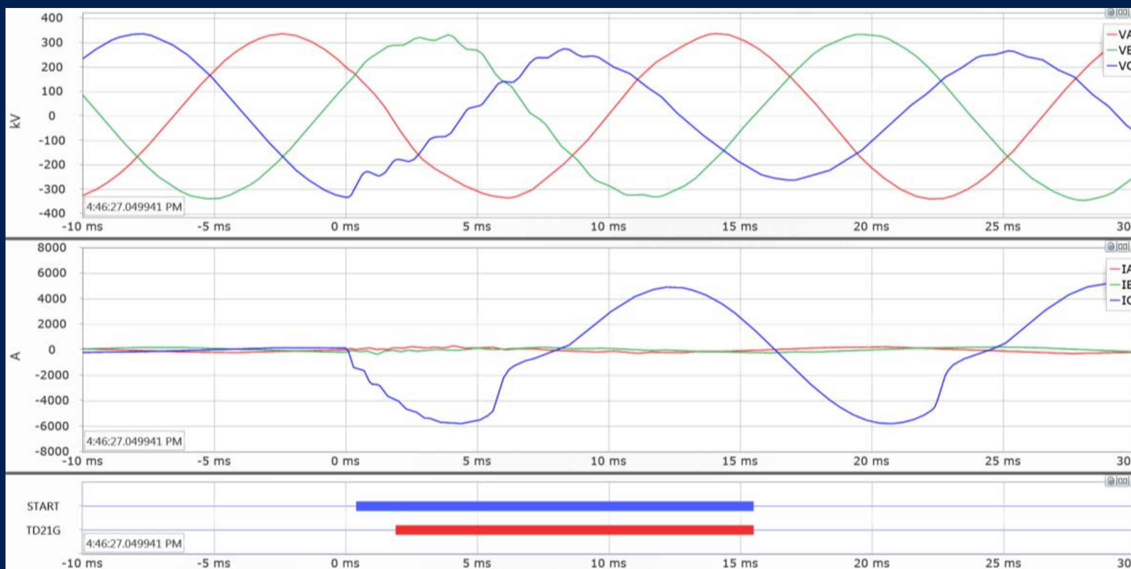
$$2 \cdot M = (t_4 - t_1) \cdot \frac{LL}{TWLPT}$$

$$M = \frac{LL}{2} \cdot \frac{t_4 - t_1}{TWLPT}$$

$$\frac{1}{2} \cdot \frac{t_4 - t_1}{TWLPT} < 0.99 \text{ pu} \rightarrow \text{TRIP}$$

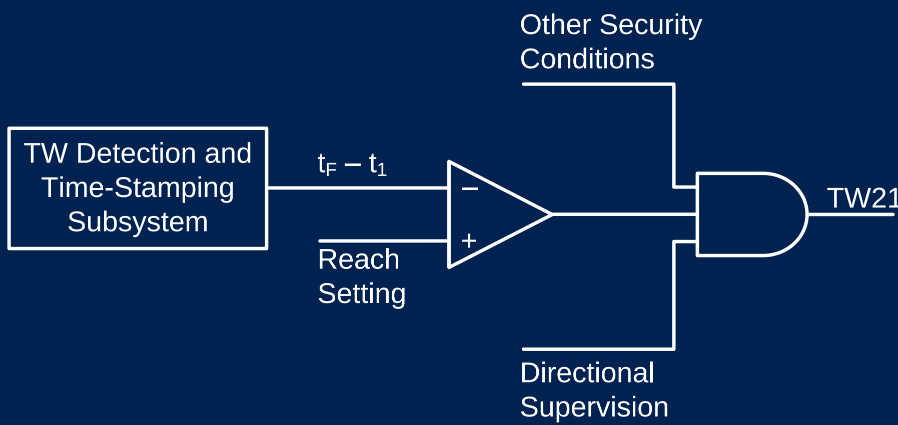


## CG Fault at 78.8 km on a 400 kV, 224 km Line




## CG Fault at 78.8 km on a 400 kV, 224 km Line

## General Implementation

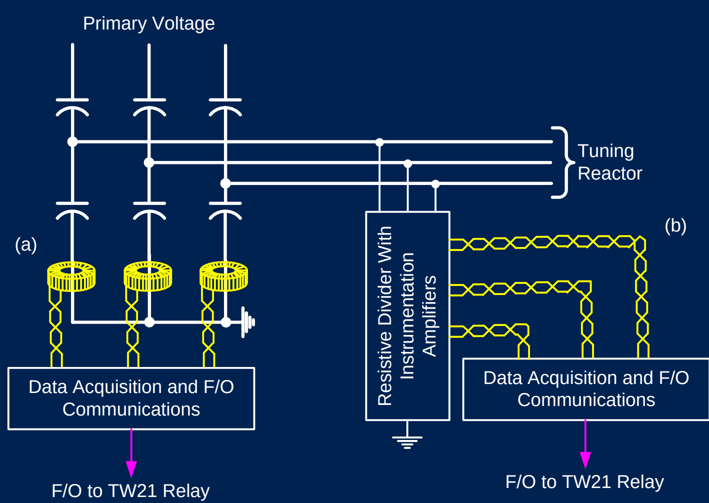



## Challenges

- Identifying the first return from the fault
- Faults close to either of the buses
- In-zone switching events
- TW attenuation and dispersion
- Same TW timing and polarity patterns at multiple buses

# Measuring Voltage Traveling Waves

## Ideas for Retrofitting CCVTs



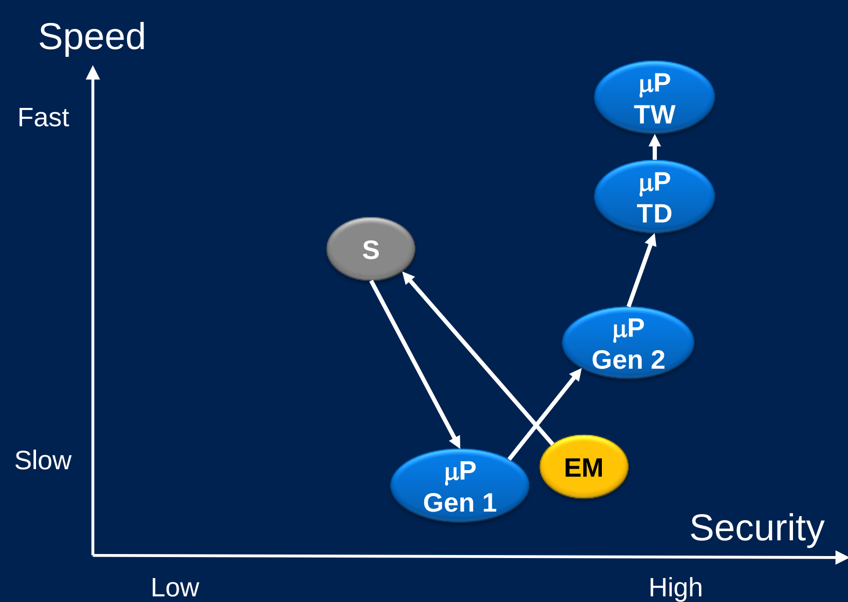

# History of Distance Elements

- Electromechanical technology shaped the characteristics we use today
- Static technology introduced wide design choices
- Initially limited by processing power, μP technology reverted to speed of electromechanical relays
- Today's μP relays with very fast sampling and vast processing can implement any distance principle

## Three Types of Distance Principles

- Apparent impedance elements: 1 cycle
- Incremental quantity elements: 2 ms – 0.5 cycle
- Traveling-wave elements: 1 – 2 ms

## Progress in Distance Element Performance



## Conclusions

- Distance elements are a cornerstone of line protection
- We have not reached performance limits yet
- Today we have access to a phenomenal relay technology ($\mu$s sampling and processing)
- We have an obligation to continue to innovate