Verandering zonder Compromissen

PAC als Fundament van Betrouwbaarheid

8 april 2026

cigre
Nederland

Impact of Invertor Based Resources on line differential and distance protection.

Jacques van Ammers,
GE Vernova

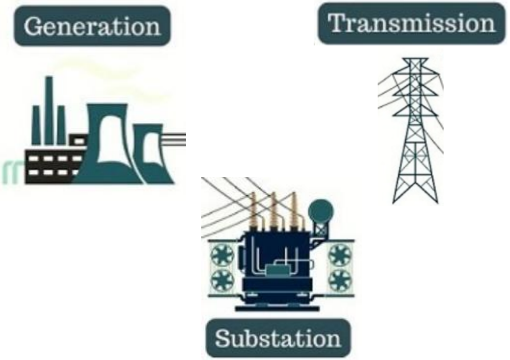
Analysis of Differential Protection Functions in High-IBR Scenarios

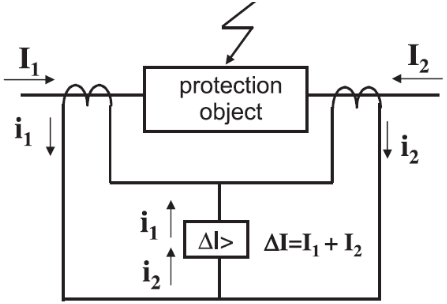
- M. Popov, TU Delft
- Jacques van Ammers, GE Vernova

The role of differential protection function in modern grids

Differential protection (87) has been the primary, unit-selective protection method for:

- Generators,
- Transformers
- Busbars
- Also used for small transmission lines





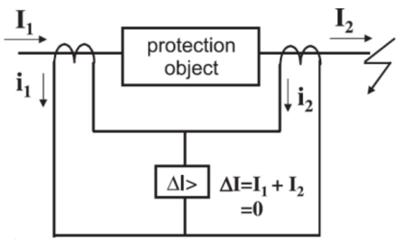
Mathematical Principle: Based on Kirchhoff's Current Law (KCL):

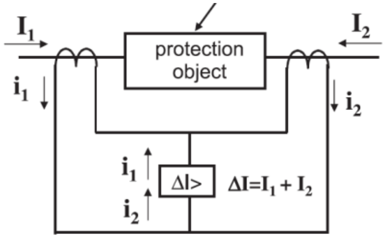
- The relay monitors the vector sum of currents entering and leaving a protected zone.
- Under normal conditions: $\sum I = 0$.
- During a fault: $I_{diff} = |\sum I_{in} - \sum I_{out}| > I_{pickup}$

The role of differential protection function in modern grids

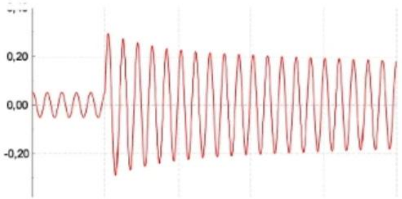
The Mayor Advantage:

- Inherently selective (only operates for faults within the protected zone).
- Independent of external fault current levels or system configurations (in theory).

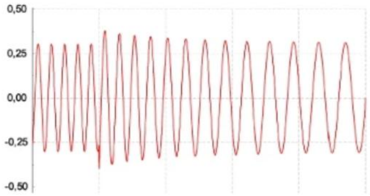




As the grid transitions from rotating inertia (synchronous) to power electronics (IBR), **can we still rely on these legacy assumptions?**



Synchronous generator



IBR generator

The IBR Shift—From Physics to Controls

The Traditional Era (Synchronous):

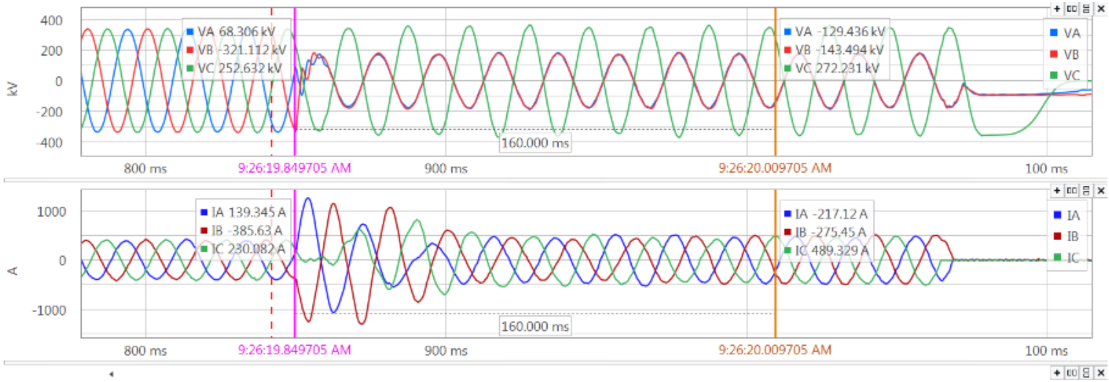
- Fault currents are dictated by machine impedance and physical inertia (X_d'').
- High magnitude, high frequency, and predictable transient behavior.

The Modern Era (IBR):

- Fault current is limited by **inverter control limits** (usually 1.1 to 1.5 p.u. of nominal current).
- Dynamics are dominated by **PLL (Phase-Locked Loop)** and **Current Control Loop** speed

The Conflict:

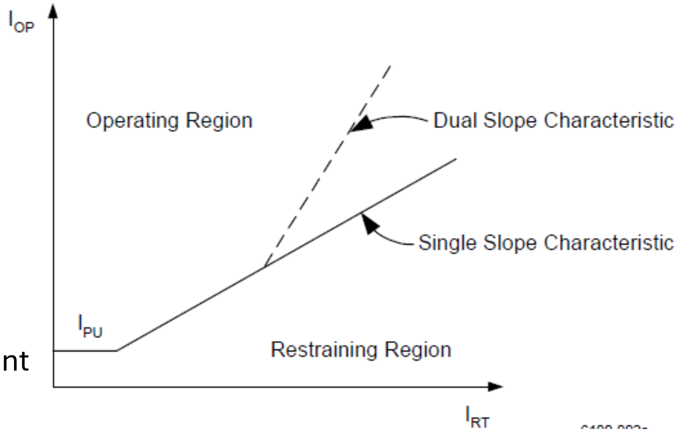
- "**Low Current**" →Risk of under-sensitivity (relay fails to "see" the fault).
- "**Fast Control**" →Risk of potential **instability** or **maloperation** due to non-sinusoidal transients



The Percentage Restrained Characteristic

Operating and Restraint Currents: The relay calculates two fundamental quantities to make a decision:

- **Differential Current ($\boldsymbol{I_{diff}}$):** The vector sum representing the fault.
- **Restraint Current ($\boldsymbol{I_{rest}}$):** The average or maximum current, representing the "through-load" or "external stress."



Dual-Slope Characteristic:

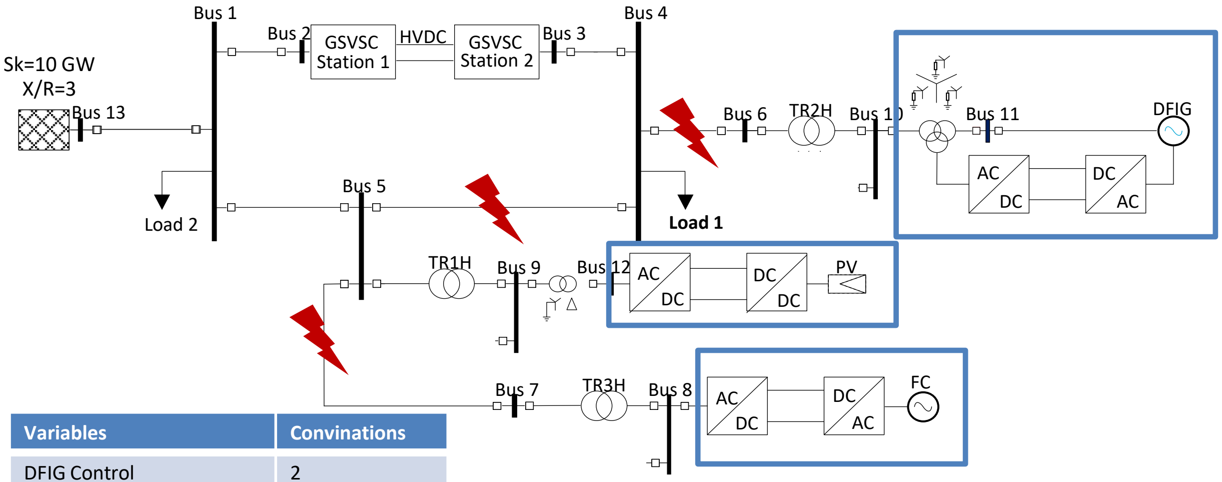
- **Slope 1:** Accounts for CT (Current Transformer) errors at low currents.
- **Slope 2:** Increases security during high-magnitude external faults to prevent "false trips" due to CT saturation.

Tripping Criterion: The relay trips only if the operating point ($\boldsymbol{I_{rest}}, \boldsymbol{I_{diff}}$) enters the **Operate Zone**:

$$I_{diff} > k \cdot I_{rest} + I_{min}$$

The IBR Problem: IBRs produce low $\boldsymbol{I_{diff}}$,often keeping the operating point dangerously close to the **Restraint Zone** boundary.

The MIGRATE benchmark with high IBRs and the differential function



Variables	Convinations
DFIG Control	2
Protection function	1
Number of lines	3
Scenarios	2
Generation levels	2
Point of line	3
Type of fault	11
Faul resistance	1
Repetitions	3
Total cases	2376

- 100% Synchronous generation
  - 40MW and 175MW
  - Weak and strong grid
- 100% Renewable generation
  - 40MW and 200MW
  - Weak and strong grid
- Intermediate scenario with strong and weak grid conditions
  - 40MW and 200MW
  - Weak and strong grid

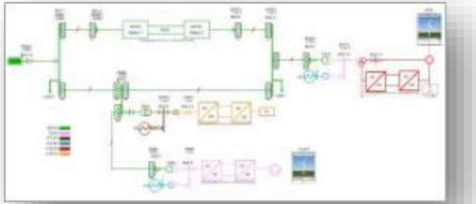
RTDS Environment

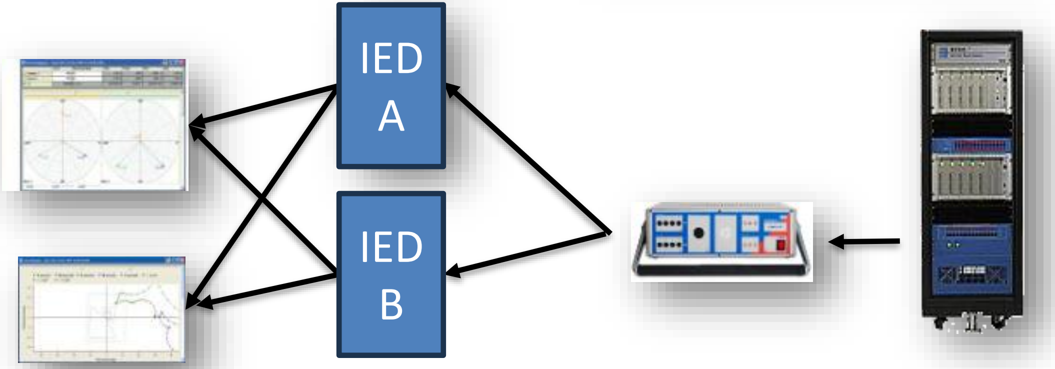
Simulation environment

- RSCADFX (Real Time Power Systems Simulator)

Hardware interconnection

- RTDS-Novacore
  - Hardware-in-the-Loop (HiL)
  - Control HiL (CHiL)
  - Power HiL (PHiL)
  - Protection equipment
- Amplifier
- Protection relay manufacturer A
- Protection relay manufacturer B



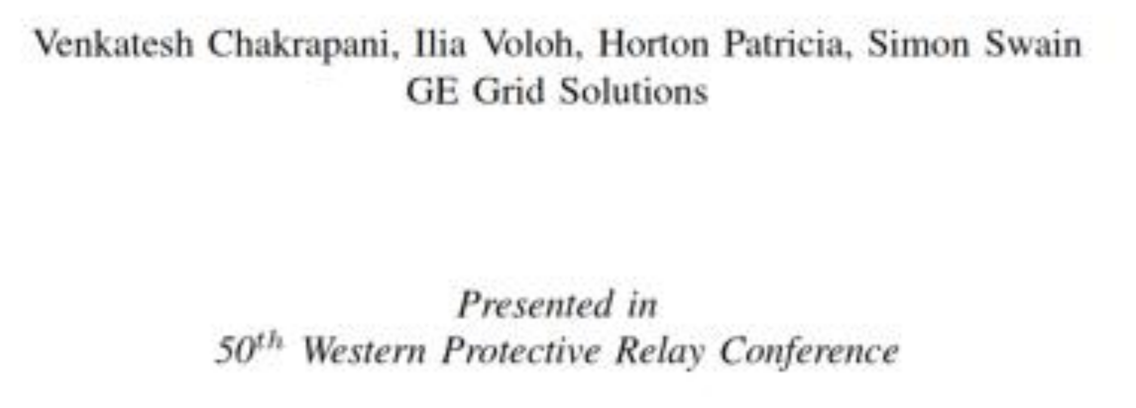


Conclusions

- **Performance:** the $87L$ function remained stable and dependable across all simulated IBR stress events. Results are currently validated for **Line Protection** only.
- **Next Steps:** Expansion to **Transformer-Cable** and **Over-stressed Transformer** scenarios is essential to map the full boundaries of the protection's reliability.
- **Synchronous Gen:** High dependability; clear I_{diff} signatures.
- **IBRs (PV and Wind Type 3 & 4):** Limited fault current and control-driven transients "stress" the restraint boundary.
    - During a fault, PV and Wind type 4 present limited and low distorted signals on the other hand, Wind type 3 presents greater fault current with distortion.
- **Key Findings:**
    - **Sensitivity:** Traditional settings may lead to delayed tripping in high-penetration PV scenarios.
    - **Selectivity:** Control loop interactions (Type 4) may mimic internal faults during external transients.
- **Recommendations:**
    - Need for **Adaptive Slopes** or "Control-Aware" protection algorithms.
    - Shift from purely RMS-based logic to Time-Domain or Sub-Cycle analysis.

Performance Assessment of an Enhanced Distance Relay in the presence of Inverter Based Resources

- Jacques van Ammers, GE Vernova



Venkatesh Chakrapani, Ilia Voloh, Horton Patricia, Simon Swain
GE Grid Solutions

Presented in
50th Western Protective Relay Conference

Overview

- Overview of the Problem
- Power System Model
- Distance Protection – Problems and solutions
  - Quad Characteristics
  - MHO Characteristics
  - Fault Type Supervision
- Conclusion

Overview of the Problem

Unreliable Negative Sequence Currents

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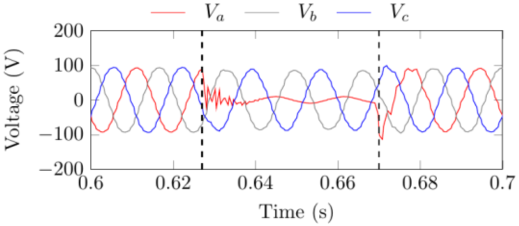
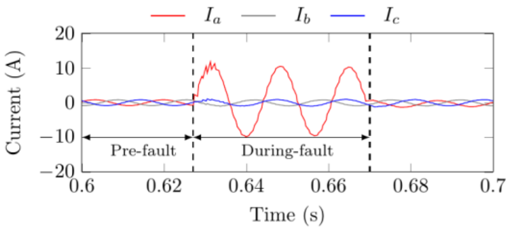
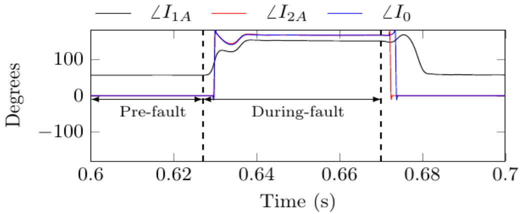


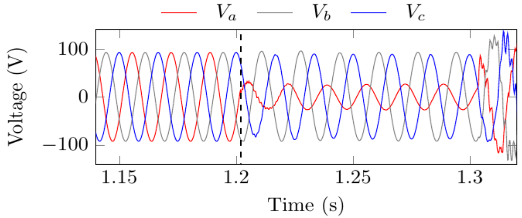
(a) Voltage signals



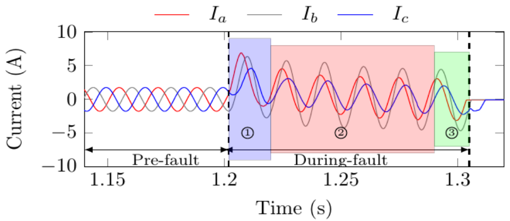
(b) Current signals



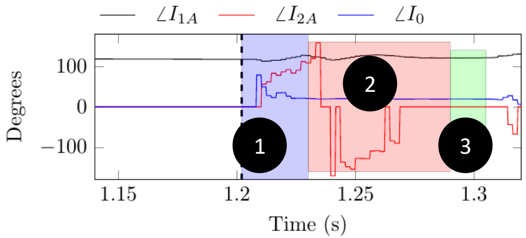
Conventional generation response for AG fault



(a) Voltage signals



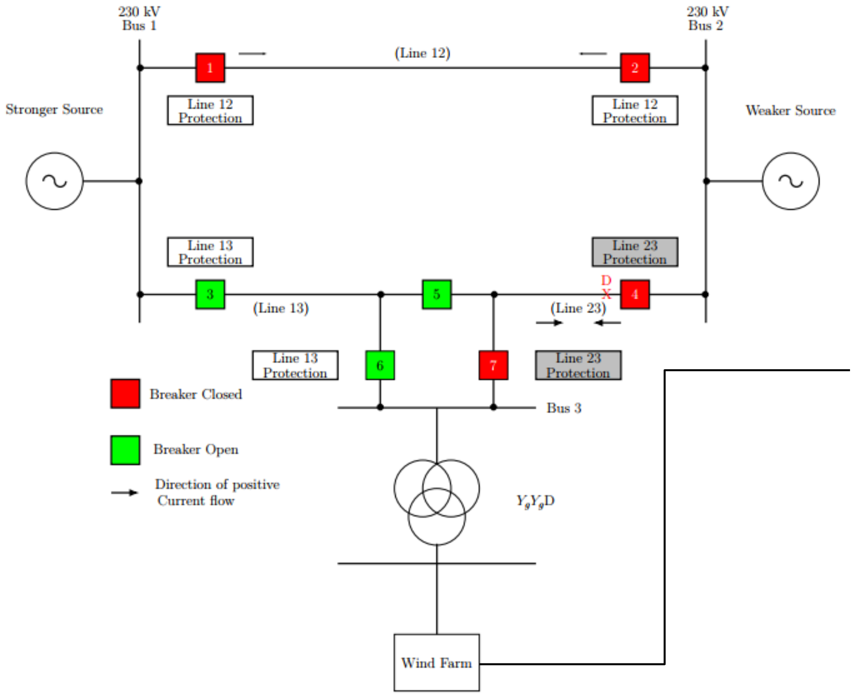
(b) Current signals

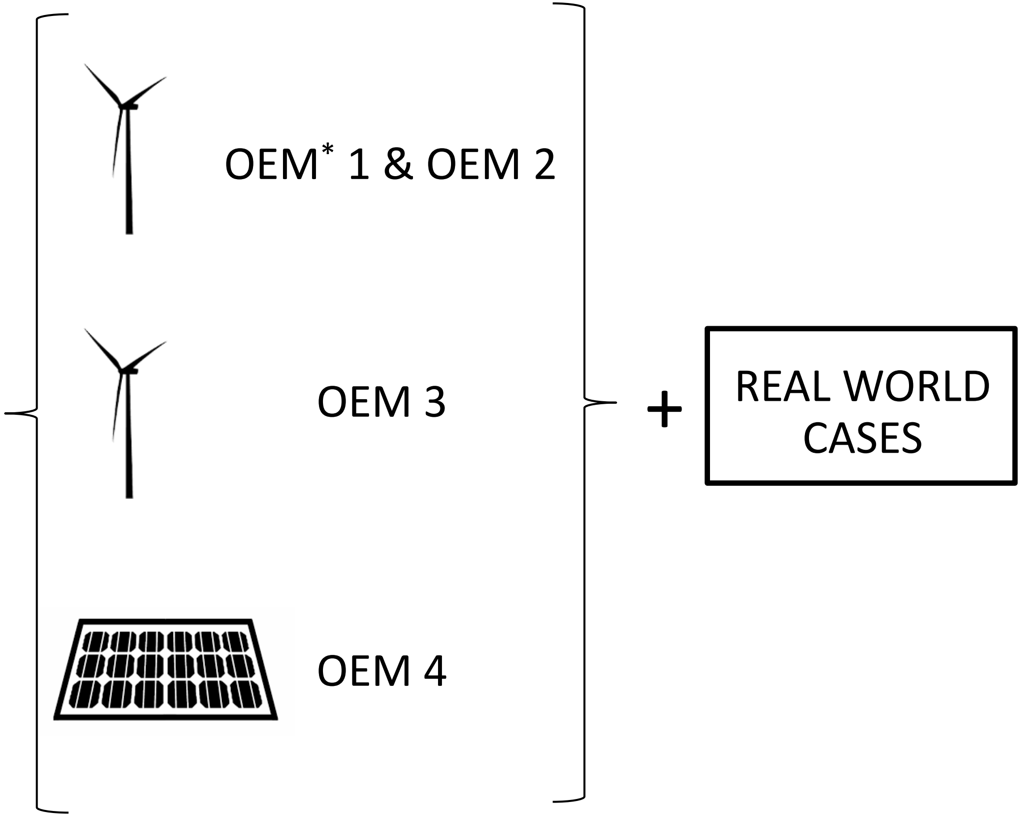


IBR response for AG fault

Power System Model

Accurate IBR Models + Real World Cases





OEM* 1 & OEM 2

OEM 3

OEM 4

+

REAL WORLD CASES

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* OEM – Original Equipment Manufacturers

Quad Characteristics

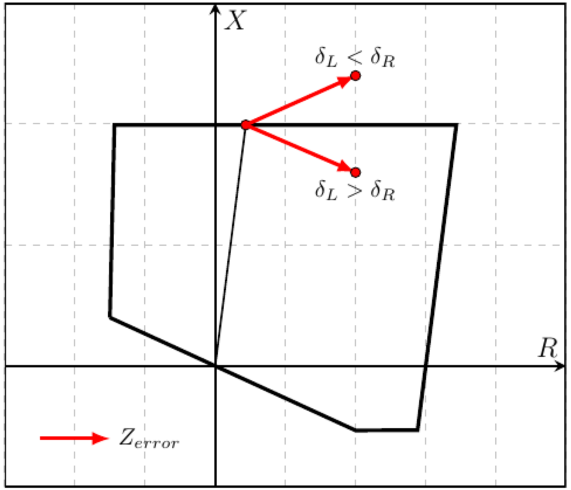
Best Polarization

$$\phi = arg\left\{\frac{I_f}{I_A(1+k)}\right\}$$

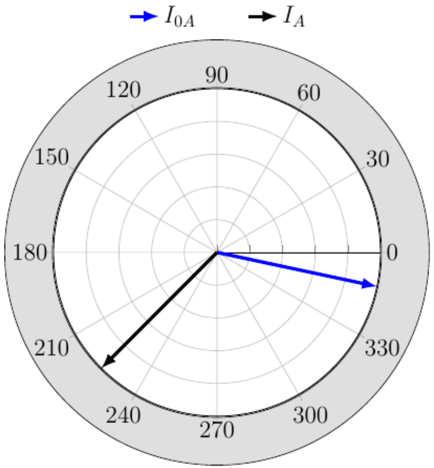
$$\angle I_{ph} \approx \angle I_f$$

$$\angle I_{0L} \approx \angle I_f$$

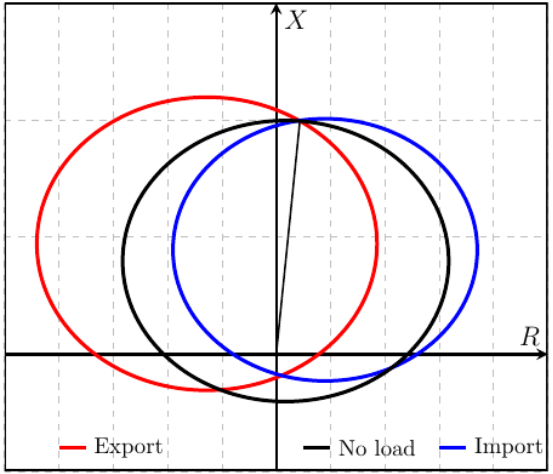
$$\angle I_{2L} \approx \angle I_f$$



Quad with adaptive tilting



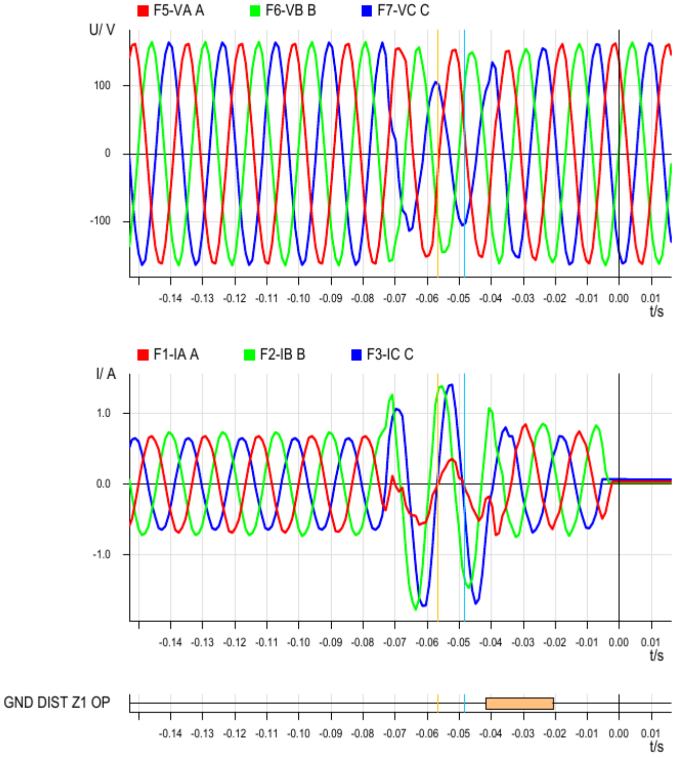
Real world case (I_0 not reliable)
(both I_2 and I_0 may not be reliable)



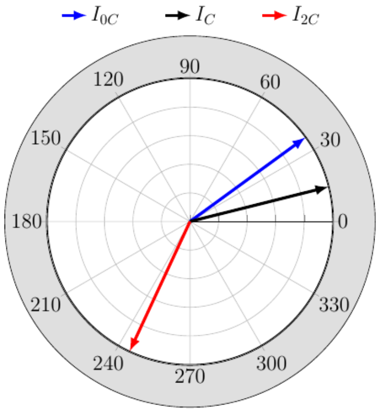
Quad to MHO Switching

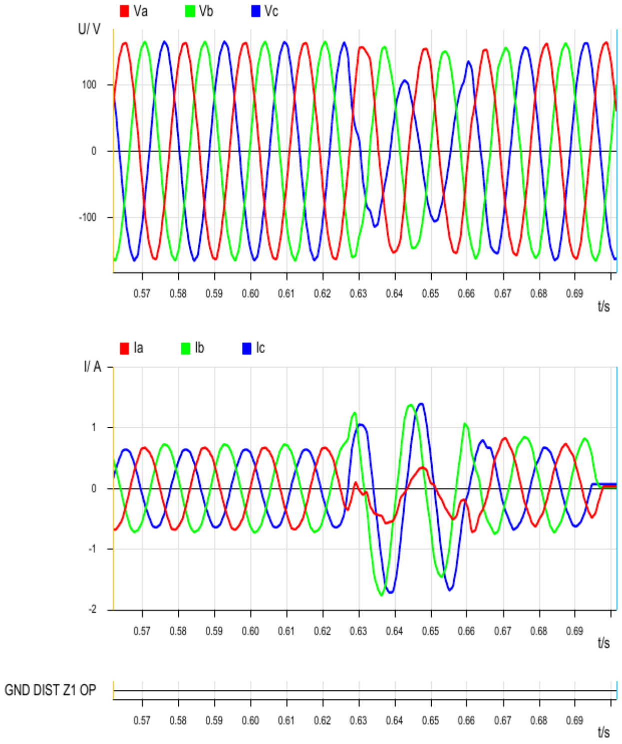
Quad Characteristics

Best Polarization solve the problem



Real world case 1 – Mis-operation (Over-reaching)

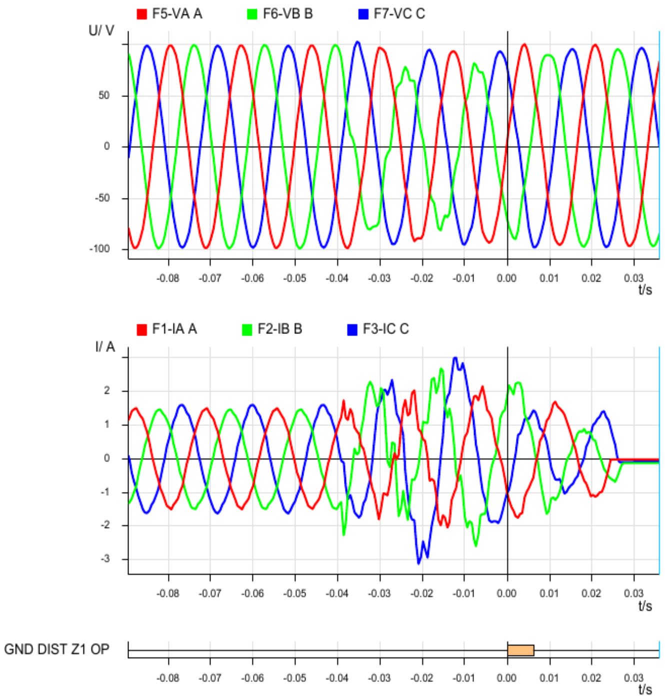




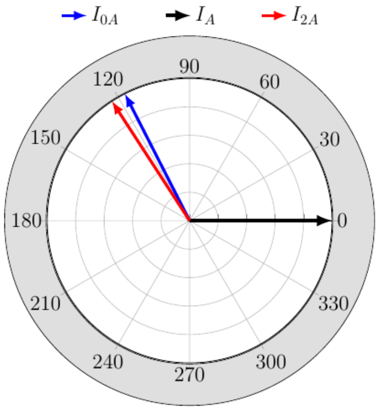
Quad with best polarization
(switching to zero sequence)

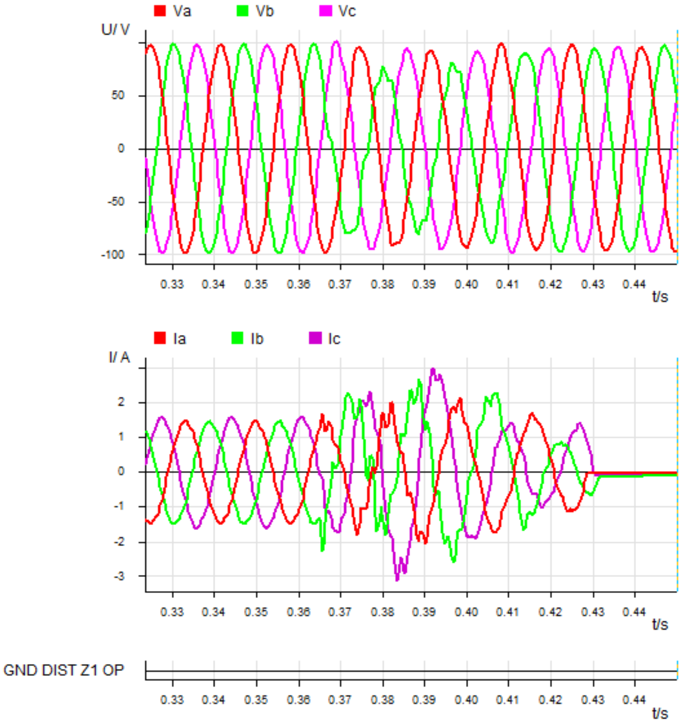
Quad Characteristics

Switching to MHO solve the problem



Real world case 2 – Misoperation (Reverse Fault)

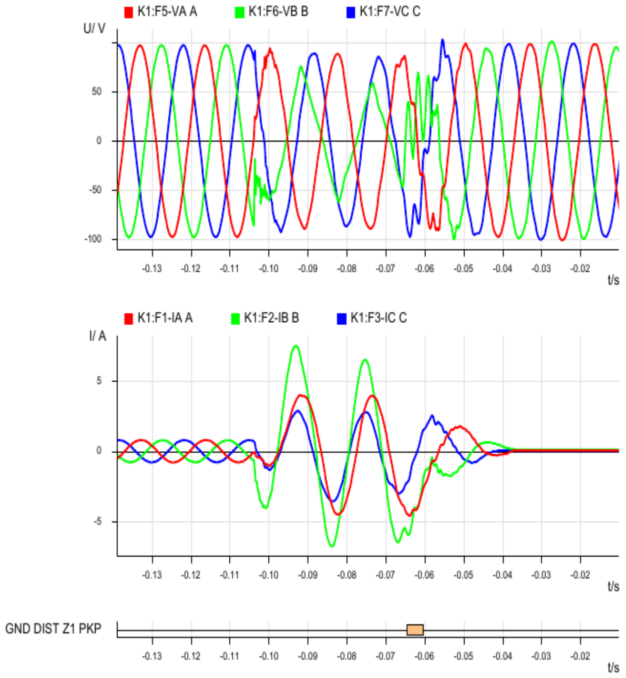




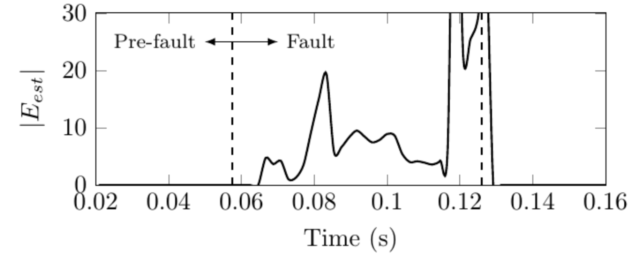
Quad with best polarization (switching to MHO)

MHO Characteristics

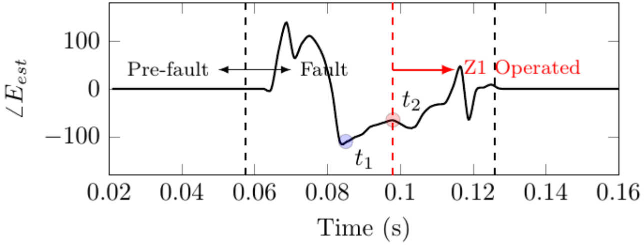
Uncontrolled MHO weakness



Case 1 : Real world Z1 mis-operation

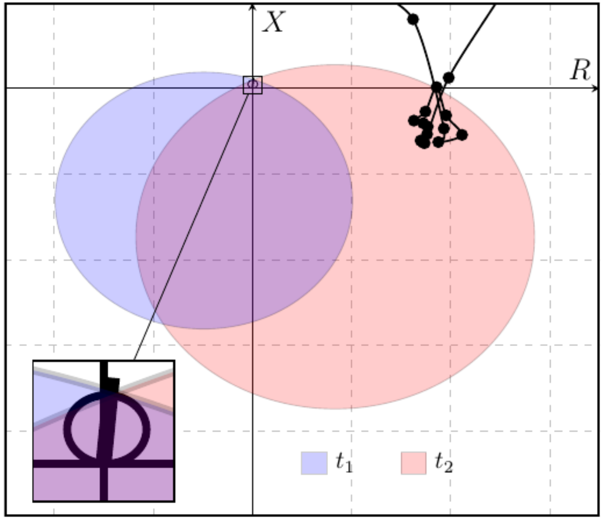


(a) Magnitude



(b) Angle

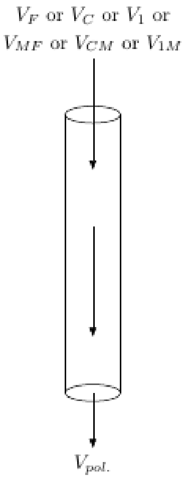
Dynamic MHO



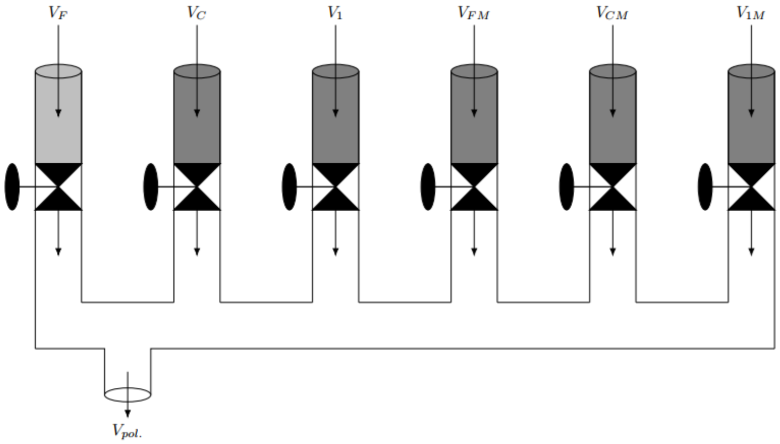
Uncontrolled MHO causing Zone 1 mis-operation

Controlled Dynamic MHO

Patent Pending



Single



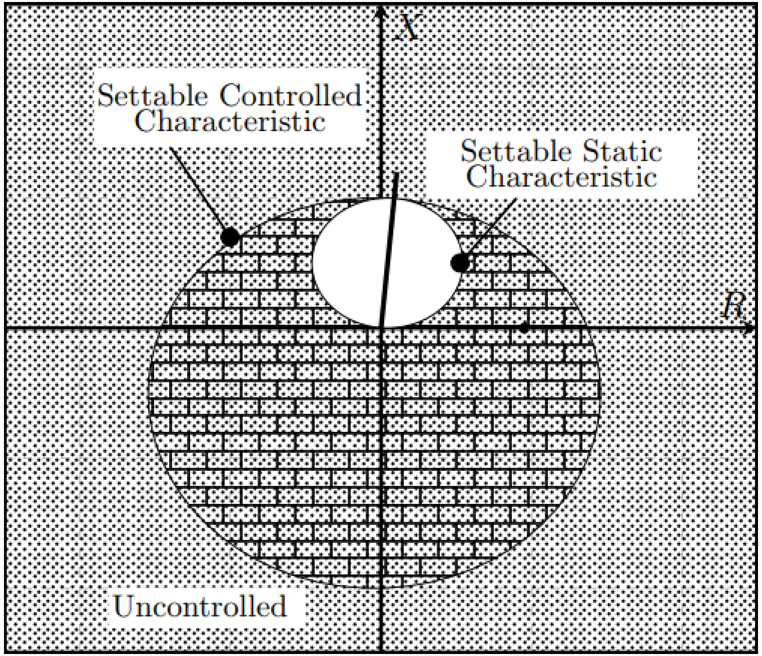
Dual

$$E_{est,ground} = \frac{V_2 + V_0 - I_1 Z_{s1}}{I_{loop}}$$

$$E_{est,phase} = -Z_{s1}$$

$$V_{pol} = G.X + P.Y$$

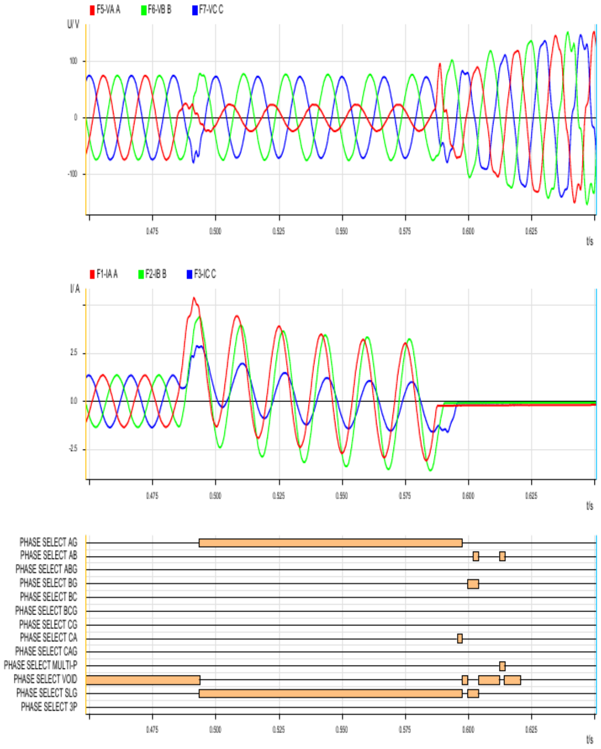
X, Y are inputs and
G, P are valve controls



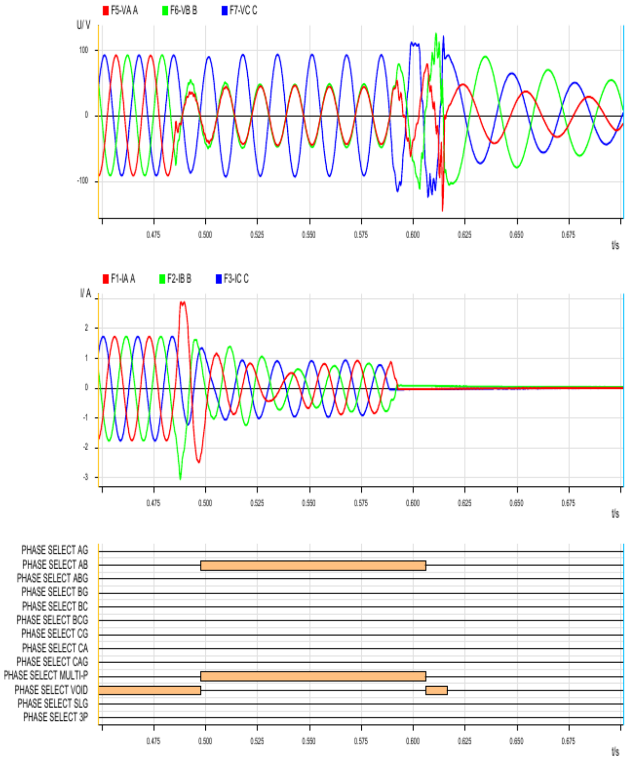
Controlled Dynamic MHO

Fault Type Supervision

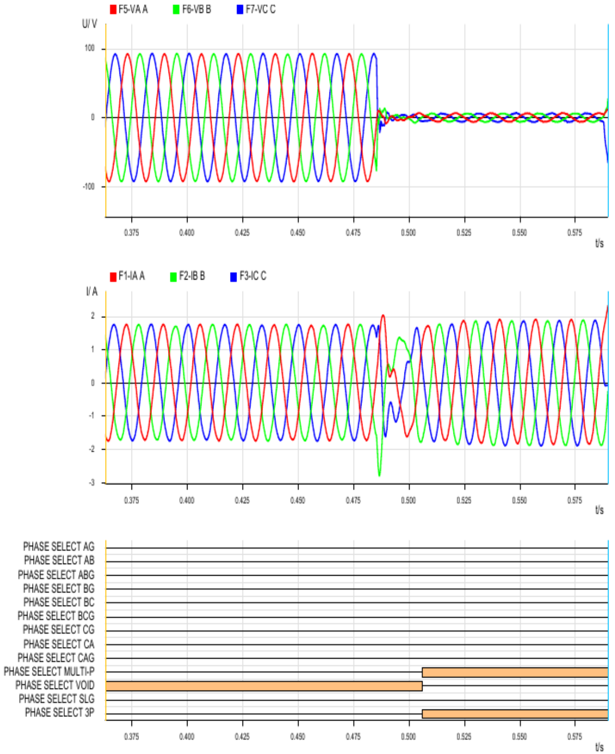
Reliable sequence voltages solve the problem



Relay securely selects AG fault

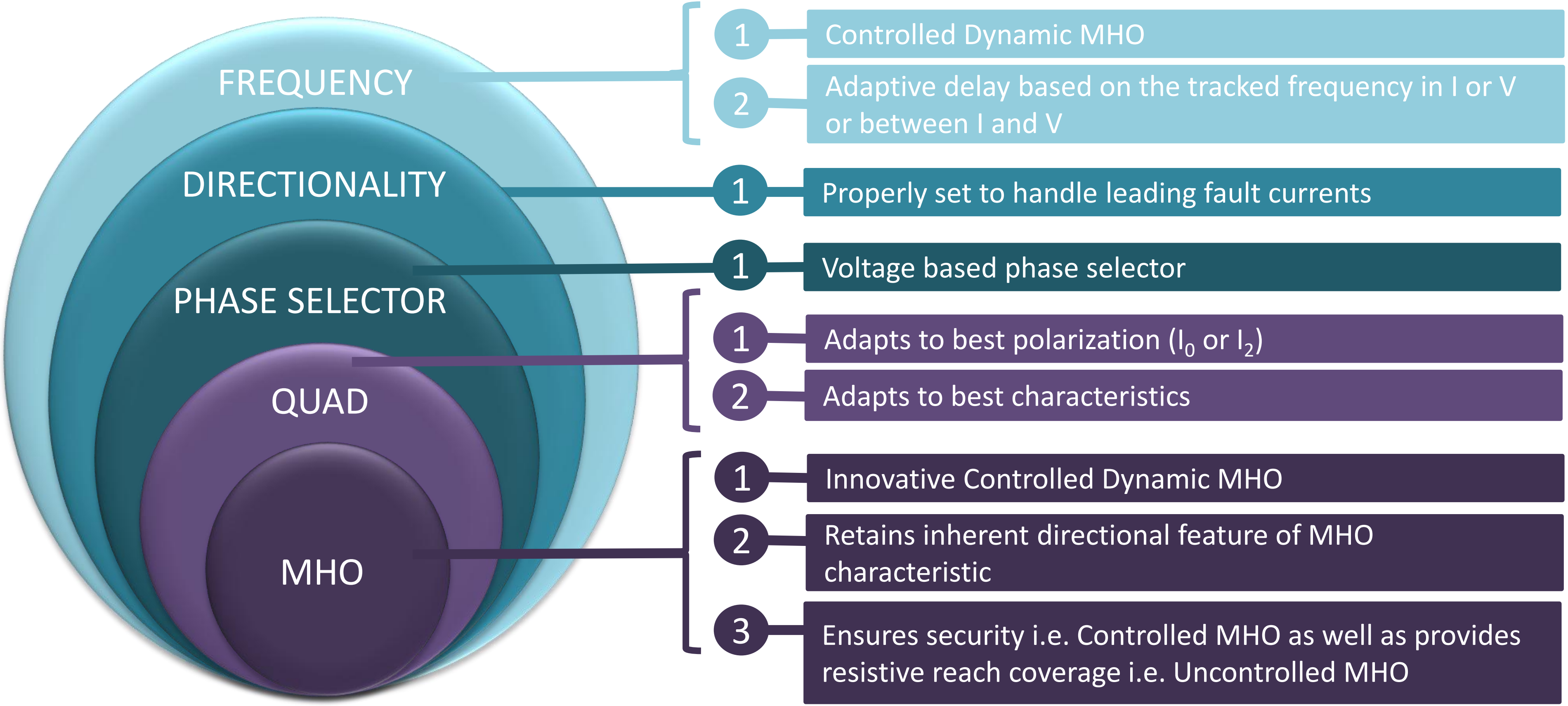


Relay securely selects AB fault



Relay securely selects ABC fault

Conclusions



FREQUENCY

1. Controlled Dynamic MHO
2. Adaptive delay based on the tracked frequency in I or V or between I and V

DIRECTIONALITY

1. Properly set to handle leading fault currents

PHASE SELECTOR

1. Voltage based phase selector

QUAD

1. Adapts to best polarization (I_0 or I_2)
2. Adapts to best characteristics

MHO

1. Innovative Controlled Dynamic MHO
2. Retains inherent directional feature of MHO characteristic
3. Ensures security i.e. Controlled MHO as well as provides resistive reach coverage i.e. Uncontrolled MHO

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