Distance Protection in Electric Grids Dominated by Wind-Powered and Inverter-Based Sources

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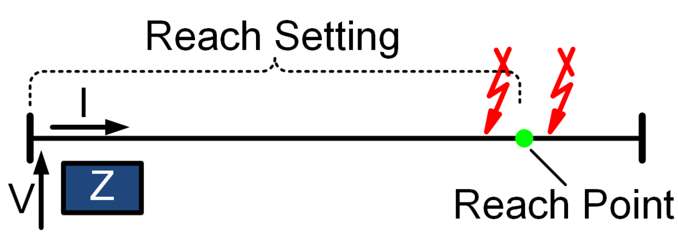
What is distance protection?



- 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

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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

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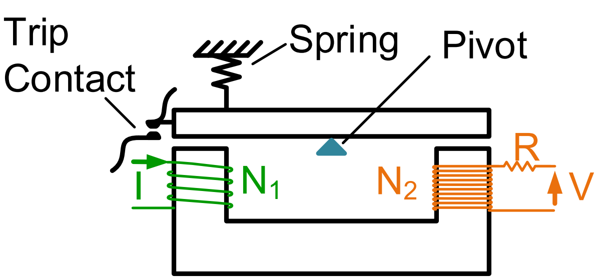
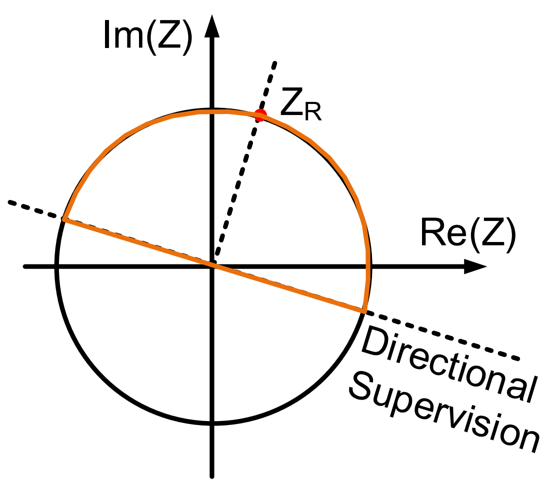
Early relaying technology

Why did we start with a circle?



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



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

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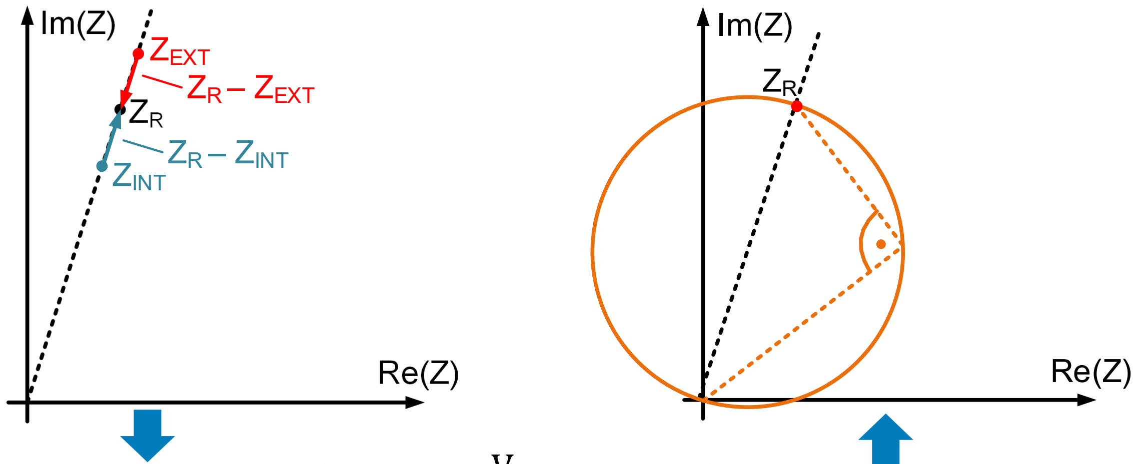
Innovation and progress

Directional mho characteristic



$Z_R - Z_{APP}$ vs Z_R ➡ $Z_R - \frac{V}{I}$ vs Z_R ➡ $I \cdot Z_R - V$ vs V

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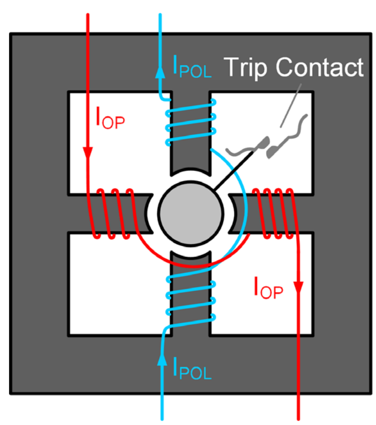
Implementation with electromechanical relays

$\angle(S_{OP}, S_{POL}) < \pm 90°$

$S_{POL} = V$

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

Replica Current



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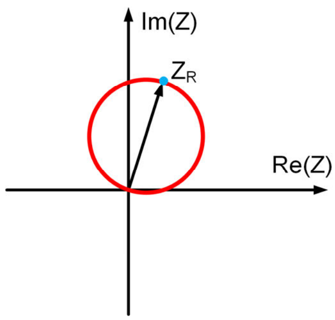
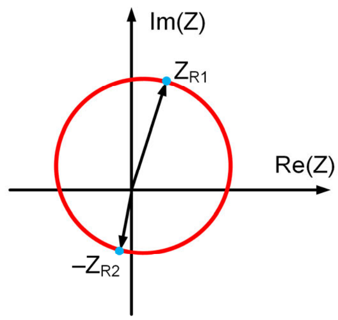
Shaping distance characteristics by using phase comparators

Directional Mho



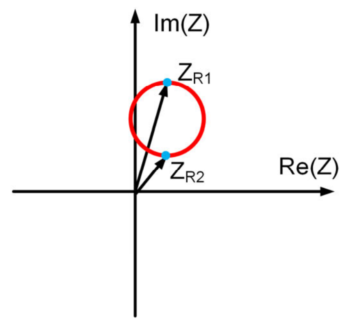
$S_{OP} = I \cdot Z_R - V$
$S_{POL} = V$

Reverse Offset Mho



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

Forward Offset Mho



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

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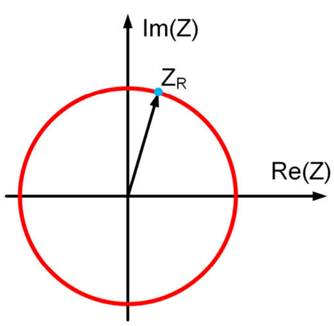
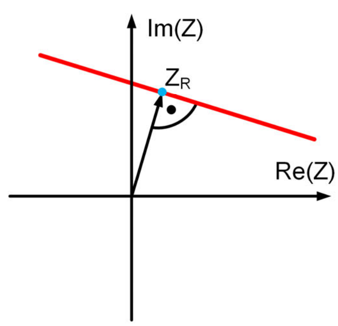
Shaping distance characteristics by using phase comparators

Nondirectional Mho



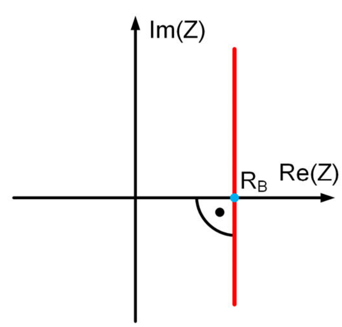
$S_{OP} = I \cdot Z_R - V$
$S_{POL} = -(I \cdot Z_R + V)$

Reactance



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

Resistive Blinder



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

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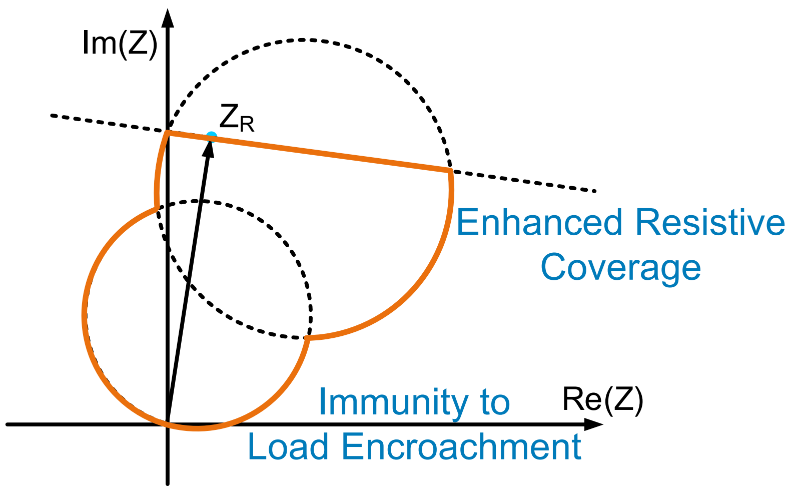
Shaping advanced characteristics



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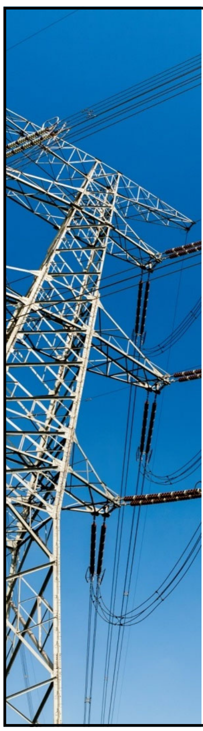

V/I does not make a distance relay

- Polarization methods
  (self, cross-phase, memory, mixed-mode)
- Faulted-loop selection
- Load-encroachment supervision
- Power-swing blocking
- Open-pole supervision
- Loss-of-potential supervision

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Wind-powered and inverter-based sources

Fault response is significantly different from that of a synchronous generator

- Fault current is low and may be shaped by converter control algorithms
- Negative-sequence current does not follow negative-sequence voltage
- Source impedance is variable and not necessarily inductive
- Small or no mechanical inertia, erroneous converter frequency control

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Line protection considerations

- Line unit protection works reasonably well
  - DCB or POTT with weak-infeed logic
  - Line current differential
- Step-up transformers provide dependable 3I0 current during ground faults
  - Ground directional elements work well
  - Ground overcurrent elements provide line and system backup protection
- Remaining challenges
  - Directional elements during phase faults
  - Backup protection (loss of channel, remote backup)

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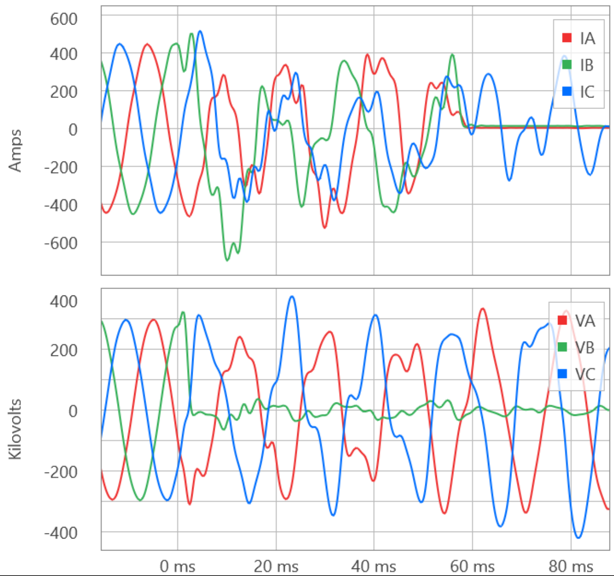
Why do we expect distance elements to work?

Sample line fault (Field case, Type III windfarm)



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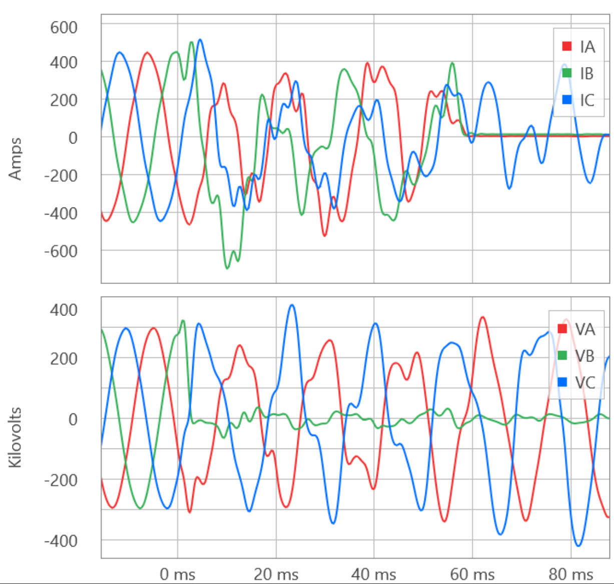
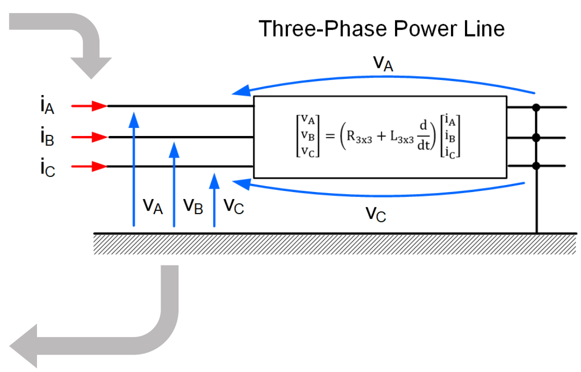
Apparent impedance principle

Think “ohmmeter”





Any current pushed through a power line creates a voltage drop across the line that is consistent with the RL parameters of the line

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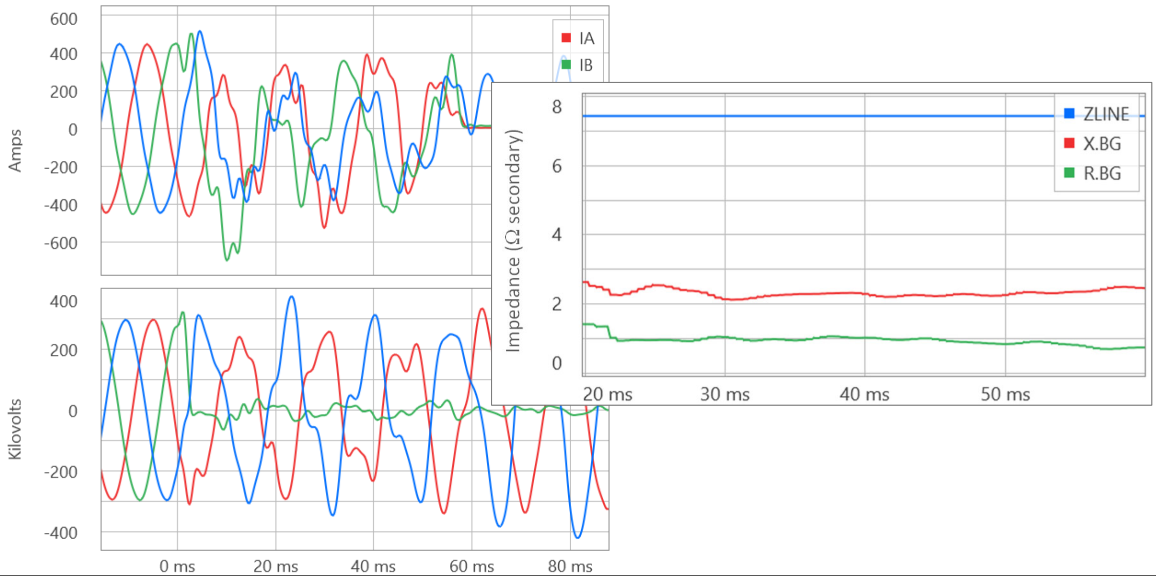
Apparent impedance principle works



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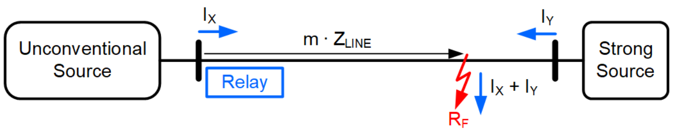
Z1 security and Z2 dependability concerns

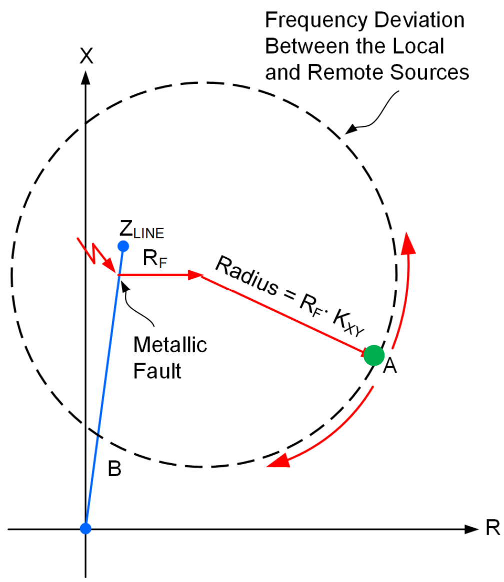
Resistive faults



$$Z_{APP} = m \cdot Z_{LINE} + R_F \left(1 + \frac{I_Y}{I_X}\right)$$

$$\frac{I_Y}{I_X} = K_{XY} \cdot 1\angle\left(\Delta f \cdot 360^\circ \cdot \Delta t\right)$$

$$K_{XY} = \left|\frac{I_Y}{I_X}\right|$$



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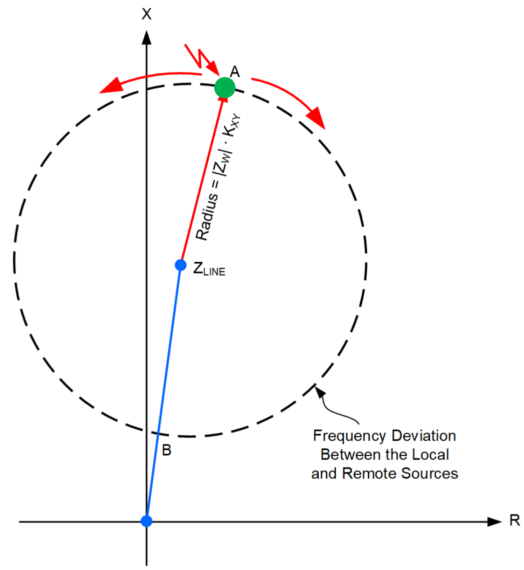
Z1 security and Z2 dependability concerns

Remote backup for external faults



$$Z_{APP} = Z_{LINE} + Z_W \left(\frac{I_Y}{I_X}\right)$$

$$\frac{I_Y}{I_X} = K_{XY} \cdot 1\angle\left(\Delta f \cdot 360^\circ \cdot \Delta t\right)$$

$$K_{XY} = \left|\frac{I_Y}{I_X}\right|$$

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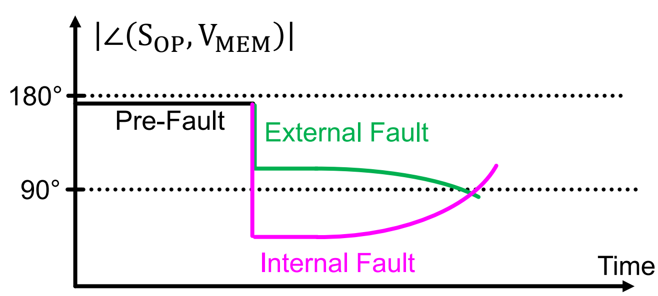
Low inertia defeats memory voltage polarizing

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

$$|\angle(S_{OP}, V_{MEM})| < 90^\circ$$

Rotates at present frequency (S_{OP})

Continues at pre-fault frequency (V_{MEM})



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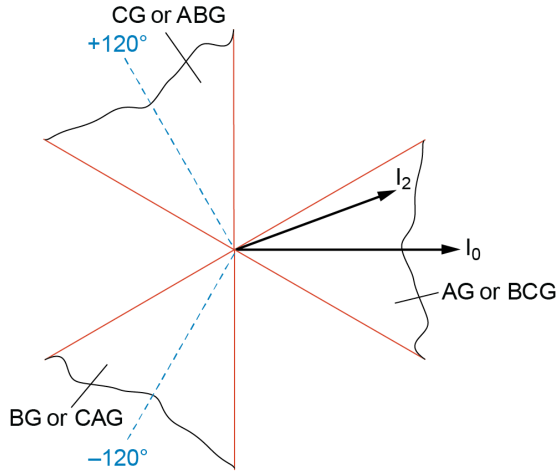
I_2 response defeats faulted-loop selection and reactance polarizing



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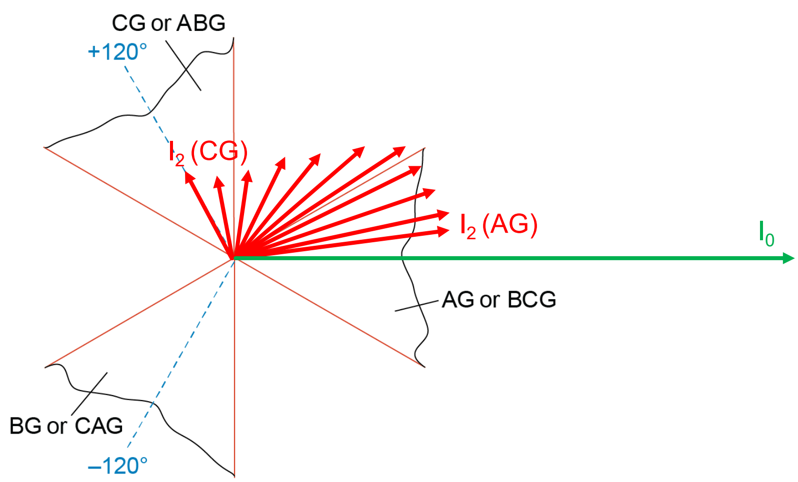
I_2 response defeats faulted-loop selection and reactance polarizing



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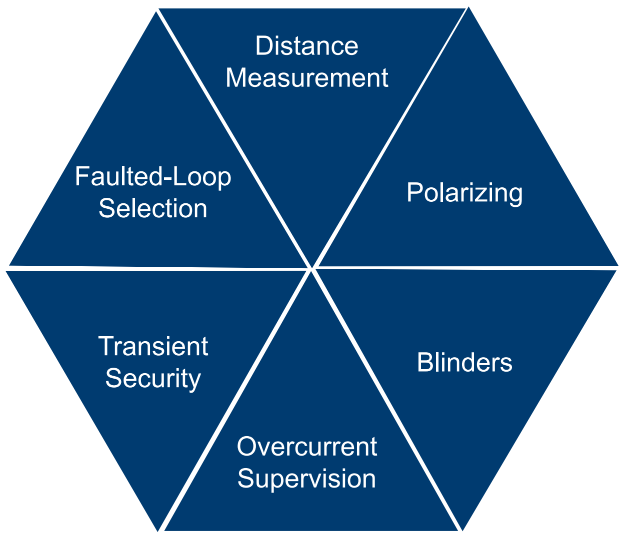
Distance elements became greatly optimized



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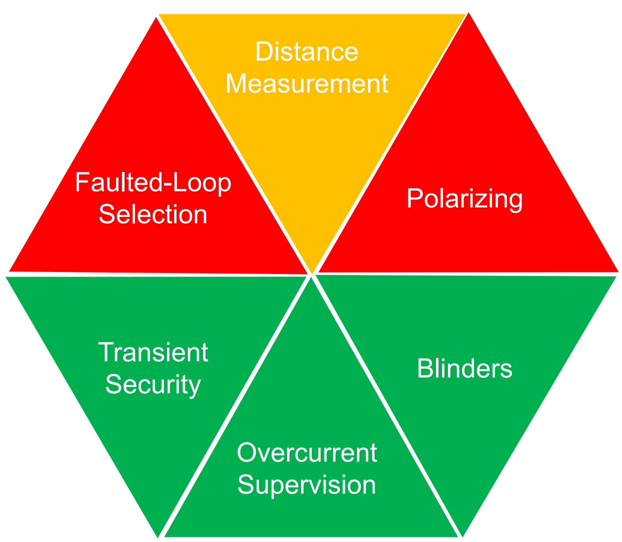
Score card for unconventional sources



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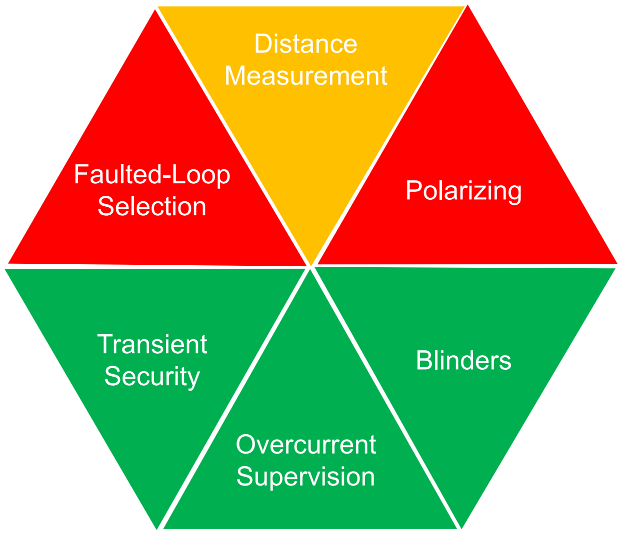
Take apart, keep what works, fix what does not



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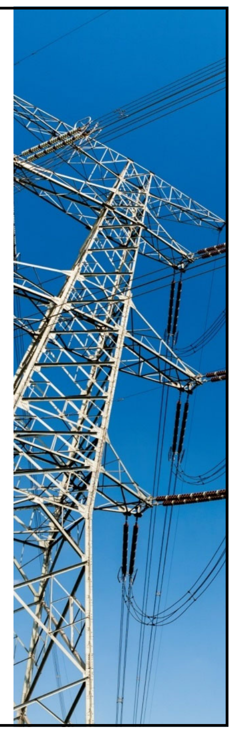
Distance element polarizing



Problem

- Cannot trust V_{MEM} (small or no source inertia) in mho elements
- Cannot trust I_2 (angle rotates) in phase quadrilateral elements

Solution

- Use apparent-impedance offset operating characteristics
- Directionalize with combination of TD32, 32G, and 32WI if needed

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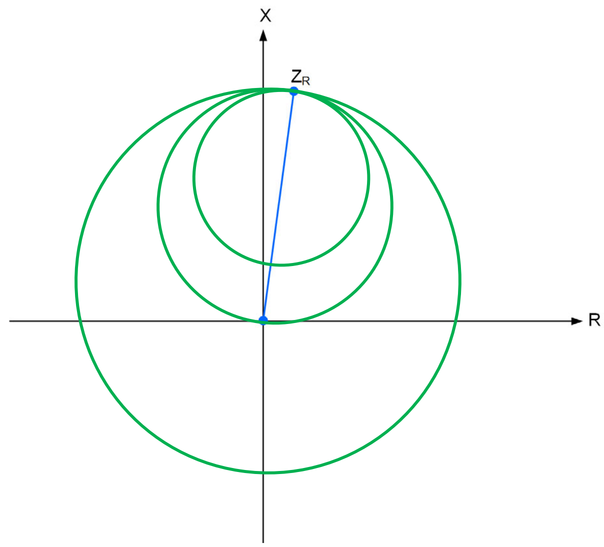
Memory-polarized mho is directional

Characteristic expands and contracts



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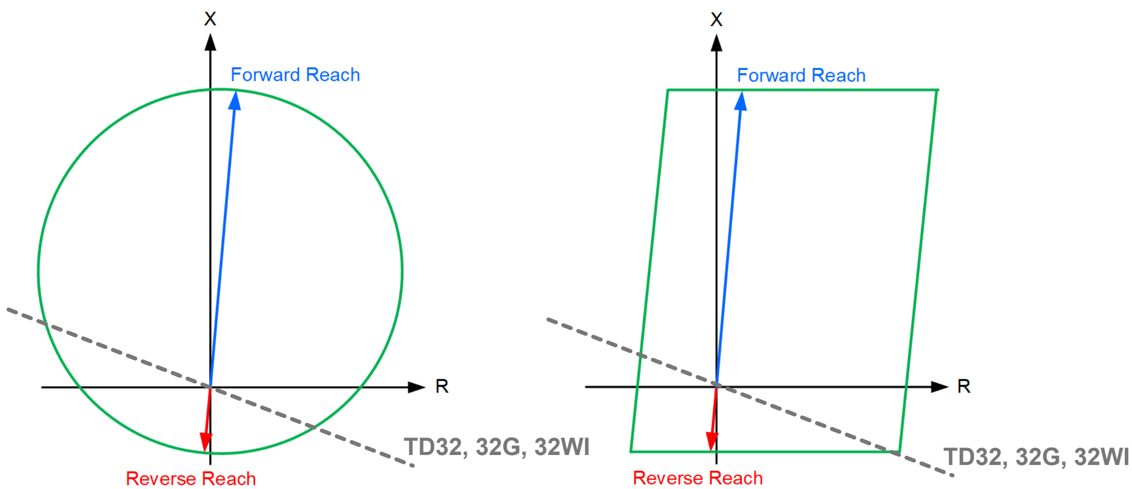
Reverse offset for dependability



Applications

- Nondirectional (local and remote backup) step distance zone
- Directional application by using TD32, 32G, and 32WI

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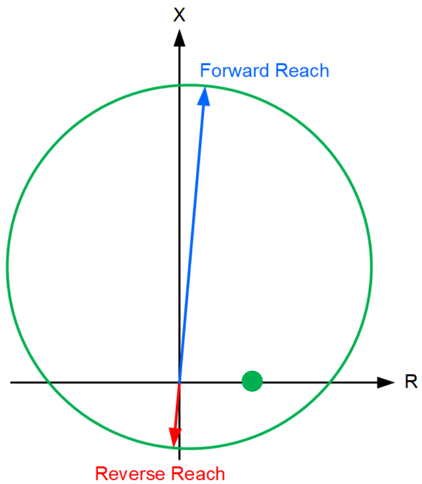
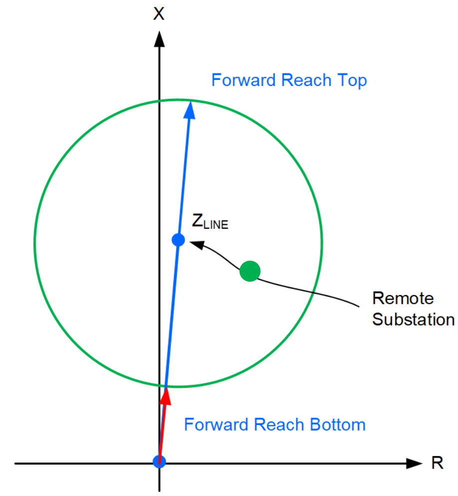
Step distance does not have to be directional

Reverse offset in local backup applications



Forward offset in remote backup applications



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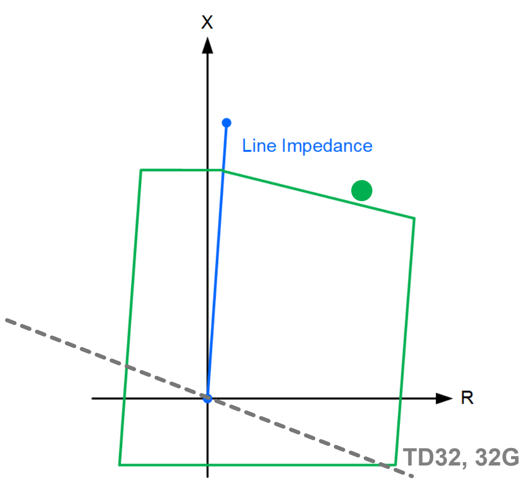
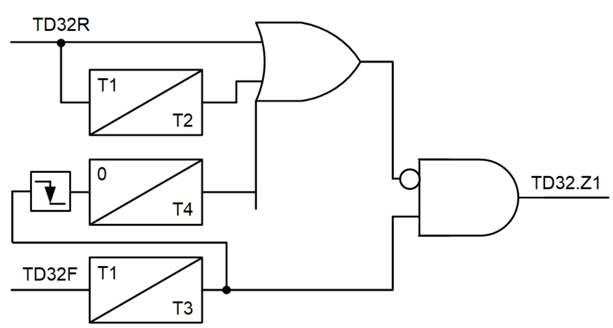
Zone 1 application



Zone 1 logic. Supervise with TD32, shut down Z1 before the imminent swing causes overreach



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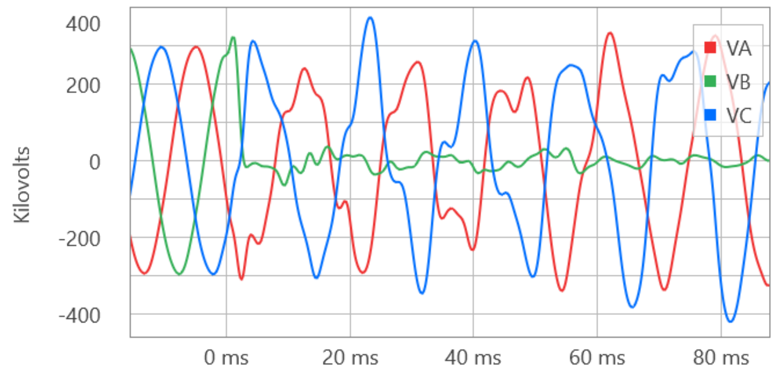
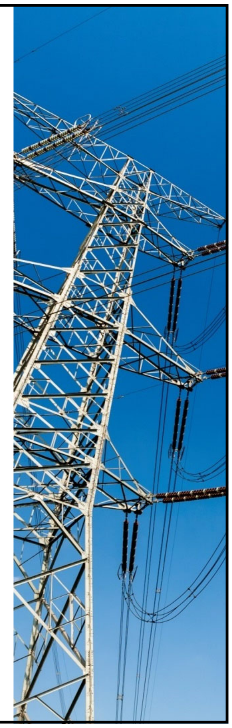
Faulted-loop selection

Problem: Cannot trust I_2
(angle rotates with respect to I_0 and V_1)

Solution: Use undervoltage





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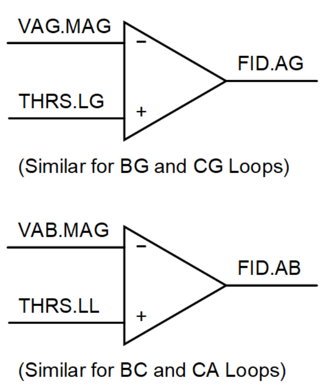
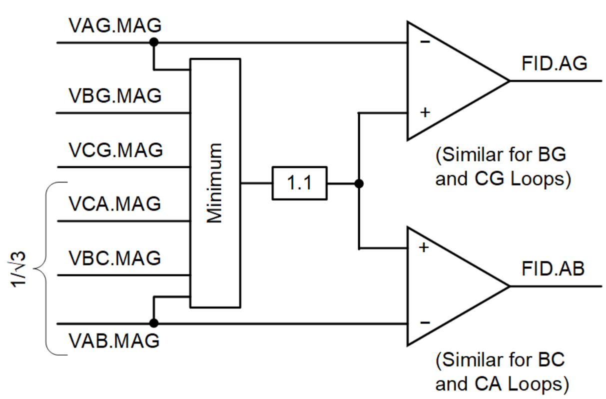
Undervoltage faulted-loop selection





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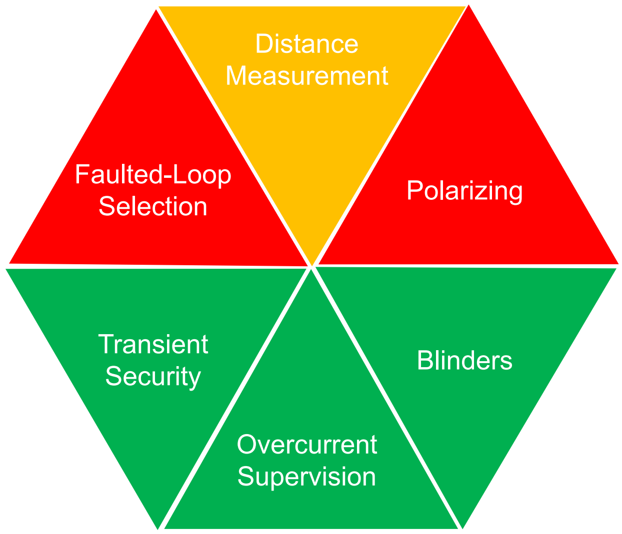
Take apart, fix, put it back together



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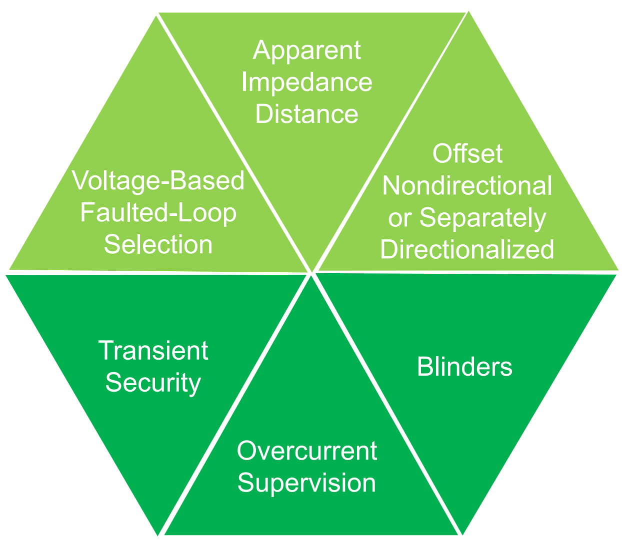
Take apart, fix, put it back together



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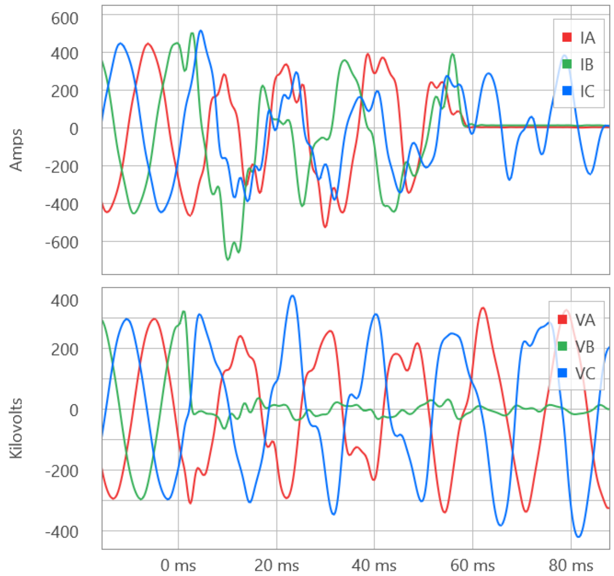
Incremental-quantity directional TD32



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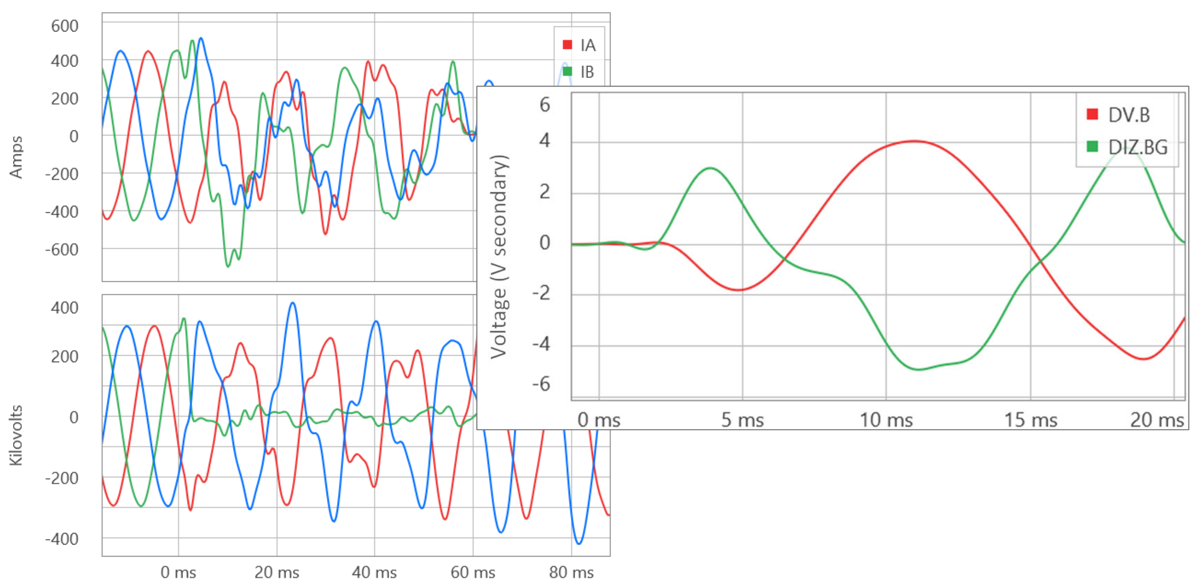
Incremental-quantity directional TD32



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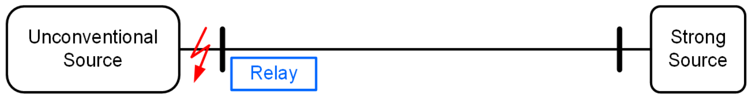
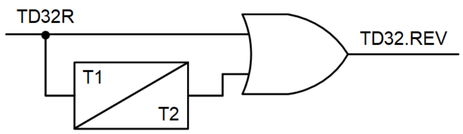
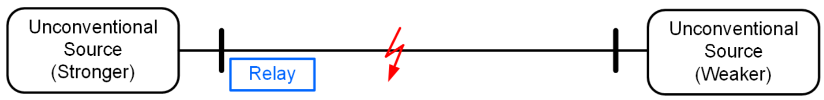
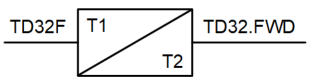
TD32 principle works… but is transient





Blocking logic. Use when the remote system is more traditional and stronger





Permissive logic. Use when both local and remote systems are unconventional, but the local source is stronger

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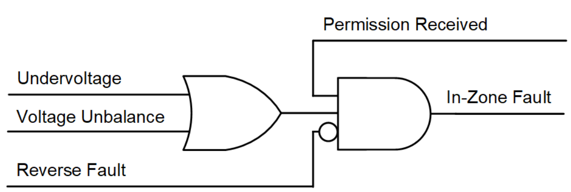
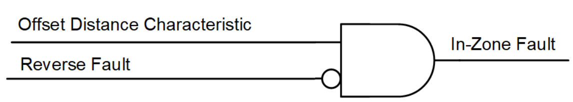
Weak-infeed directional element 32WI

Draws inspiration from the weak-infeed pilot logic



Weak-infeed directional principle



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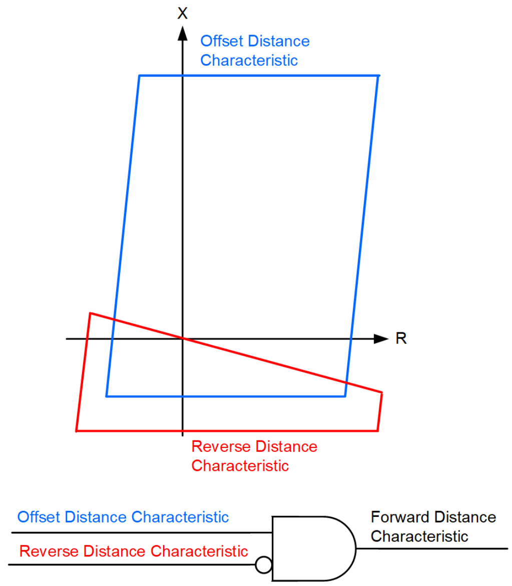
Weak-infeed directional element 32WI



Operating principle

- Detect a fault (forward or reverse) within a controlled reach
- Do not detect forward fault direction but instead…
- Operate if the fault is not reverse

Net result

- Count on the system current for reverse faults
- Do not count on the source current for forward faults

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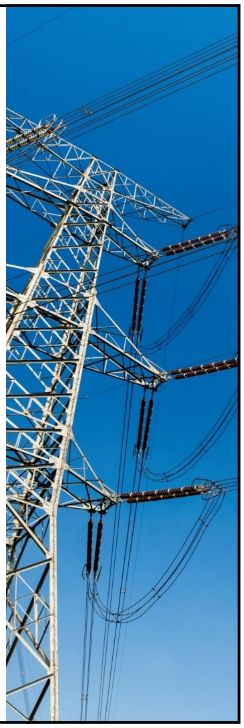
Conclusions

- Line protection, especially distance and directional elements, is a key concern
- Distance elements near unconventional sources work reasonably well when properly simplified
  - Avoid directional polarizing (offset instead)
  - Avoid negative-sequence (undervoltage instead)
  - Use Z1 for a limited time only
- Directional elements that work well
  - Ground directional (32G)
  - Incremental-quantity directional (TD32)
  - Weak-infeed directional (32WI)



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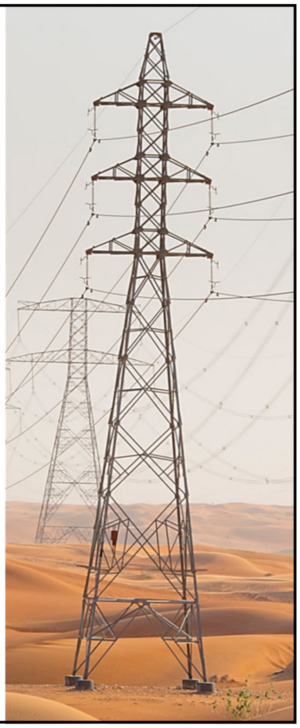
Conclusions

- Protection philosophy changes
  - Rely more on protection channels
  - Use redundancy and monitoring to maintain channel availability
  - Pivot from remote backup to local backup (BF with DTT and redundancy)
  - Step distance zones do not have to be directional
- Today, you can apply custom logic
  - Repurpose PSB and OOST impedance characteristics for offset distance elements
  - Use programmable logic to set up new distance elements



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