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CIGRE 2024 Paper on Transmission Line Protection

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A Review on Protection Challenges of Transmission Lines Connected to Inverter-Based Resources

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Outline

- Introduction to IBRs
- Motivation & Landscape of IBRs
- Protection Challenges with IBRs
- Impact of IBRs on Protection Elements & Potential Solutions
  - Line Differential Element
  - Distance Element
  - Directional Element
  - Phase Selection Element
- Conclusions

Introduction

Introduction to IBRs

Synchronous Generator (SG)

- Traditional rotating machines (e.g., coal, natural gas, hydro) that produce AC power directly through mechanical rotation.
- Natural coupling with the grid frequency due to their rotational inertia, providing stability to the power system.

Inverter-Based Resource (IBR)

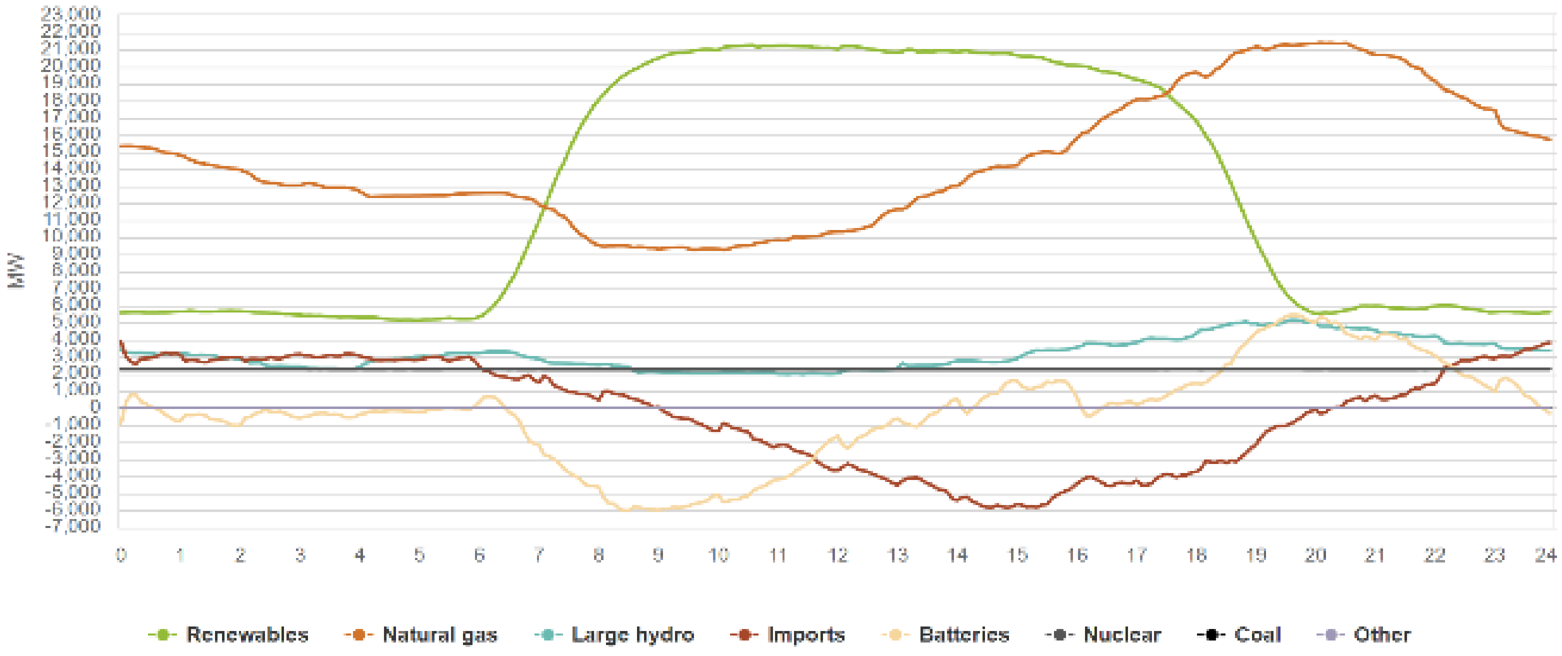
- Power generation sources that use inverters to convert direct current (DC) to alternating current (AC).
- Solar photovoltaic (PV) systems, wind turbines, and battery energy storage systems (BESS).

Motivation & Landscape of IBRs

- Growing demand for decarbonization and renewable energy sources
- IBRs contribute significantly to reducing reliance on fossil fuels
- IBRs, particularly solar and wind, have rapidly increased in the energy mix

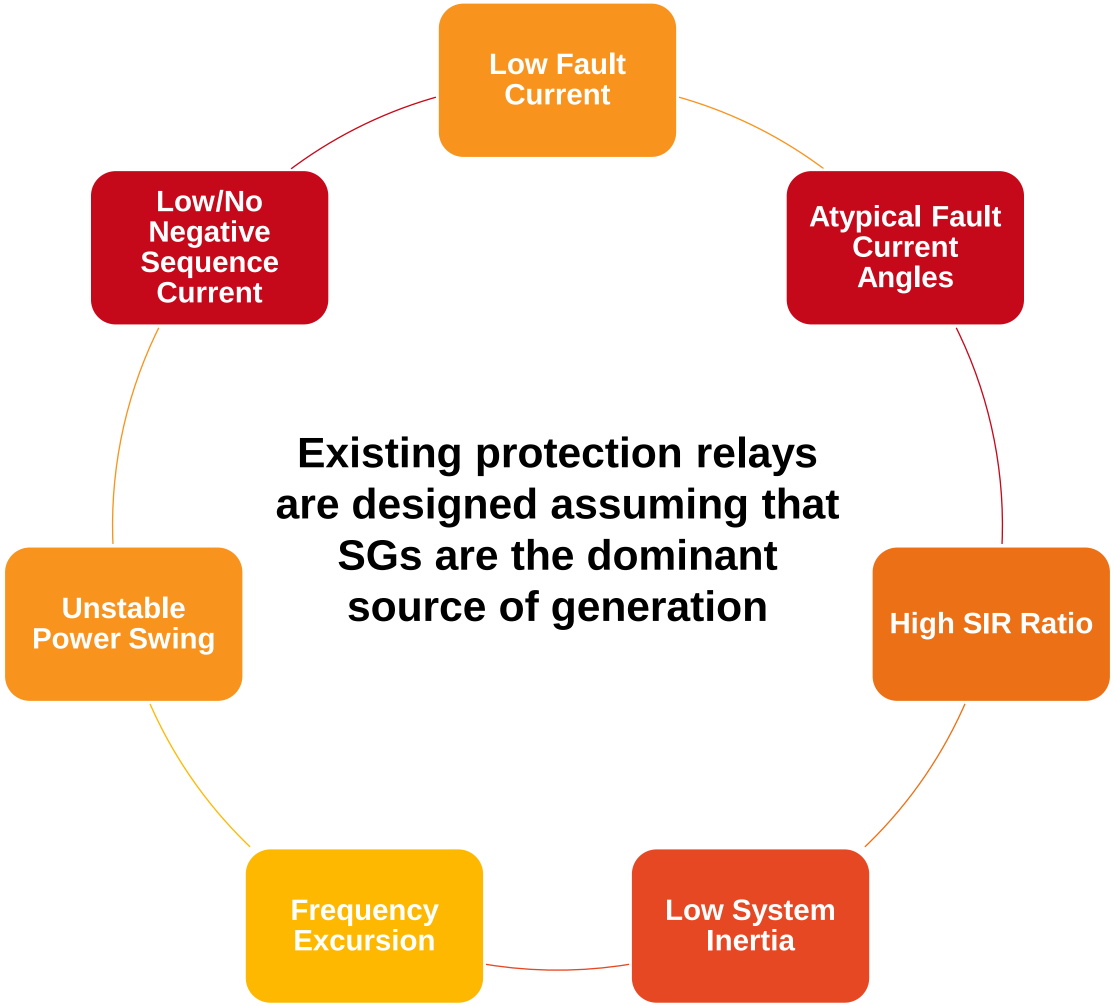
California – Example of IBR Growth

- California's IBR generation almost doubled between 2018 and 2024, covering over 58% of daytime demand



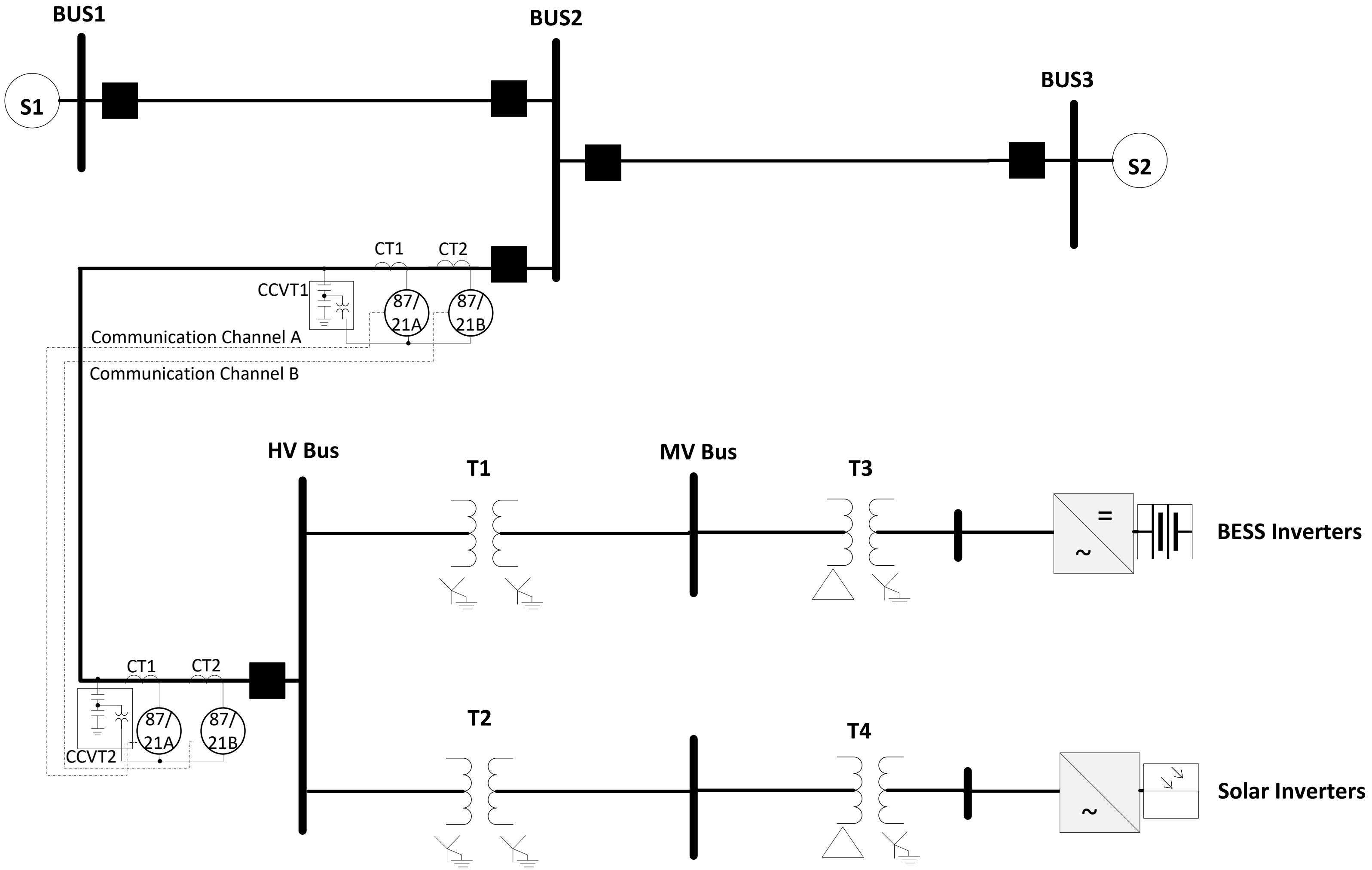
24-hour generation profile on July 9, 2024

Protection Challenges with IBRs



Impact of IBRs on Protection Elements & Potential Solutions

Typical Transmission Line Protection Scheme



Impact on Protection Elements – Overview

Line Differential

- Sensitive to current imbalances; challenges arise with IBRs due to limited and inconsistent fault current contribution.

Distance

- Designed to measure impedance, which can become inaccurate with IBRs' high SIR and oscillating fault currents.

Directional

- Determines fault direction, but accuracy is affected by IBRs' inconsistent negative-sequence currents.

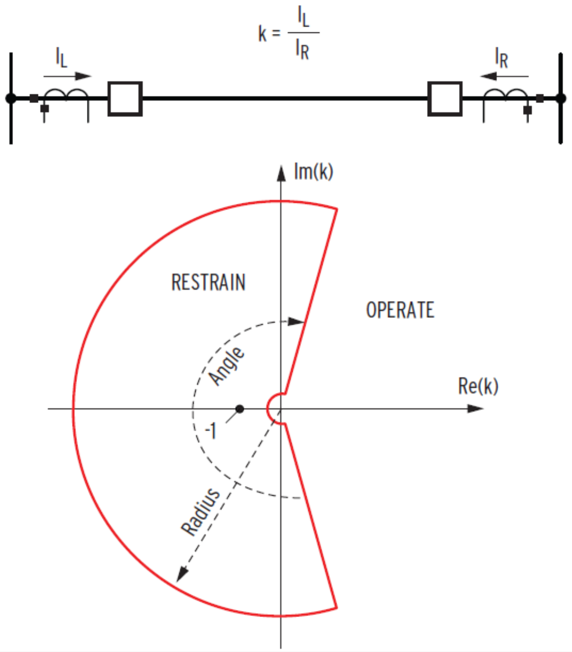
Phase Selection

- Identifies faulty phases; IBR characteristics can lead to incorrect phase selection.

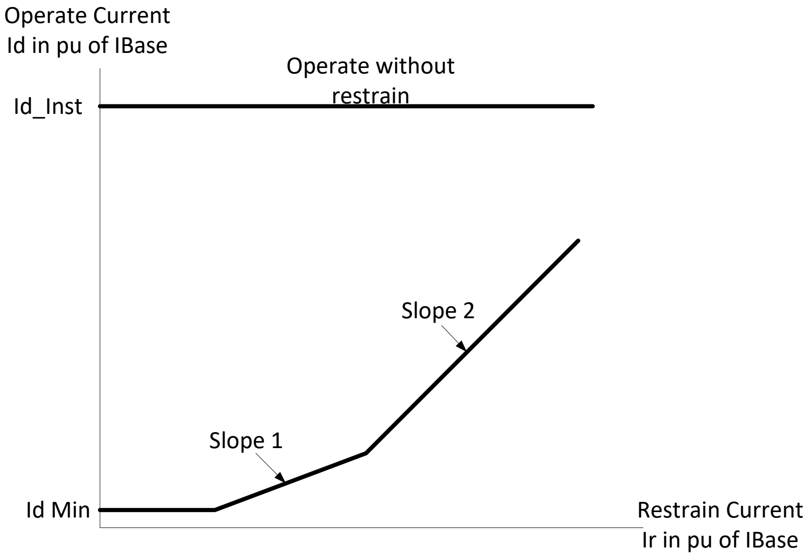
Line Differential Element – Operating Principle

- Compares incoming and outgoing currents.
- Operates on the principle of Kirchhoff's laws: the sum of currents at a node should equal zero.

Alpha-plane



Percentage Differential



Line Differential Element – IBR Impacts & Mitigation

Impact of IBRs

- Significant changes in un-faulted phase currents.
- Harmonics and weak negative-sequence current.

Challenges Faced

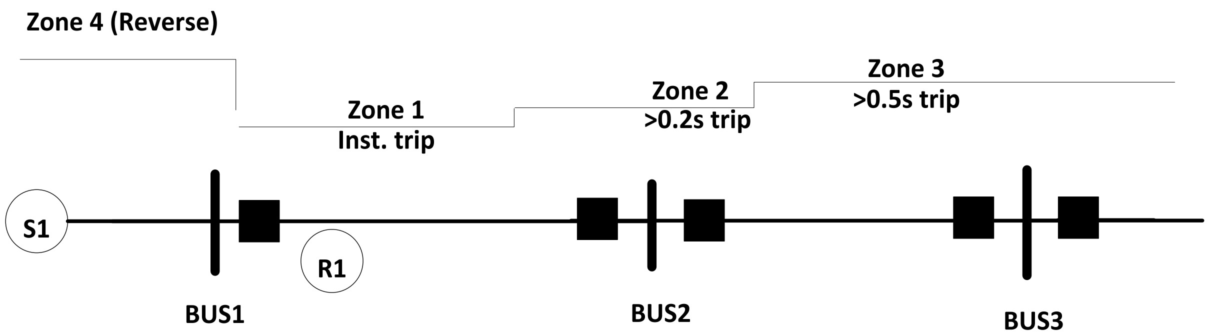
- Increased risk of relay misoperations
- Reduced effectiveness with longer line length

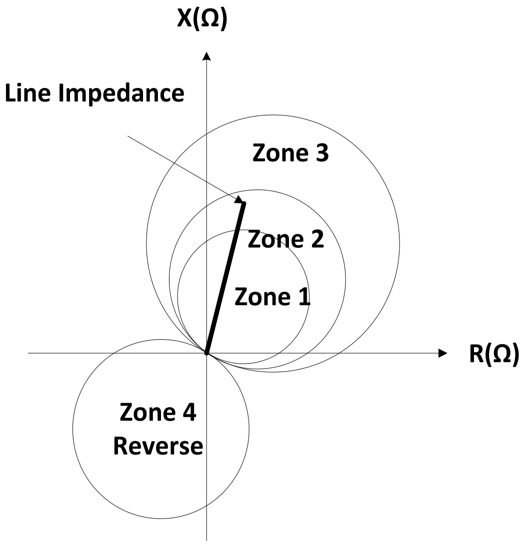
Mitigation

- Use with shorter transmission lines
- Backup and/or alternative schemes for longer lines

Distance Element – Operating Principle

- Measures the impedance between the relay location and fault location to detect and isolate faults within defined zones.
- Typically operates in three main zones: Zone 1 (instantaneous), Zone 2 (time-delayed), and Zone 3 (backup).





Distance Element – IBR Impacts & Mitigation

Impact of IBRs

- High SIR
- Oscillating apparent impedance
- Frequency excursions

Challenges Faced

- Risk of Z1 overreach
- Incorrect relay response

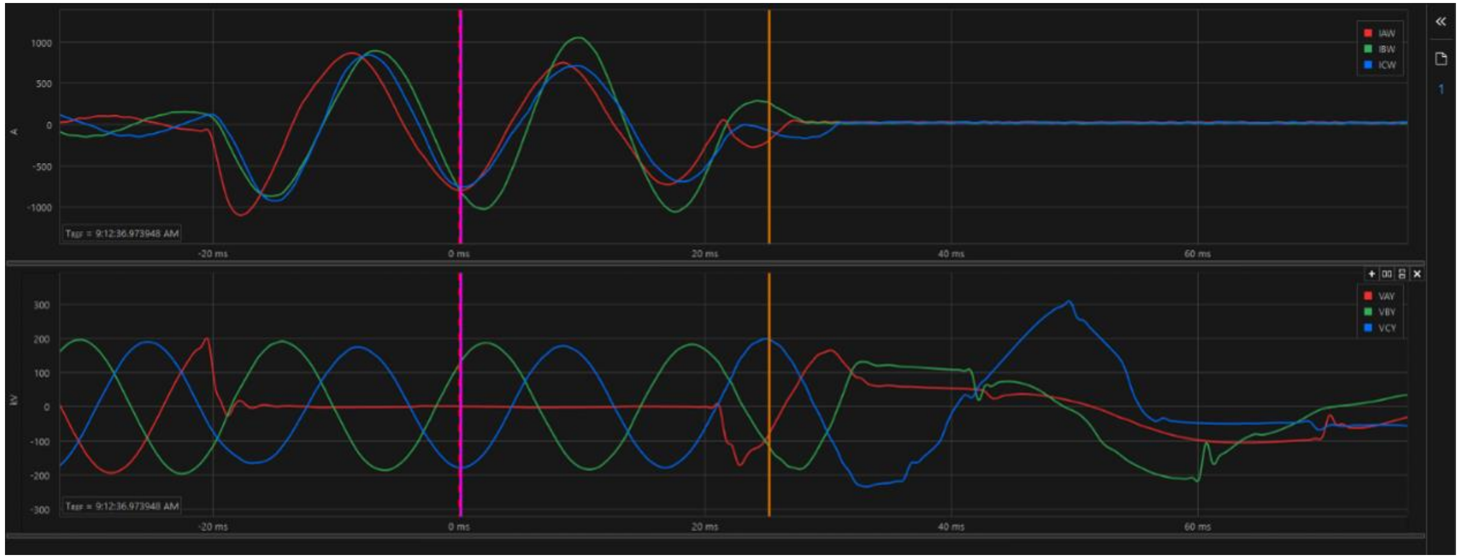
Mitigation

- Delay Z1 operation
- Increase fault detector levels
- Utilize transient blocking logic for CVTs

Directional Element – Operating Principle

- Determines the direction of the fault relative to the relay location by comparing the phase shift between fault current and reference voltage.
- Commonly uses negative- or zero-sequence components for directionality, especially in unbalanced faults.

Current and Voltage During Fault Conditions



Directional Element – IBR Impacts & Mitigation

Impact of IBRs

- Inconsistent Negative-Sequence Currents making directional elements less reliable.
- Unstable Polarizing Angles leading to incorrect fault direction
- Vendor Variability, further complicating directionality.

Challenges Faced

- Risk of false directional declaration.
- Increased likelihood of misoperation

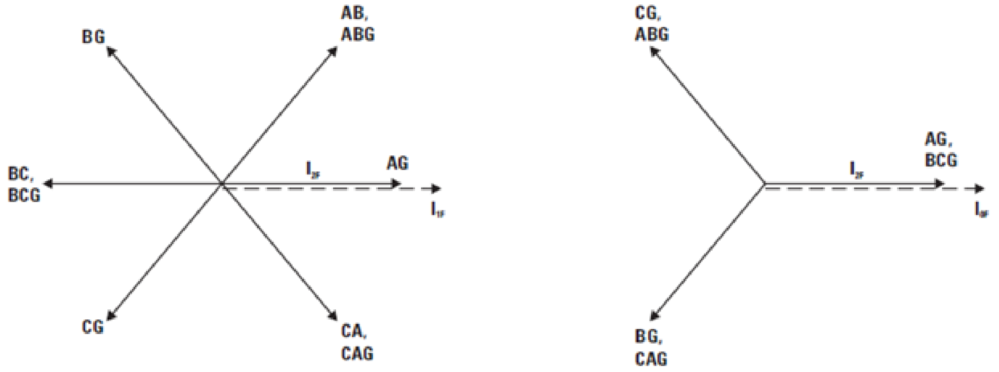
Mitigation

- Increase thresholds for negative-sequence current detection to improve reliability.
- Prioritize zero-sequence current as a polarizing quantity

Phase Selection Element – Operating Principle

- Identifies the specific phase(s) involved in a fault, which is crucial for accurate fault isolation and single-pole tripping.
- Utilizes phase angles between positive-, negative-, and zero-sequence currents to differentiate fault types (e.g., phase-to-phase, phase-to-ground).

Phase Selection Principle



Phase Selection Element – IBR Impacts & Mitigation

Impact of IBRs

- Reduced Negative-Sequence Current impacts phase selection accuracy.
- Sequence components do not stay at constant angle during a fault

Challenges Faced

- Inaccurate phase identification
- Increased risk of incorrect tripping

Mitigation

- Set priorities ground- and phase-directional polarization
- Decrease sensitivity of negative-sequence-based elements

Conclusion

Conclusion & Future Work

- **Summary of Key Challenges:**
  - High penetration of IBRs introduces unique protection challenges across multiple elements.
  - Traditional protection systems, designed for synchronous generators, are not fully suited to handle IBR characteristics like low fault current, unstable polarizing angles, and limited negative-sequence current.
- **Future Work:**
  - Continued development of industry standards for IBR fault behavior and further testing is critical for reliable system protection.
  - Advancements in modeling IBRs within protection software will enhance coordination and response strategies.

Addressing protection challenges with high IBR penetration is key to ensuring dependable and resilient grid operations as renewable energy continues to grow

Questions or Comments?

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