Relay Protection for Offshore Export Cables, Challenges and Solutions

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For power system expertise

Acknowledgements and context

This presentation is based on the paper

"Relay Protection for Offshore Export Cables, Challenges and Solutions"

Study Committee: SC B5 – Protection and automation

Preferential subject PS1: Integration of renewable energy resources to the grid

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Current role: Lead Protection Specialist at Ørsted Wind Power A/S

- Providing technical expertise to all our wind farms in operation
- Power system fault investigations, RCA and solutions
- Protection settings calculation
- 24/7 Remote protection support to wind farm operation

Previous role: Senior Protection Engineer

- Tendering and execution of large offshore wind farms

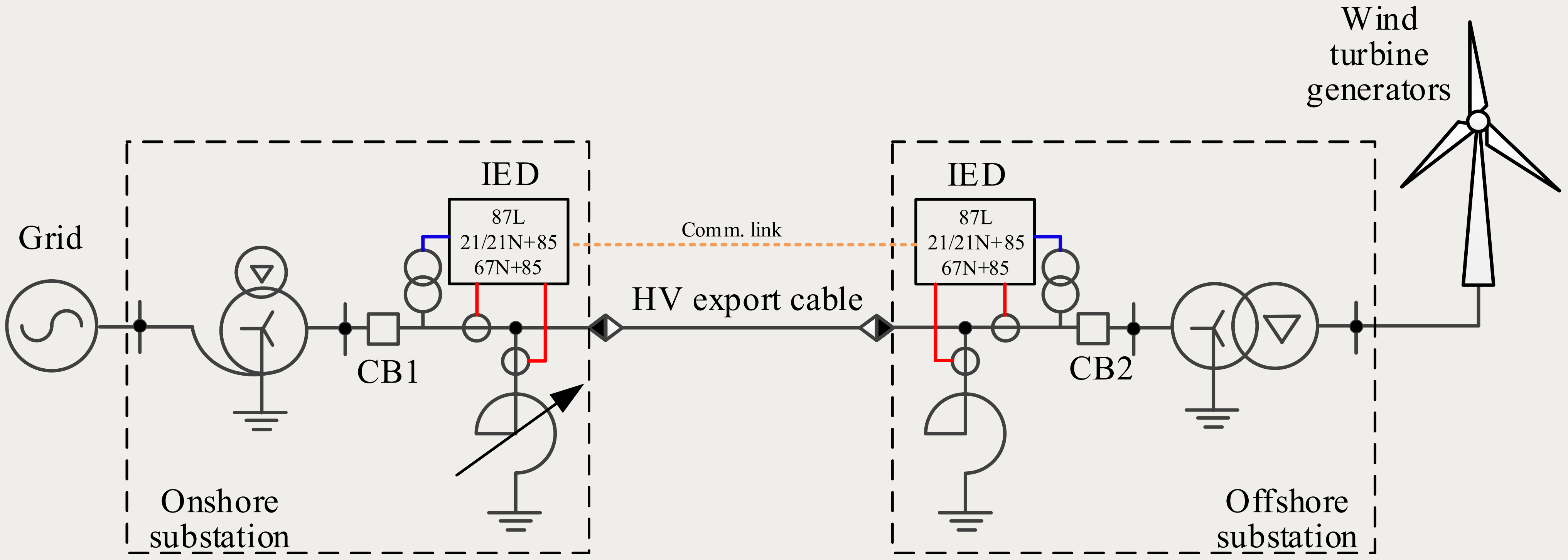
Educational background: MSc in Electrical Engineering from DTU - Denmark

Agenda

- Introduction
- Influencing factors
  - Cable capacitance
  - Wind turbine generators’ fault response
  - Ringing-down phenomenon
  - Power transformers configuration at cable ends
  - Inhomogeneous cable sequence impedance
  - Short circuit contribution from the grid side
- Line differential protection (87L)
- Distance protection (21/21N + 85)
- Directional earth fault protection (67N + 85)
- Key points

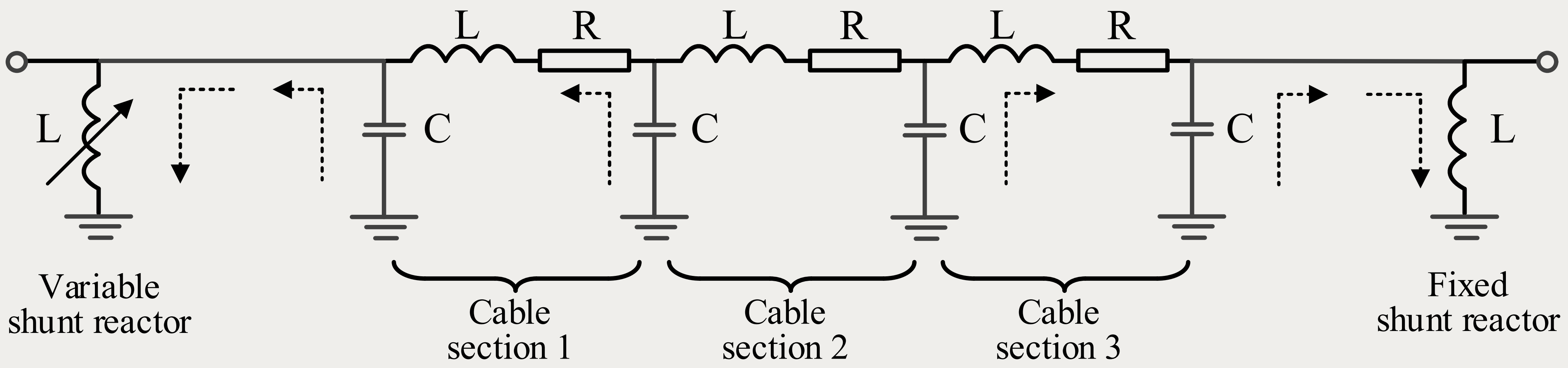
Introduction

Typical configuration of an offshore wind farm and export cable system



Influencing Factors
Cable capacitance

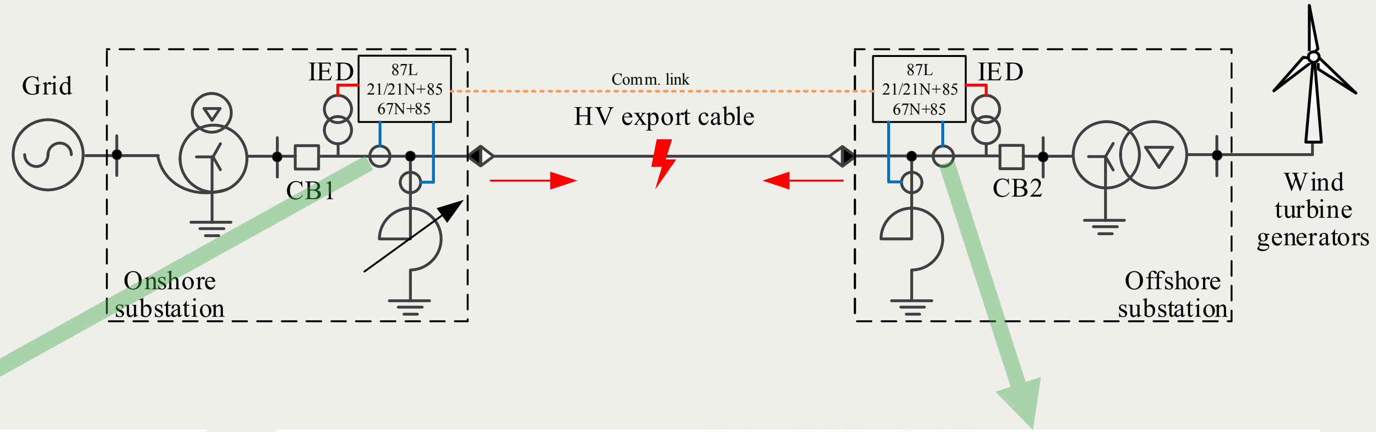
- Export cable system length may exceed 100 km and operate HV levels up to at 275 kV
- Charging current can be above 1000A
- Variable/fixed shunt reactors maybe switched in and out as needed

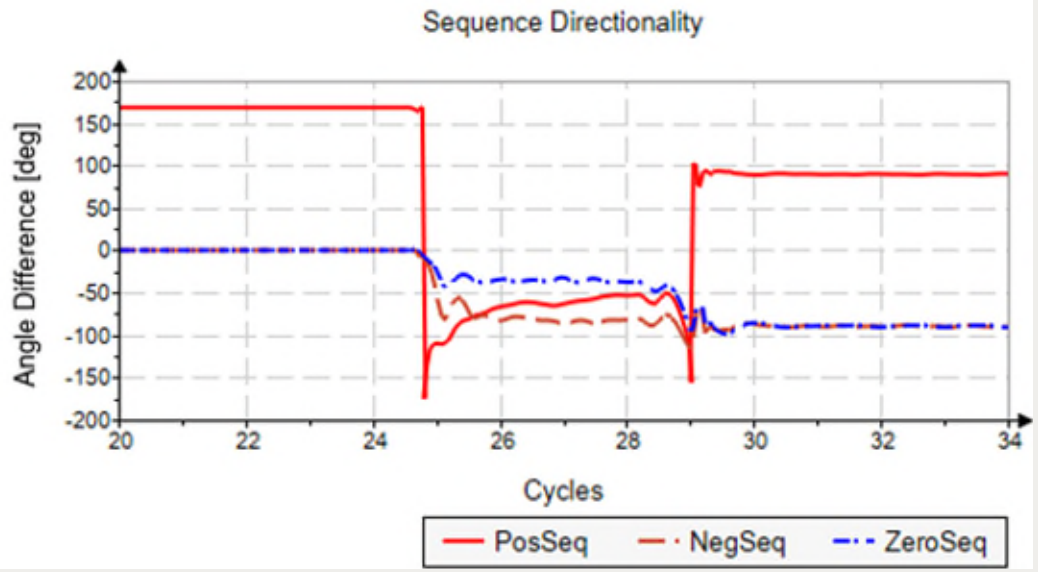


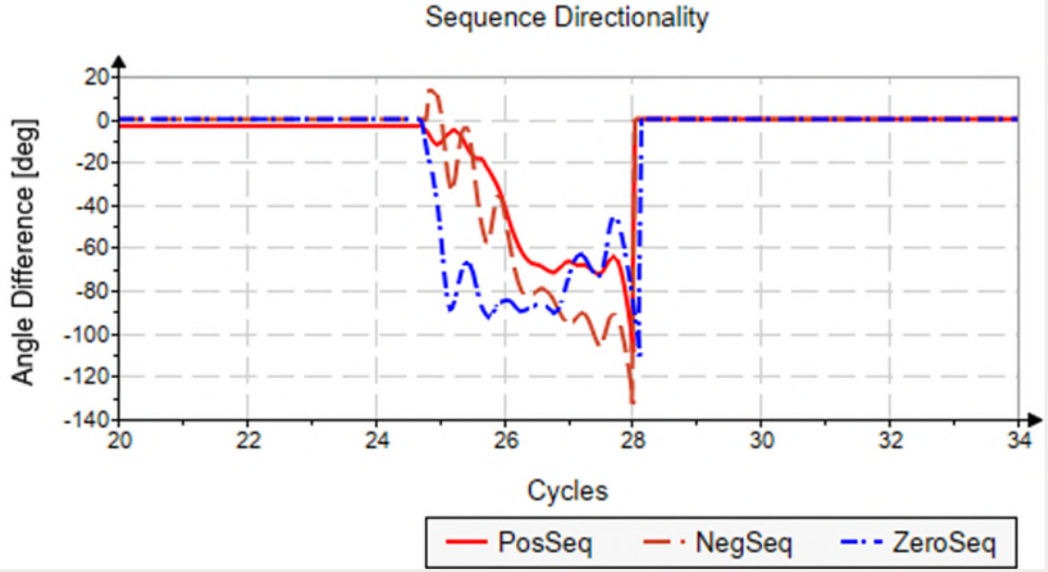
Influencing Factors
Wind turbine generators' fault response

Type IV machines:

- Source impedance is highly non-linear depend on control philosophy and dynamic fault response
- Limited fault current 0-1.1/1.3 p.u



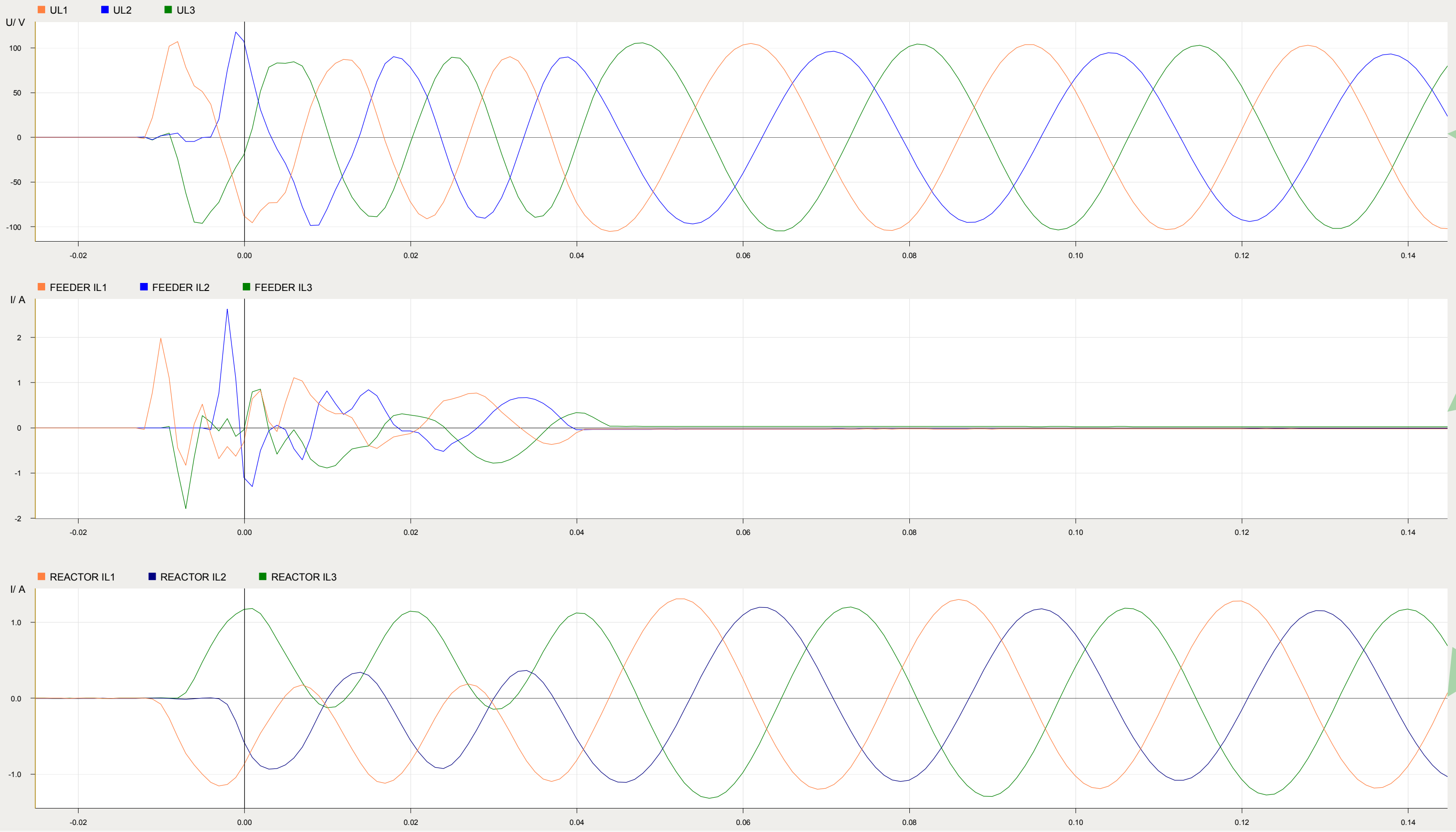


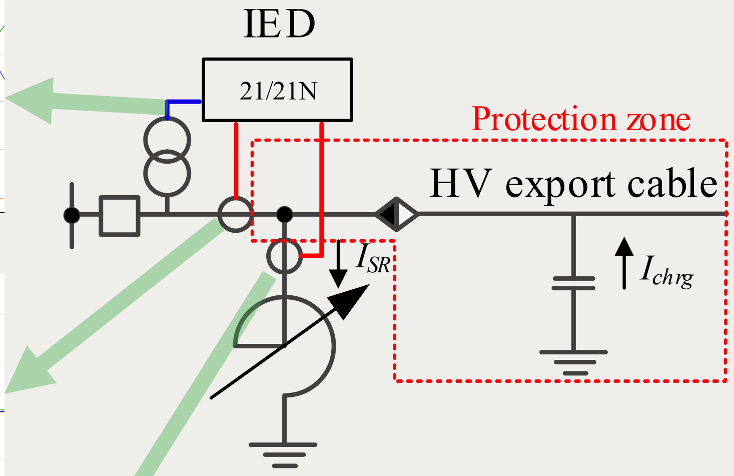


Influencing Factors

Ringing-down phenomenon

Ringing-down phenomenon for an export with a T-off SR during energisation and its subsequent trip

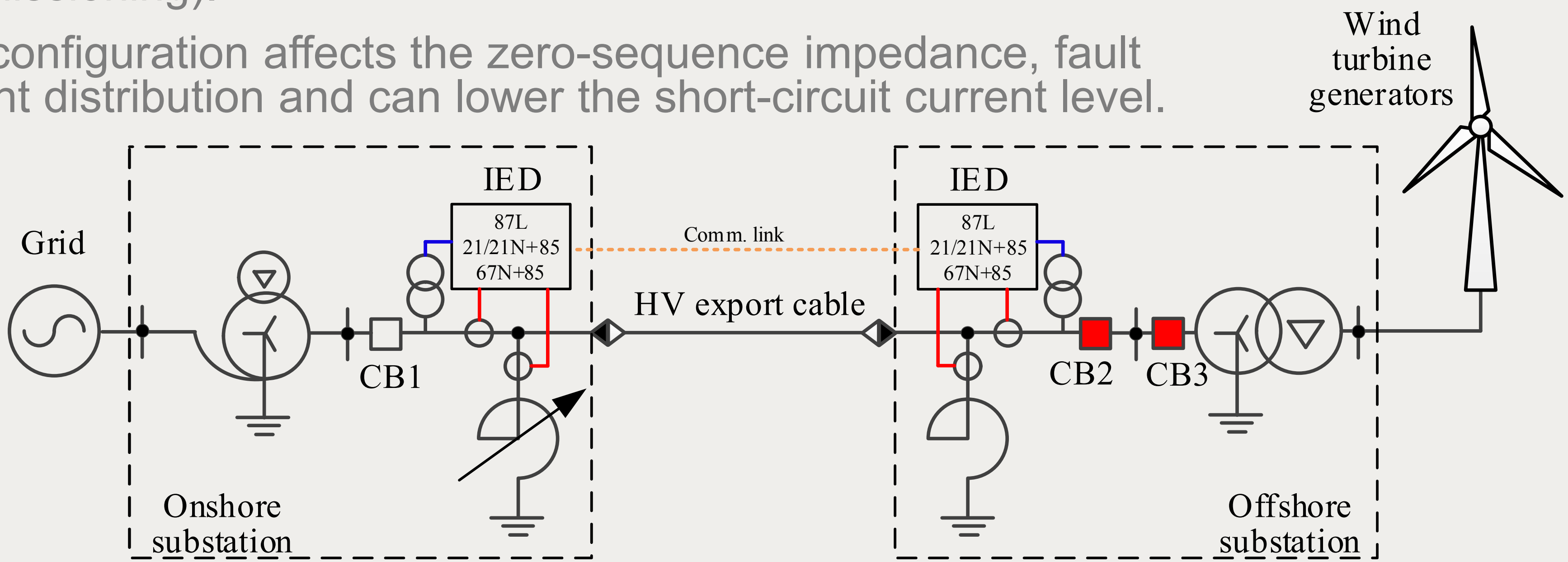




Influencing Factors

Power transformers configuration at cable ends

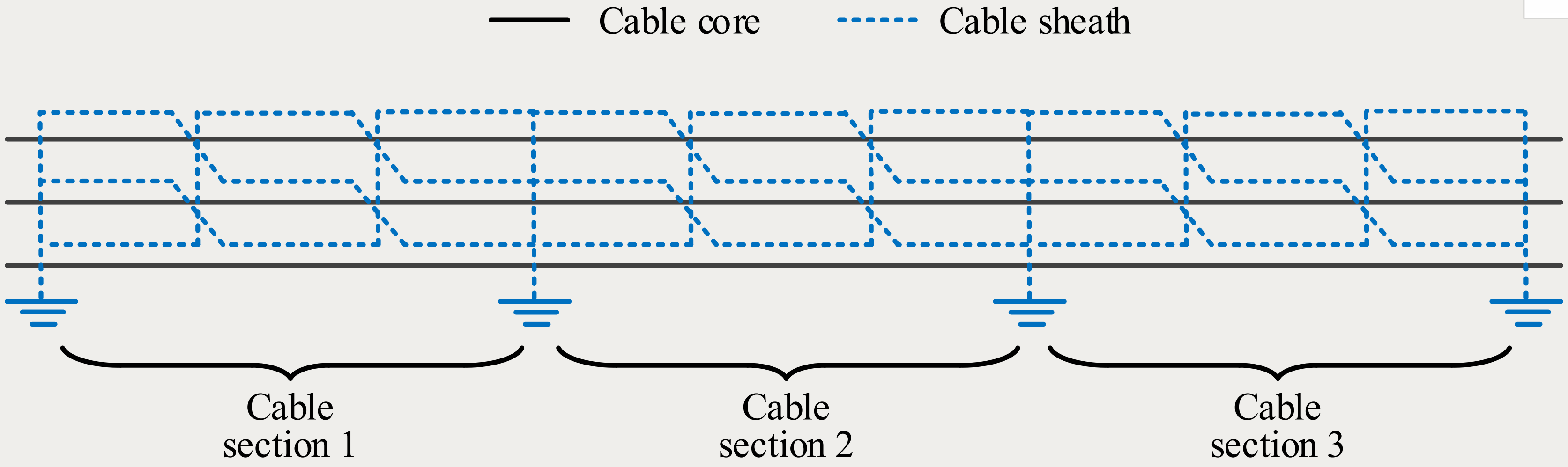
- The connection group and grounding configuration of power transformers at both export cable (EC) ends may vary.
- Typically, transformers with a solid grounded neutral are used at both ends to ensure stable protection operation.
- In certain operating scenarios, one end of the export cable may be without a solid ground - (e.g., during energization or commissioning).
- This configuration affects the zero-sequence impedance, fault current distribution and can lower the short-circuit current level.

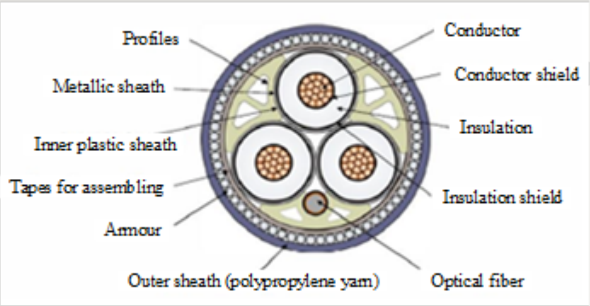


Influencing Factors

Inhomogeneous cable sequence impedance

- Inhomogeneous sequence impedance caused by differences in the export cable sections:
  - Length
  - Cross-section
  - Laying formation
  - Bonding of sheath (e.g., cross-bonding)
  - Mutual coupling effect from parallel cable routes





Influencing Factors

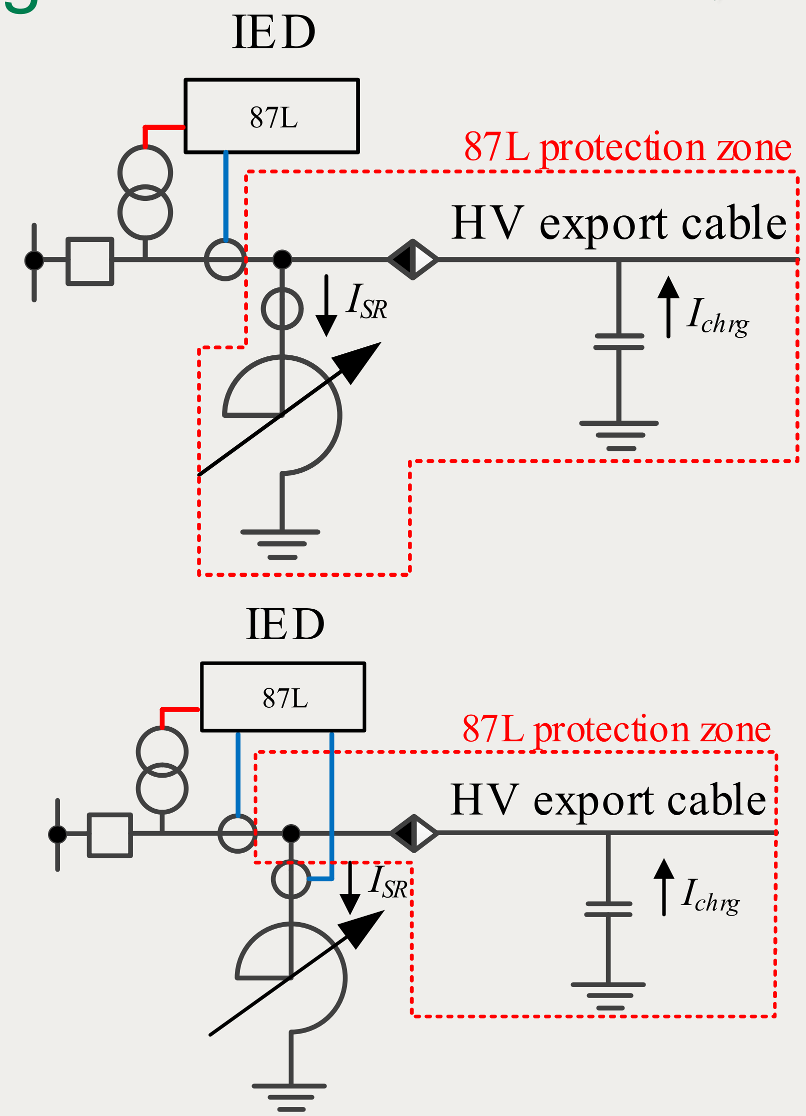
Short circuit contribution from the grid side

The protection system design must consider relevant contingency scenarios and potential/planned future changes to the grid.

- Large envelop for the short circuit level (Ikmin << Ikmax)
  - Affecting the sensitivity and coordination of protection schemes.
- Weak grid
  - Affecting the source impedance ratio (SIR)
- Strong grid
  - Affecting the grid-to-wind-farm infeed ratio

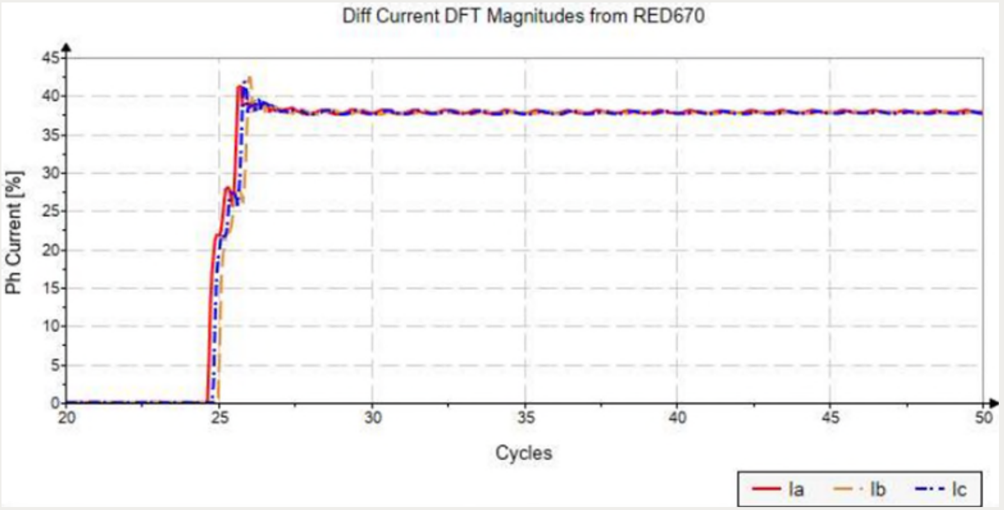
Differential Protection (87L) – Challenges

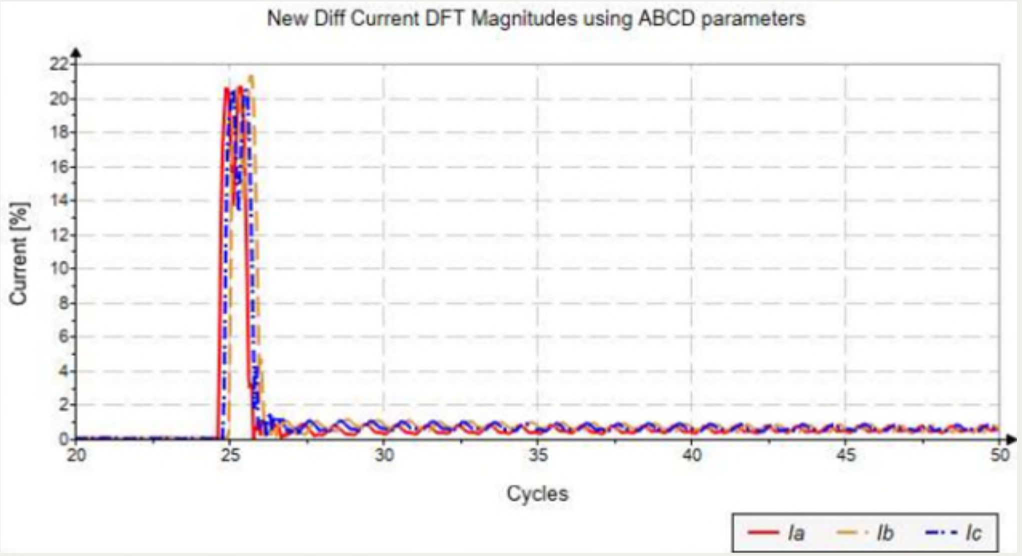
- 87L high pickup setting
  - Due to high charging currents
- Charging current compensation
  - Can lead to maloperation of 87L
- Inclusion or exclusion of the SR in the 87L protection zone
- Negative sequence-based criteria
  - Affected by inverter-based fault current contribution from the WTGs



Differential Protection (87L) – Solutions

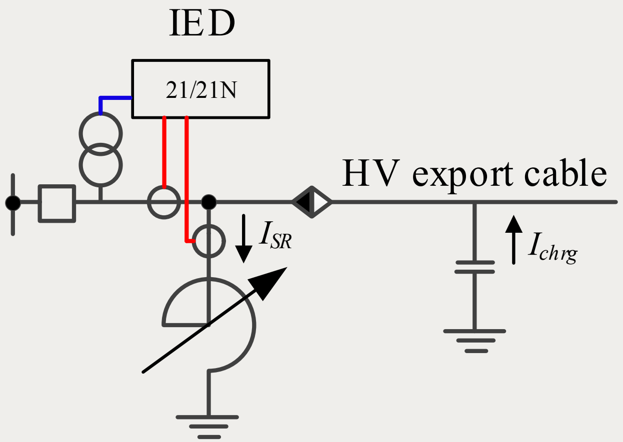
- Include fixed/variable shunt reactor in the 87L zone
- Avoid using charging current compensation
- Coordinate 87L with 1.5–2.5 times the charging current (for long export cable >2000A)
- Apply 67N + 85 and/or 21/21N + 85 for low short circuit scenarios
- Avoid negative sequence-based criteria
- New model-based differential protection that incorporates information about the cable sections and the state of the fixed/variable shunt reactors

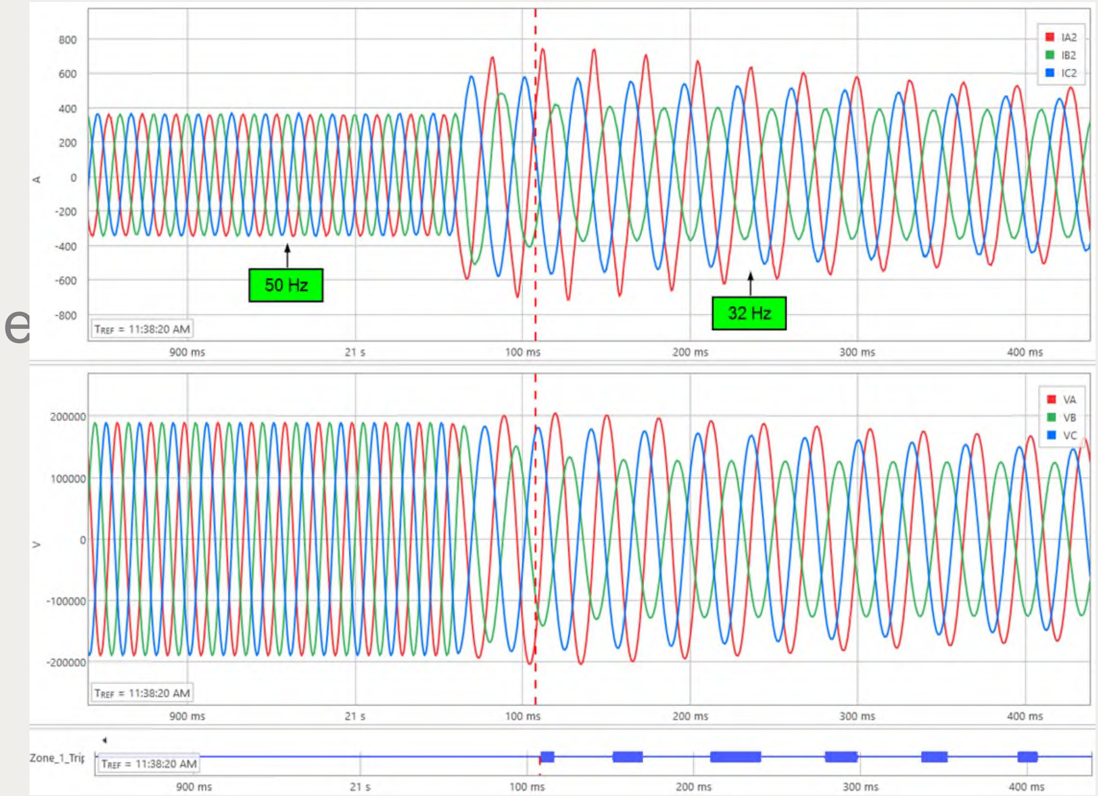




Distance Protection (21/21N + 85) – Challenges (1/2)

- Impact of cable capacitance are in general neglected and not well understood
- Earth fault compensation factor K_N is non-linear
  - Due to the inhomogeneous export cable system
- Ringing-down phenomenon leads to spurious tripping

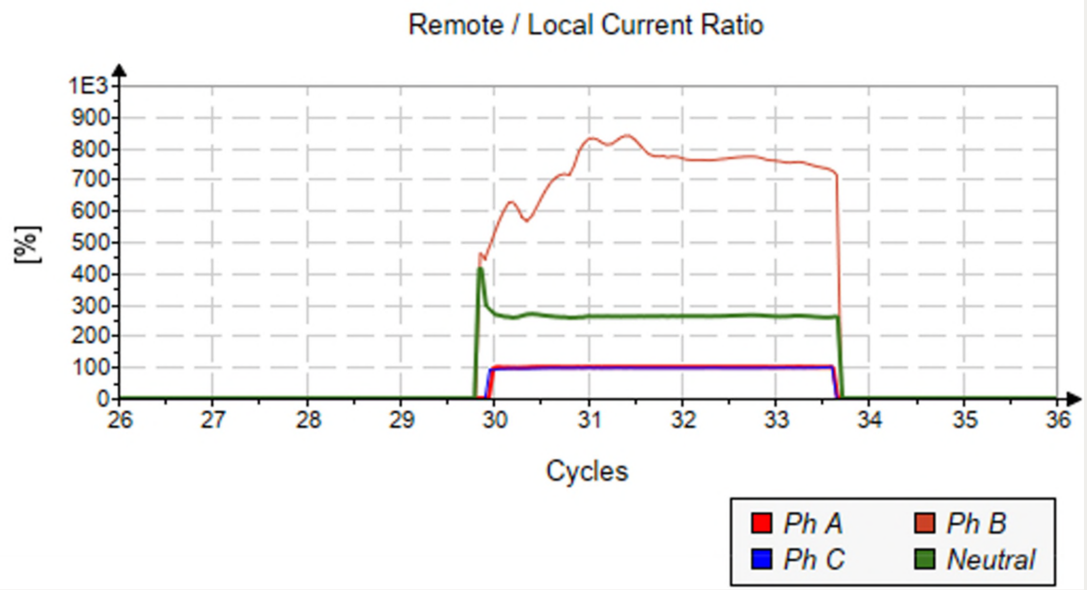




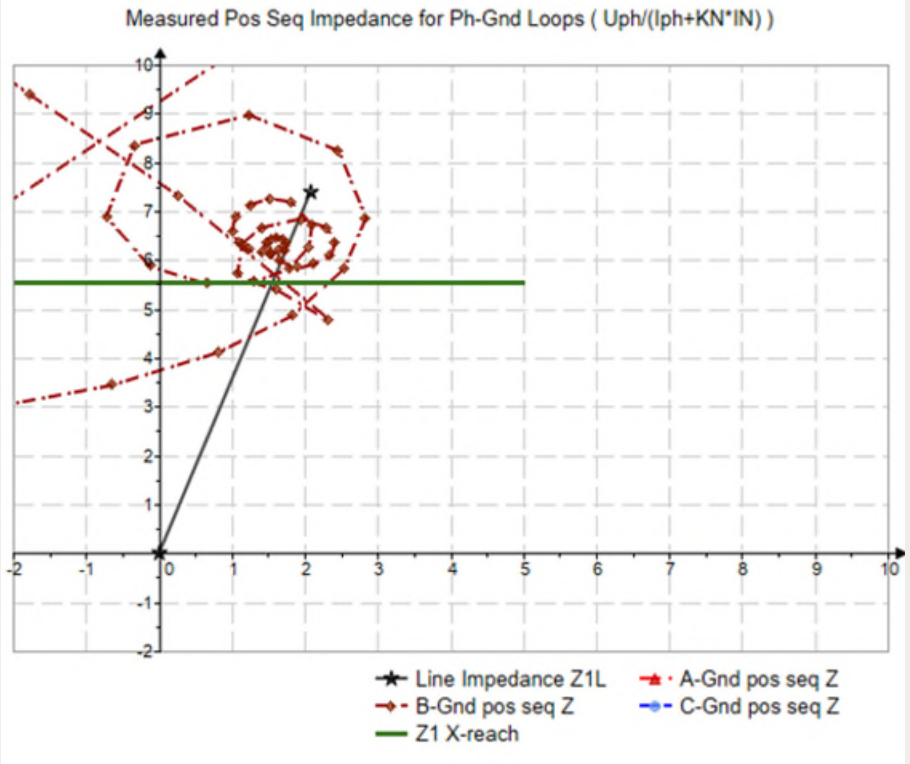
Zone 1 trip during de-energisation of 132 kV 46 km long export cable

Distance Protection (21/21N + 85) – Challenges (2/2)

- Grid-side to wind farm side infeed ratio
- Incorrect reach and direction determination



Remote/local current ratio a phase B-to-ground fault



Wind farm end impedance trajectory for phase B-to-ground fault at 100% of 60 km long export cable

Distance Protection (21/21N + 85) – Solutions

- Avoid using the shunt reactor branch measurement
- Do not apply traditional transmission protection setting philosophies indiscriminately
  - Apply special considerations for Zone 1 on the wind farm end. E.g.;
    - Add small time delay and consider shorter reach
    - Consider blocking Zone 1 if communication is ok and 87L not blocked
    - New time-domain distance protection may address several of the challenges
  - Apply 21/21N Zone 2 communication-aided schemes for faster fault clearance
  - Always transfer local trip to remote end
- Run power system simulations to clarify the compromises and risks
- Consult the OEM!

Directional Earth Fault Protection (67N) – Challenges (1/3)

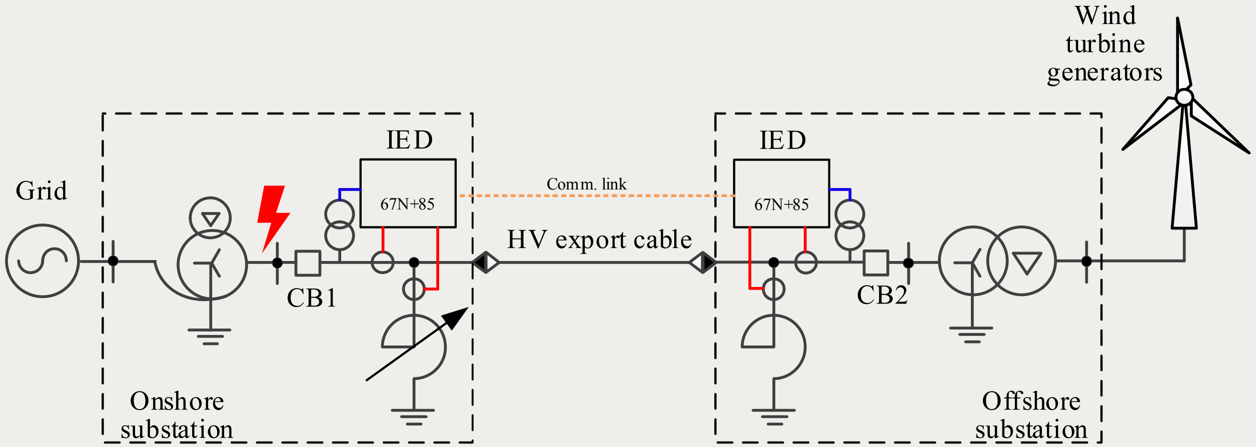
In certain operating scenarios the wind farm end do not have a solid earthing points:

- During construction and commissioning
- During contingency scenarios

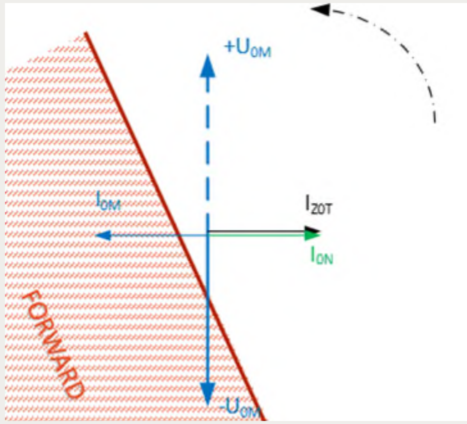
The open export cable end and the cable capacitance influences the Z0 impedance.

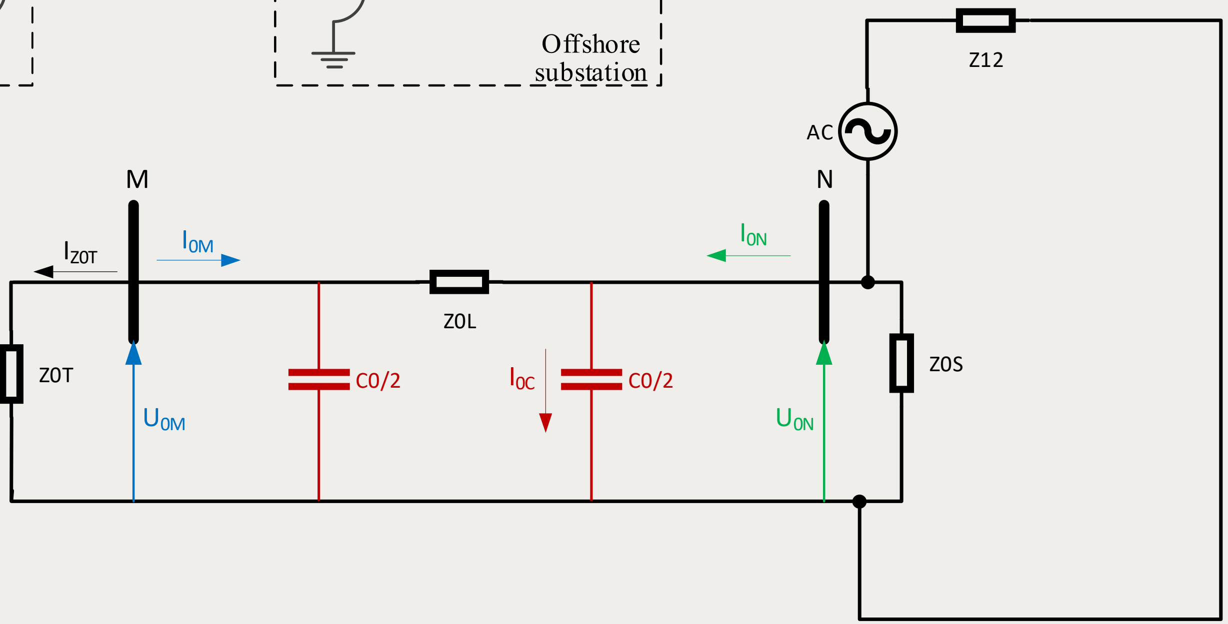
- Grid-side 67N susceptible to maloperation
- Negative-sequence 67Q is also affected by the same issue

Directional Earth Fault Protection (67N+85) – Challenges (2/3)



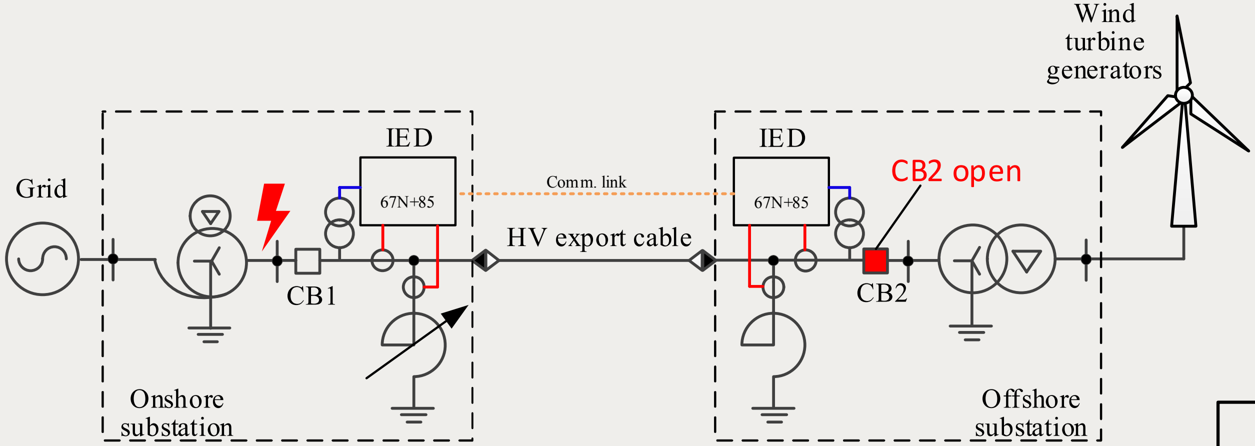
Counterclockwise rotation



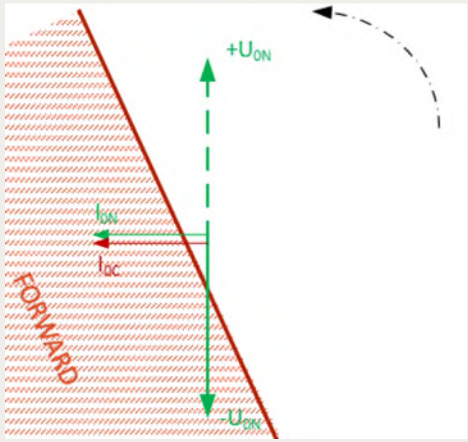


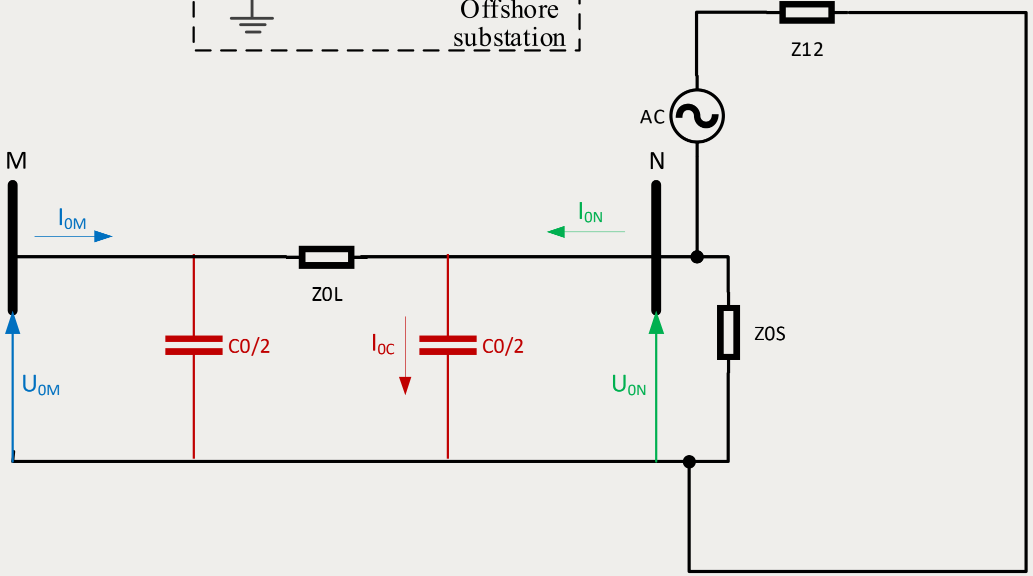
Phasor diagram and equivalent circuit for an EC external fault at the grid side end N. Circuit breaker at OWF end M is closed, offshore power transformer connected, RCA = 65°, 67N protection at bus M sees forward fault and 67N protection at bus N sees reverse fault

Directional Earth Fault Protection (67N +85) – Challenges (3/3)



Counterclockwise rotation





Phasor diagram and equivalent circuit for an export cable external fault at the grid side end N. Circuit breaker at OWF end M is open, offshore power transformer disconnected, RCA = 65°, 67N protection at bus N sees forward fault regardless the fact that fault is behind the IED

Directional Earth Fault Protection (67N) - Solutions

- Use power transformer with solid neutral grounding on both side of the export cable system
- Select higher pickup setting and/or longer time delay (67N)
- Carefully consider the suitable option for the communication-scheme (67N + 85)
  - Consider applying a permissive-scheme over a blocking scheme
  - When blocking scheme is used the reverse looking 67N has to be more sensitive than forward looking 67N element
- Select RCA based on studies (+65° - 90°)

Key points

- Unique challenges: high cable capacitance, WTG fault response, grid short circuit level, ringdown- phenomena and sequence impedance.
- Conventional protections (87L, 21/21N, 67N) may underperform.
- Protection systems must be tailored to offshore wind farm specific conditions to ensure reliability and accuracy.
- Consulting with relay experts from the manufacturers is essential for optimizing the performance, determining optimal settings, and developing new protection algorithms for future applications.