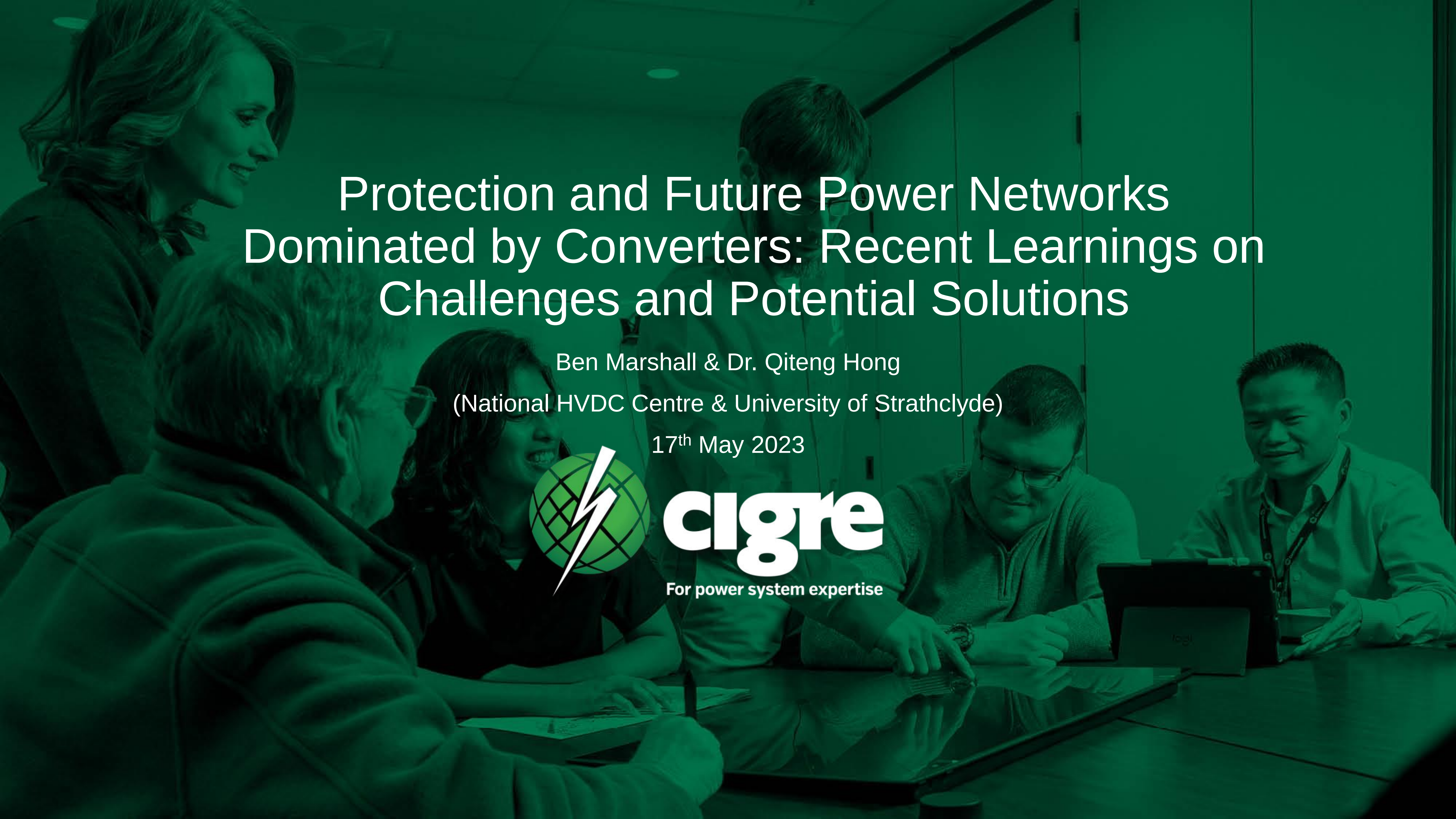


Protection and Future Power Networks Dominated by Converters: Recent Learnings on Challenges and Potential Solutions

Ben Marshall & Dr. Qiteng Hong

(National HVDC Centre & University of Strathclyde)

17th May 2023

For power system expertise

The National HVDC Centre – *About us*

The National HVDC Centre is an Ofgem funded simulation and training facility available to support all GB HVDC schemes.

Ofgem determination takes us from Innovation to BAU for RIIO-T2

The National HVDC Centre

part of Scottish & Southern Electricity Networks

together with nationalgrid SP ENERGY NETWORKS

The National HVDC Centre is part of Scottish & Southern Electricity Networks and is funded through the Electricity Network Innovation Competition as the Multi-Terminal Test Environment (MTTE) Project. Scottish and Southern Electricity Networks is a trading name of Scottish Hydro Electric Transmission plc, Registered in Scotland No. SC213461, having its Registered Office at Inveralmond House, 200 Dunkeld Road, Perth, PH1 3AQ; and is a member of the SSE Group www.ssen.co.uk

Tools

RTDS and HiL environment

(Enhanced Testing, Multi- Device Grid Integration, Protection & Control system, modification acceptance, post event investigation validation analysis)

Simulation environment (RTDS->EMT->RMS)

(Validation, Benchmarking, analysis)

Systems

Collaboration

(models, analysis, direction)

Codes, Standards, R&D

(expert input, workstream support)

The National HVDC Centre · SP ENERGY NETWORKS · Scottish & Southern Electricity Networks · nationalgrid · nationalgridESO · Grid Code · cigre · entsoe · EPRI ELECTRIC POWER RESEARCH INSTITUTE · PROMOTioN PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Skills

Structured Training

(Webinars, Courses, Application & Implementation)

Control training

(Operator Certification, Scenario Planning, Updates)

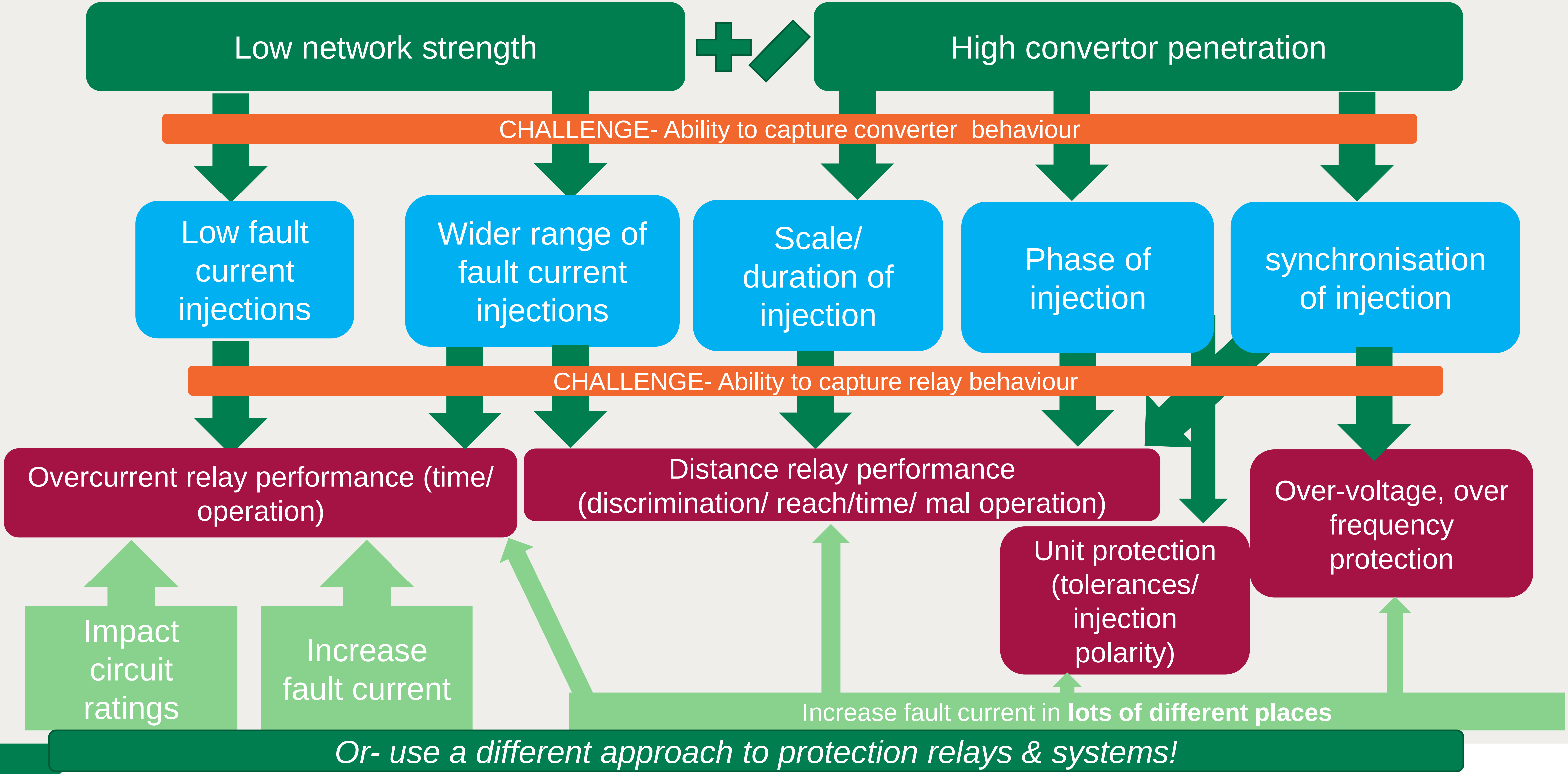
Research dissemination

(Analysis Techniques, Risk Quantification, Solution Definition)

What am I going to talk about..

- Why classical approaches to Protection relays can encounter problems?
- Why should we be interested in this.
- How can we understand & address/ test the problem?
- Why we are interested in this?
- What are the options?
- NIA PSL-FC; what is it doing & why.

So what's the problem?



Low network strength

+/

High convertor penetration

CHALLENGE- Ability to capture converter behaviour

Low fault current injections

Wider range of fault current injections

Scale/ duration of injection

Phase of injection

synchronisation of injection

CHALLENGE- Ability to capture relay behaviour

Overcurrent relay performance (time/ operation)

Distance relay performance (discrimination/ reach/time/ mal operation)

Unit protection (tolerances/ injection polarity)

Over-voltage, over frequency protection

Impact circuit ratings

Increase fault current

Increase fault current in **lots of different places**

Or- use a different approach to protection relays & systems!

Why are we interested?

- Net Zero= transition to convertor technologies (wind, solar, batteries)
- New approaches to convertor control, e.g. Grid forming.
- Increase in interconnection & HVDC grid reinforcement.
- HVDC largest of convertor injections of fault current-
  - What do we want these to do?
  - How do we want protection to perform?
- By 2030 more convertors than typical demand.
- By 2030 as much Scotland-England transmission via HVDC as via AC

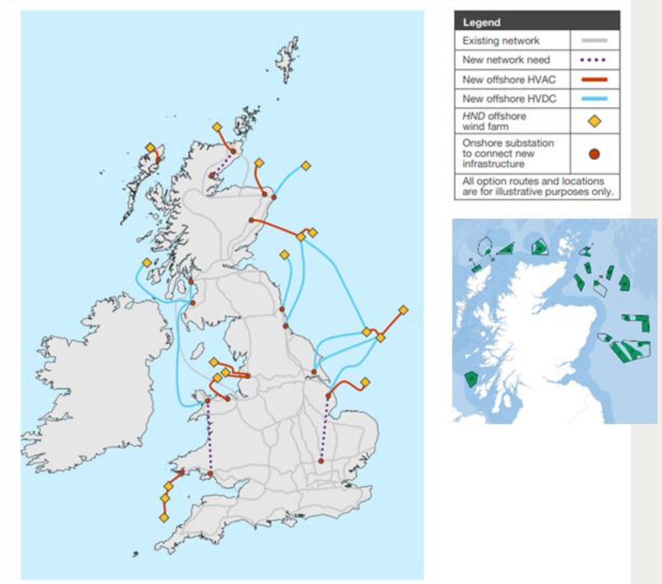


Figure 2: The new network needs identified through the HND.

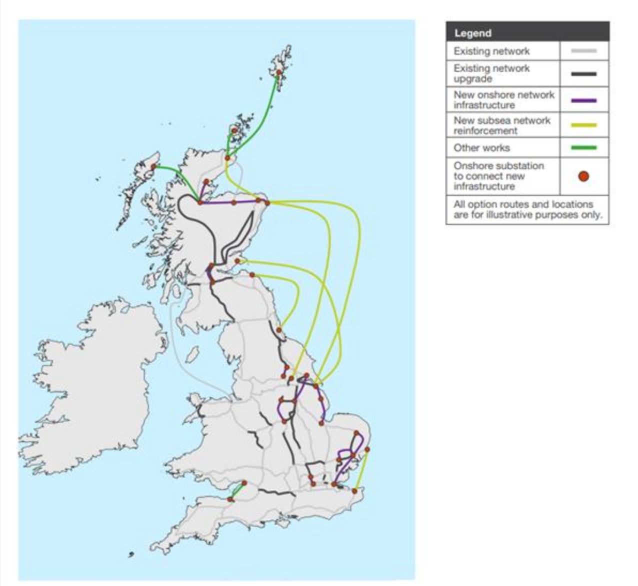


Figure 1: Those recommendations that have been identified as necessary previously.

National Grid ESO, Holistic Network Design: https://www.nationalgrideso.com/document/262676/download

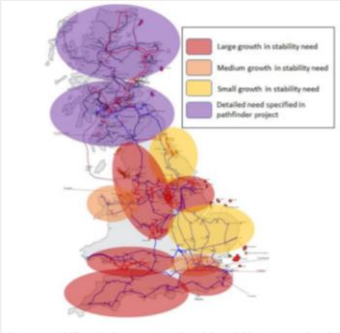
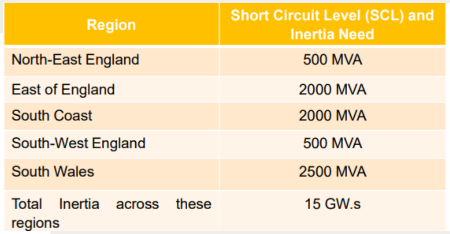
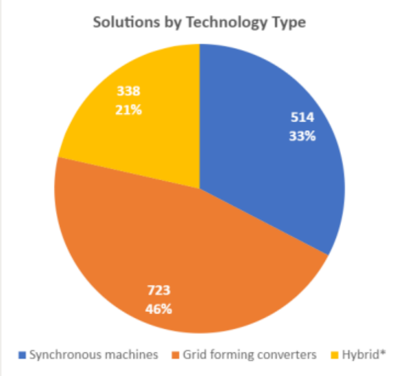


Figure 2: Stability needs across GB electricity grid (Source: National Grid ESO)



Region	Short Circuit Level (SCL) and Inertia Need
North-East England	500 MVA
East of England	2000 MVA
South Coast	2000 MVA
South-West England	500 MVA
South Wales	2500 MVA
Total Inertia across these regions	15 GW.s



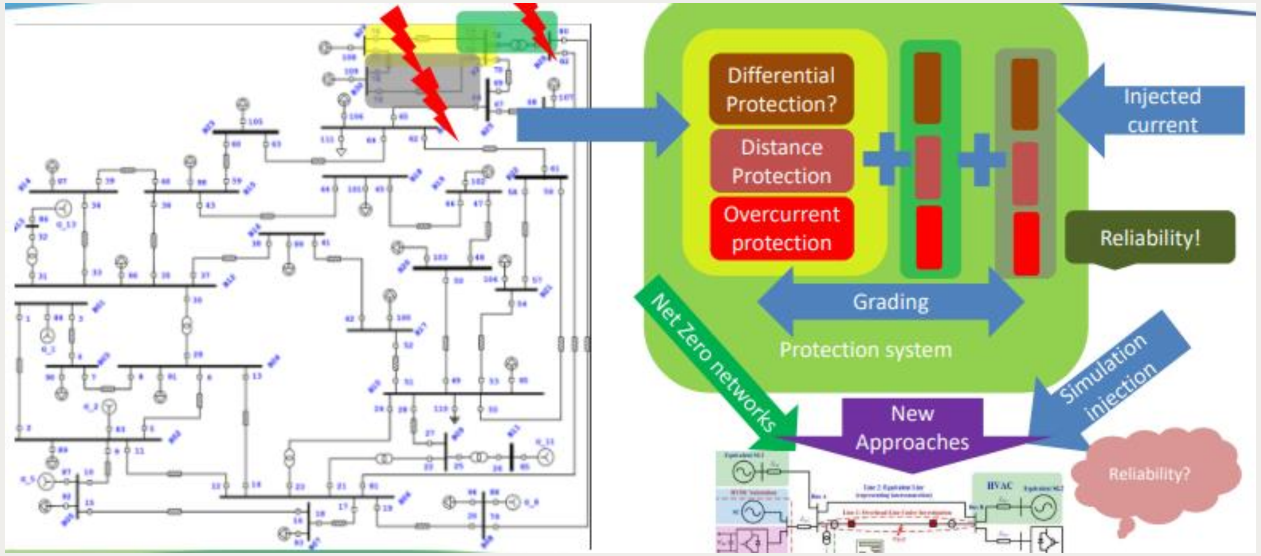
Solutions by Technology Type

[NOA Stability Pathfinder | ESO (nationalgrideso.com)](https://www.nationalgrideso.com)

How to address/ understand this-

Understanding requires-

- RT-CHIL of system areas,
  - Real protection devices,
  - Real protection systems & strategies
  - Real converter behaviour,
  - Real protection systems,
  - Real performance.



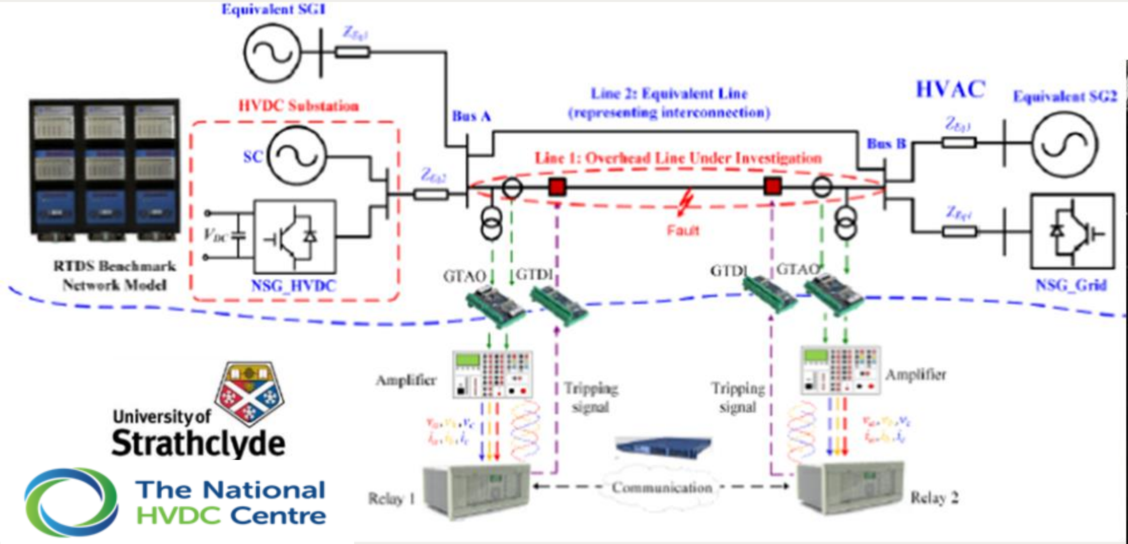
Testing requires-

- Either the above,

or

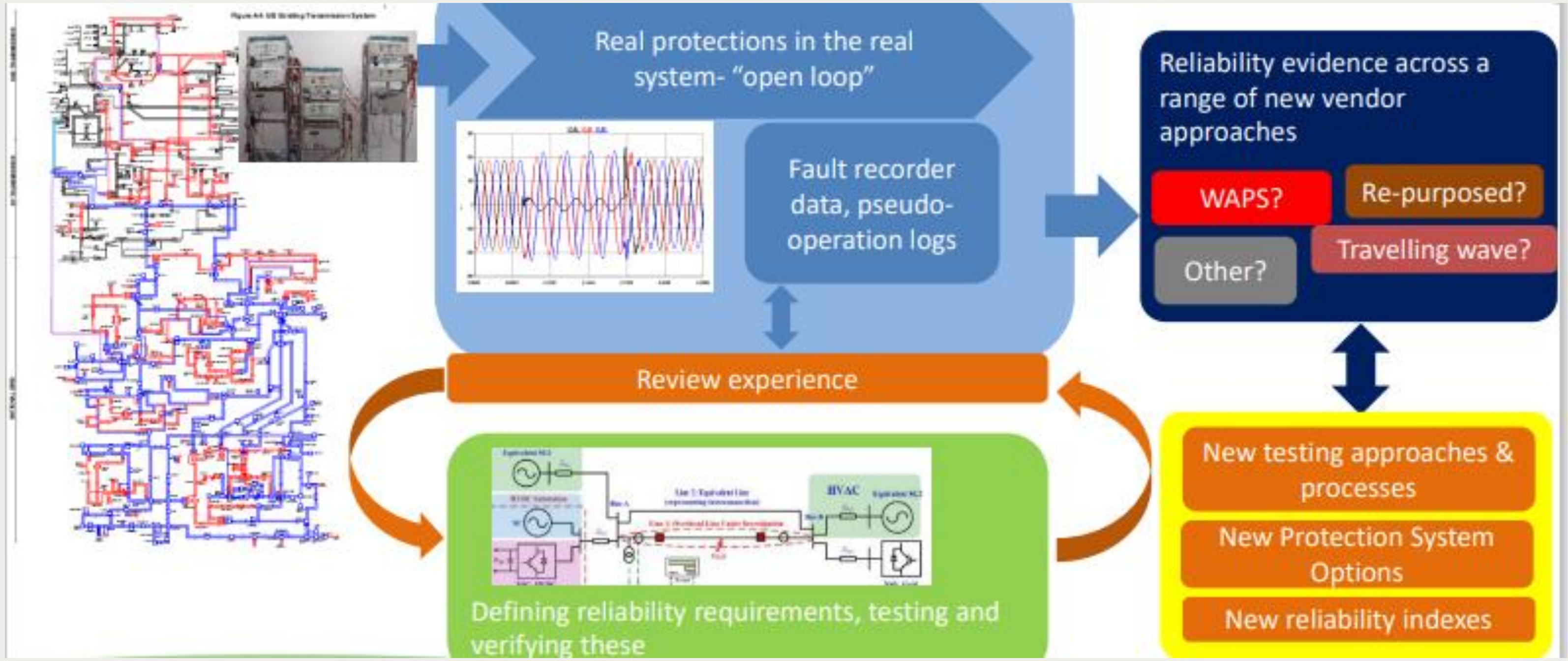
- A representative test bench informed by the above to test the individual components

If behaviour and performance need can be sufficiently distilled.



Testing new solutions

- Open loop= testing the real responses of relays to real system behaviour without the relays then acting on the network.
- Solutions less dependent on the magnitude and polarity of current
- Solutions more complex with greater dependency/ vulnerabilities, e.g. upon communications
- New performance criteria
  - Additional tests
  - Additional data for setting
- New overall protection systems & philosophies



Real protections in the real system- "open loop"

Fault recorder data, pseudo-operation logs

Review experience

Defining reliability requirements, testing and verifying these

Reliability evidence across a range of new vendor approaches

WAPS?

Re-purposed?

Travelling wave?

Other?

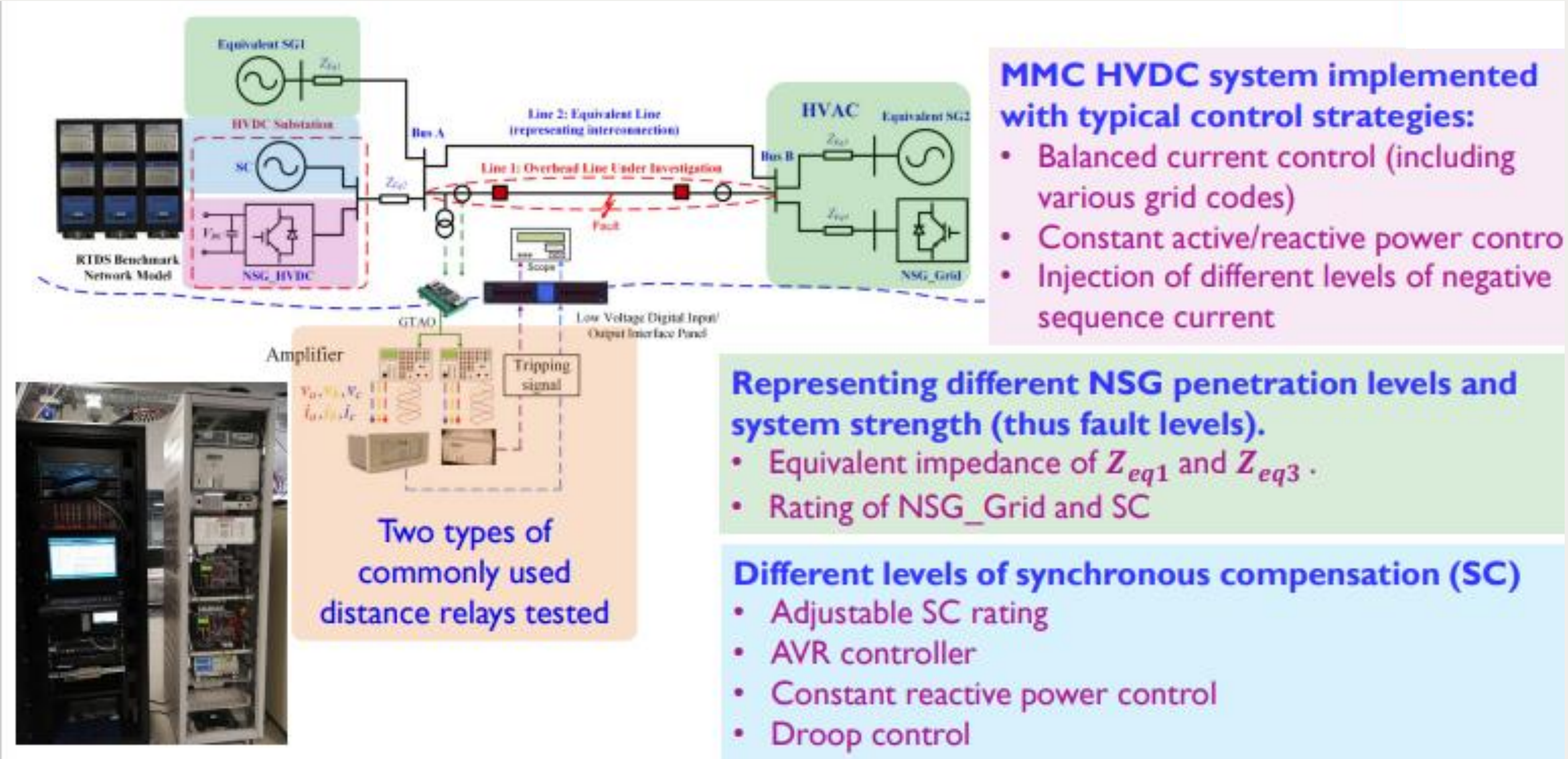
New testing approaches & processes

New Protection System Options

New reliability indexes

NIA Protection solutions Project - what is it/ why are we doing it?

- Previous work identified and quantified protection risks to conventional resources
- We now are using an adapted test bench working with UoS, SSEN and vendors to explore and demonstrate solutions



Two types of commonly used distance relays tested

MMC HVDC system implemented with typical control strategies:

- Balanced current control (including various grid codes)
- Constant active/reactive power contro
- Injection of different levels of negative sequence current

Representing different NSG penetration levels and system strength (thus fault levels).

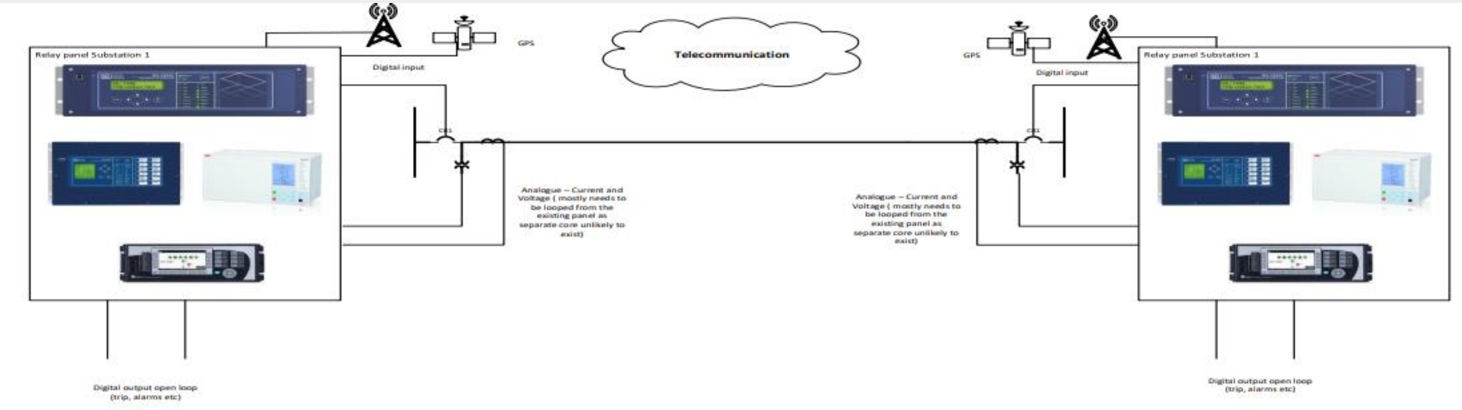
- Equivalent impedance of Z_{eq1} and Z_{eq3} .
- Rating of NSG_Grid and SC

Different levels of synchronous compensation (SC)

- Adjustable SC rating
- AVR controller
- Constant reactive power control
- Droop control

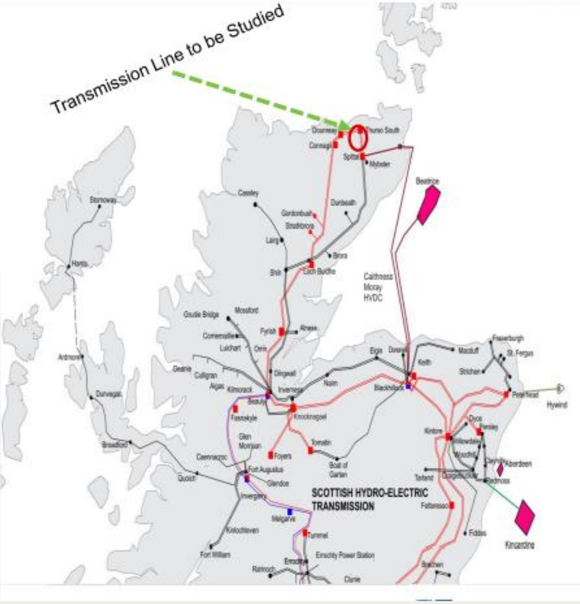
NIA Protection solutions Project- Key Highlights.

- We have simulated a range of options
- We have identified an “open loop” demonstration location.
- We ***have*** now progressed a range of tests, and ***defined*** monitoring and ***are setting up*** for open loop demonstration



Line Protection Schemes Planned :

- ➢ Distance Protection
- ➢ Neutral Current Differential Protection
- ➢ Line Differential Protection
- ➢ Travelling wave protection



Thank you!

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Protection and Future Power Networks Dominated by Converters: Recent Learnings on Challenges and Potential Solutions

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University of Strathclyde
17/05/2023

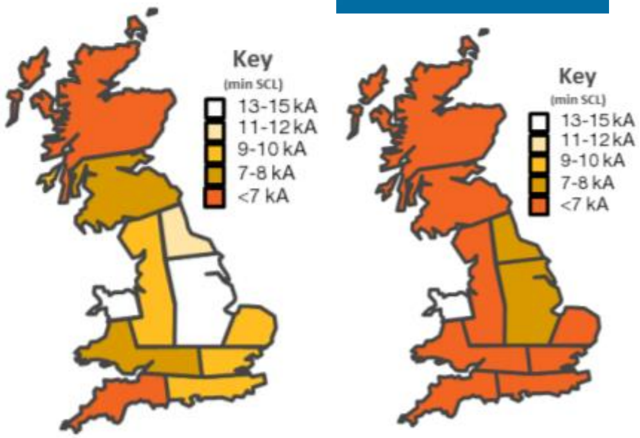
Overview

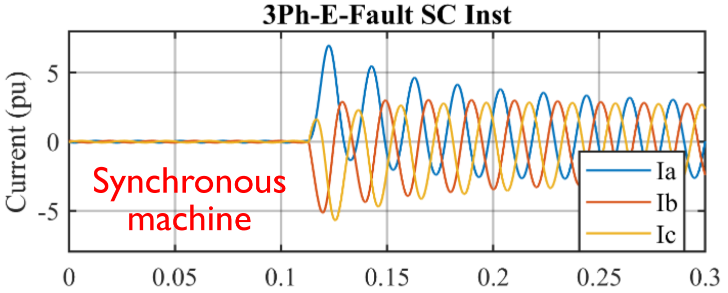
- **Research Background**
- **Assessment of fault level required for protection**
- **Impact of converter control on protection performance**
- **Explored potential solutions**
  - Travelling wave protection
  - Revised distance protection
  - Refined control to facilitate protection operation
- **Conclusions**

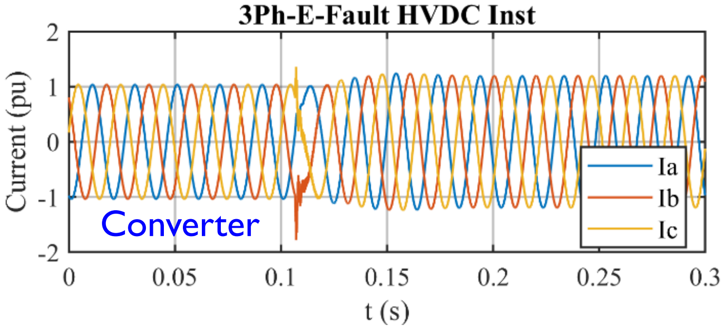
Research Background

- **Rapid increase Converter-Based Resources (CBRs)**
- **Significant changes to system fault behaviour**
  - Reduced fault level
  - Control-dependent fault characteristics
- **Risks of compromised AC protection performance**

- **Our research focuses on:**
  - Assessing impact of reduced fault level and CBR control on protection performance
  - Understanding causes for protection failure
  - Developing new protection solutions/revising existing protection algorithm for CBR dominated systems
  - Refining CBR control to support protection





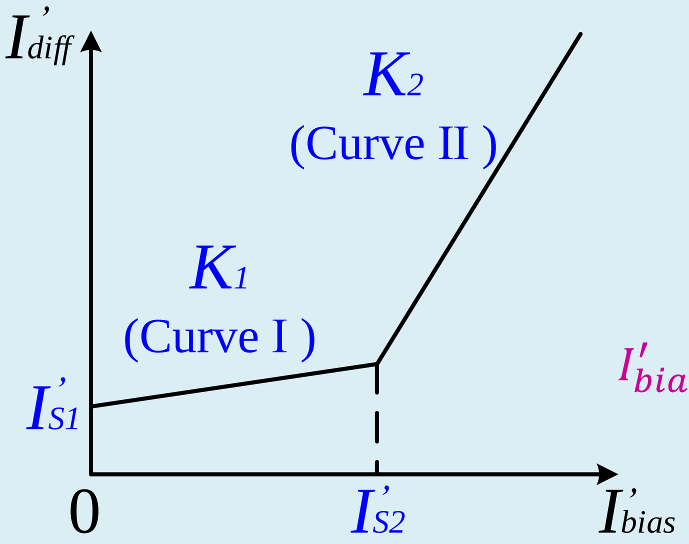


How Much Fault Level is Required for Protection?

Assessment of Fault Level Required for Differential Protection

Differential protection characteristics

$$I'_{diff} = |I'_1 + I'_2|$$

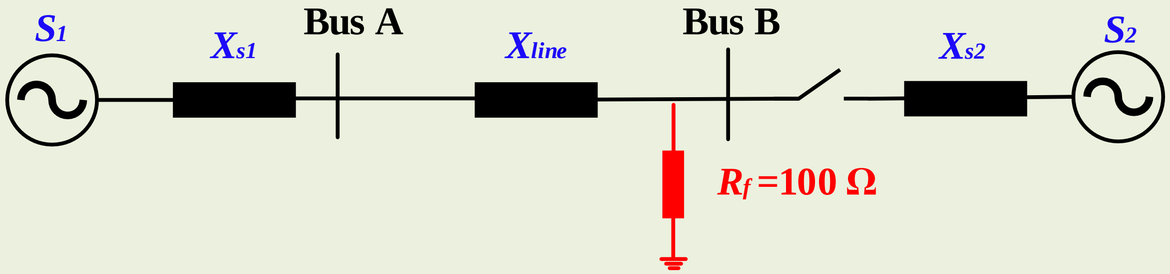


$$I'_{bias} = \frac{|I'_1| + |I'_2|}{2}$$

- I'_1 and I'_2 are the secondary currents at two ends of the protected line

Differential protection requirements

To ensure dependability:



Capable of detecting worst case scenario:

- Single-end source with no pre-load
- Able to detect high resistance earth fault (100 Ω used in the study)

Assessment of Fault Level Required for Differential Protection

Differential protection zone:

1. I'_{bias} on Curve 1: $I'_{bias} \le I'_{S2}$

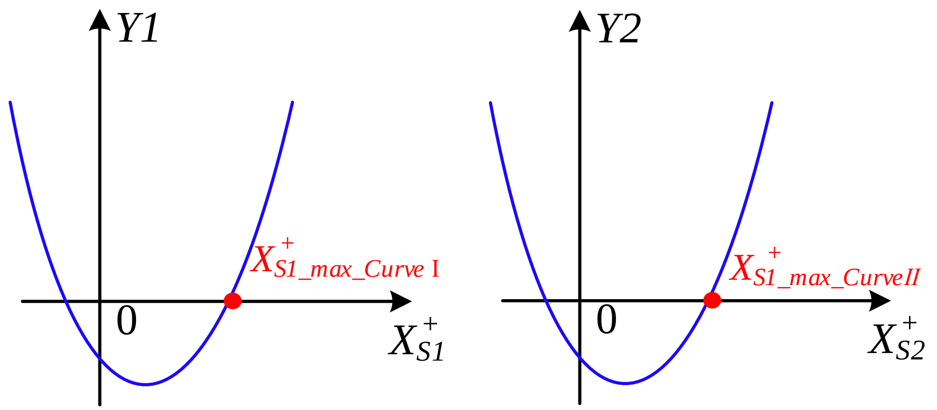
$$Y_1 = C_1^2 {X_{S1}^{+}}^2 + 2C_1C_2X_{S1}^{+} - \left(\left(\frac{C_3}{1.2C_4}\right)^2 + \left(\frac{C_5}{C_4}\right)^2 - 2\frac{C_3C_5}{1.2C_4^2} - 300^2 - C_2^2\right) \le 0$$

2. I'_{bias} on Curve 2: $I'_{bias} \le I'_{S2}$

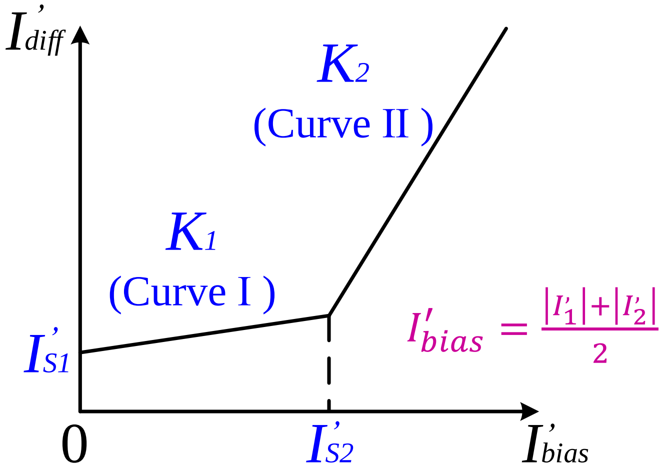
$$Y_2 = C_1^2 {X_{S1}^{+}}^2 + 2C_1C_2X_{S1}^{+} - \left(\left(\frac{C_3}{1.2C_6}\right)^2 + \left(\frac{C_7}{C_6}\right)^2 - 2\frac{C_3C_7}{1.2C_6^2} - C_2^2 - 300^2\right) \le 0$$

Key observations:

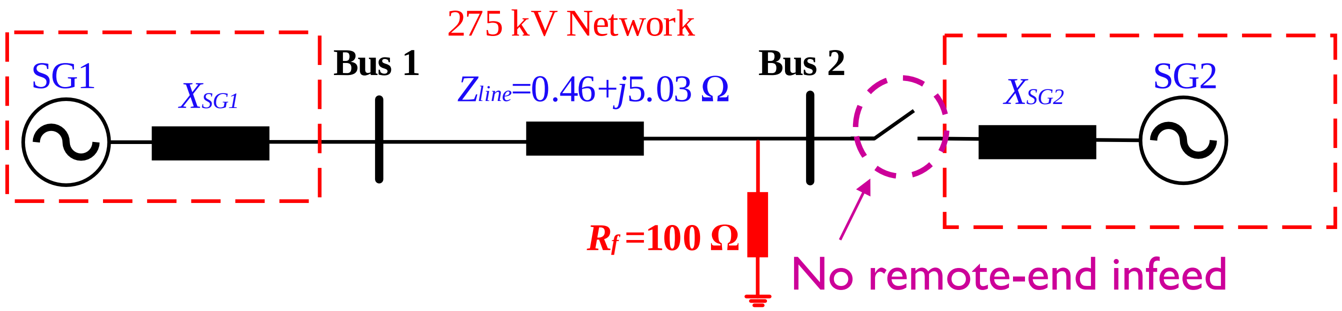
- The relations of Y_1 and X_{S1}^{+}, Y_2 and X_{S2}^{+} are quadratic
- The maximum source impedance is the greater positive solution of the quadratic curve, i.e. the minimum fault level can be detected for differential protection



$I'_{diff} = |I'_1 + I'_2|$



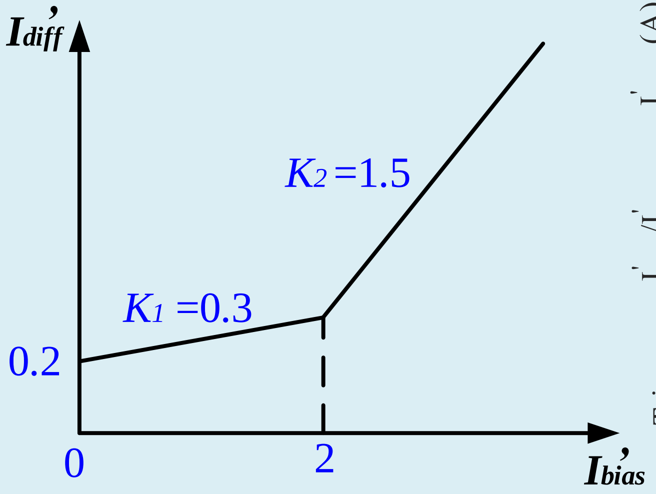
Case Study for Differential Protection



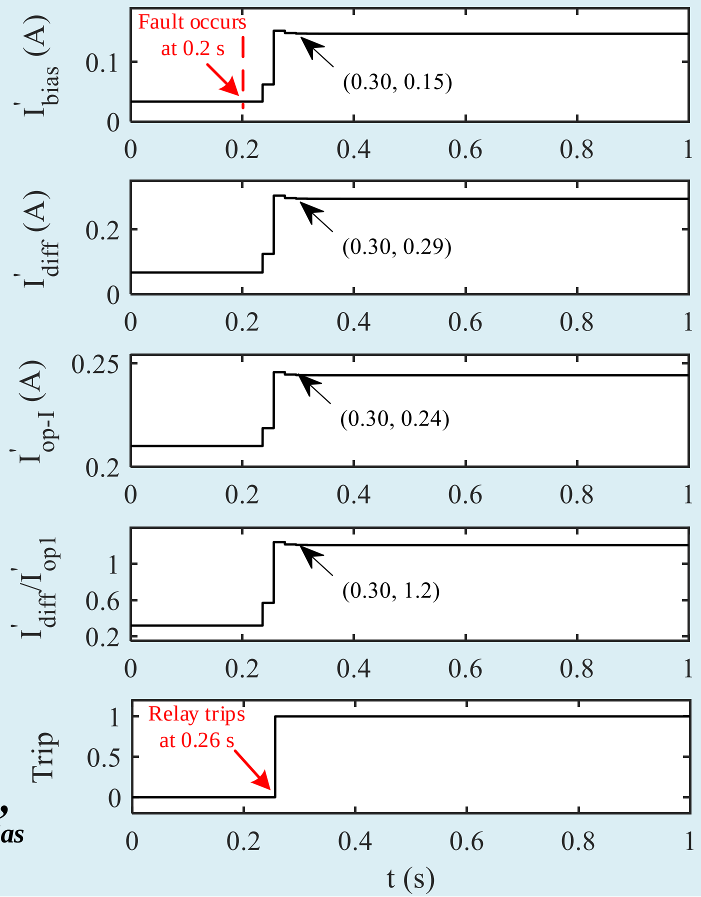
Calculated Required Minimum Fault Level

$$FL_{min} = 174.47\ MVA$$

- Protection Settings

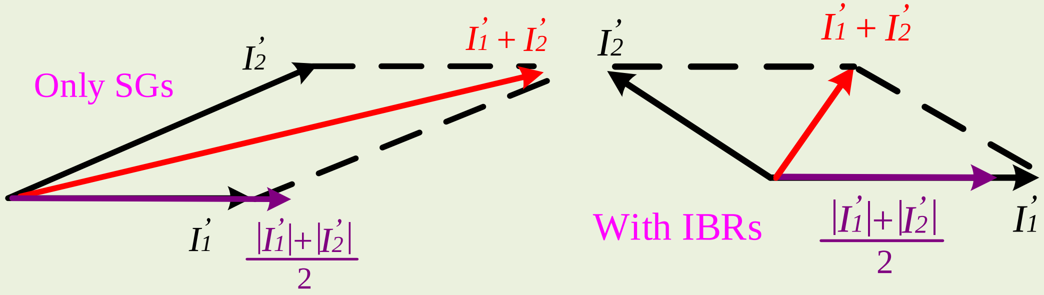


RTDS Results

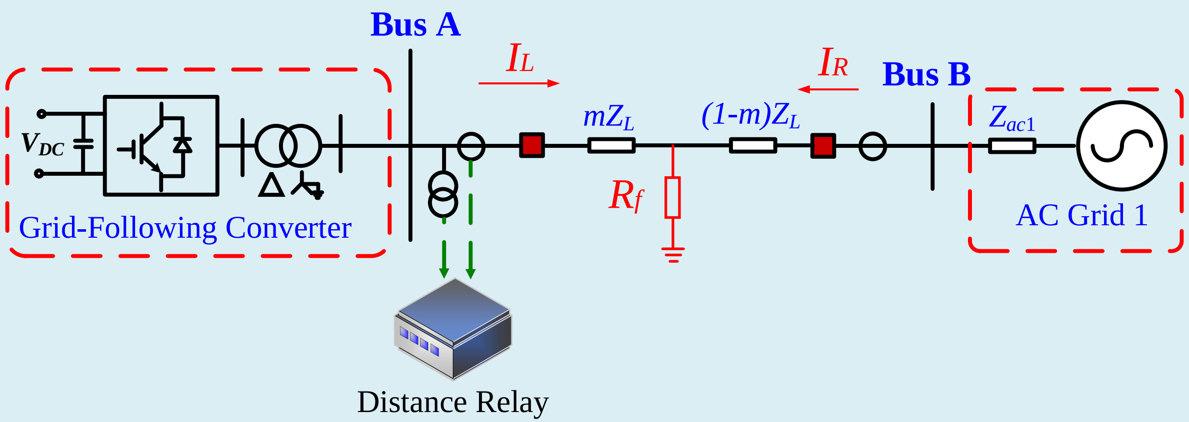


Key findings:

- In networks only with SGs, differential protection can still operate with very low fault level (e.g. 174MVA @275kV).
- Angle of currents play a more important role than fault level – vastly different in CBR dominated networks.

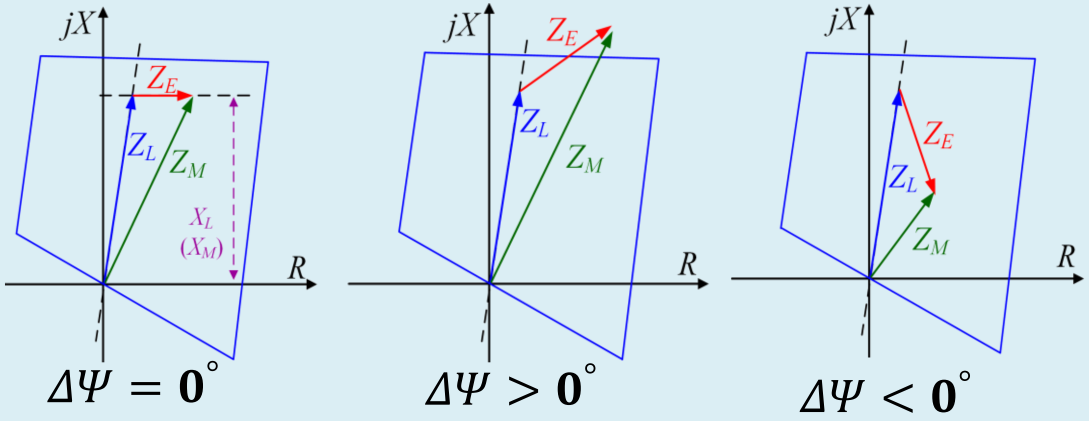


Assessment of Fault Level Required for Distance Protection



- Impedance Measured by Distance Relay

$$Z_M = mZ_L + \left(1 + \overset{A\angle\Delta\Psi}{\boxed{\frac{I_R}{I_L}}}\right) R_f = Z_L + Z_E$$



$\Delta\Psi = 0^\circ$ $\Delta\Psi > 0^\circ$ $\Delta\Psi < 0^\circ$

Key findings:

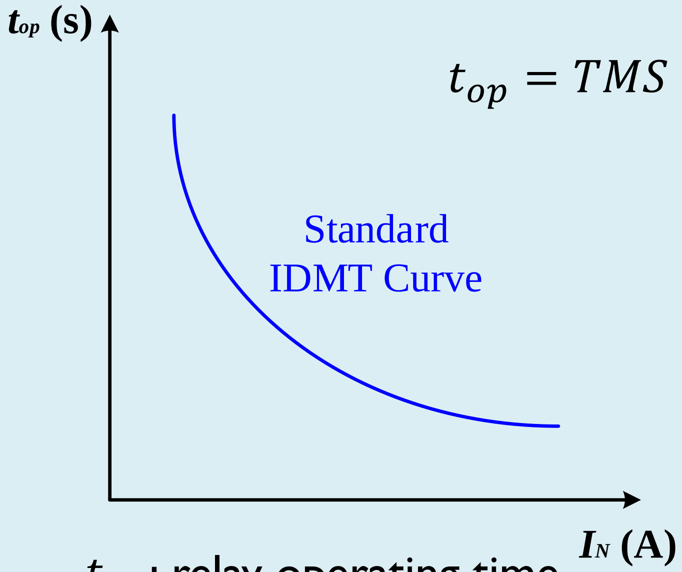
1. Impedance measurement:

- Network only with SGs: small angle difference $\angle\Delta\Psi$.
- IBRs can increase $\angle\Delta\Psi$, and lead to the severe under/over-reach issues.
- Measured impedance depends on both magnitudes and angle of fault infeed from two ends - subject to CBR control

2. Phase selection and others: also subject to CBR control

Assessment of Fault Level Required for Backup Earth Fault Protection

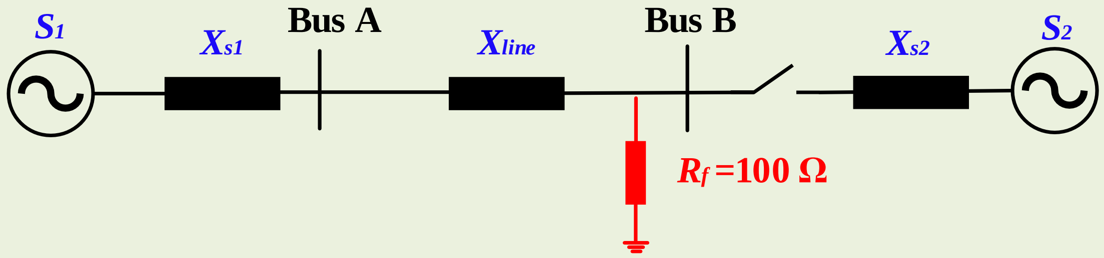
Backup earth fault protection characteristics



$$t_{op} = TMS \times \frac{0.14}{\left(\frac{I_N}{I_{s\_BER}}\right)^{0.02} - 1}$$

- t_{op}: relay operating time
- TMS: time multiplier setting
- I_N: relay detected neutral current
- I_{s_BER} :setting currents of backup earth fault relay

Earth fault protection requirements



Capable of detecting worst case scenario:

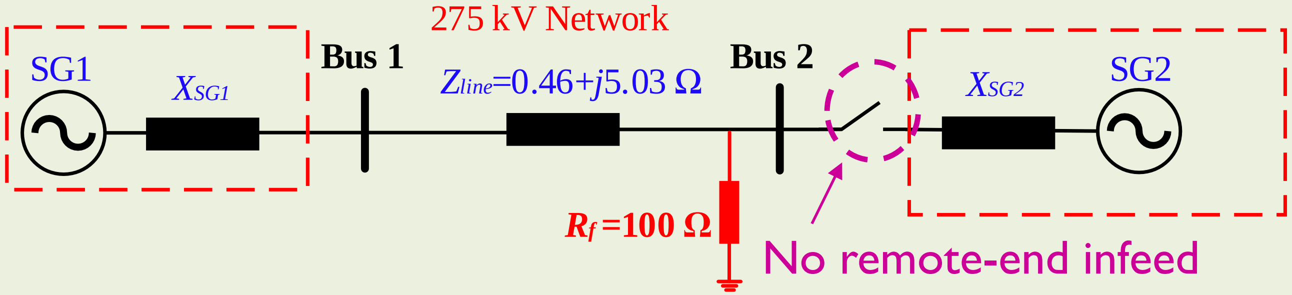
- Able to detect high resistance earth fault (100 Ω used in the study)
- Operate with required time delay

Assessment of Fault Level Required for Backup Earth Fault Protection

Backup earth fault protection:

$$X^{+}_{S1\_max\_BER} = \frac{\sqrt{\left(\frac{3V_S}{I_{s\_BER}}\right)^2 - 300^2 - 2X_L^{+} - X_L^{0}}}{(2+n)}$$

- V_S : system phase voltage
- X_L^{+}, X_L^{0}: positive, zero-sequence line reactance
- n is the ratio between the zero, positive-sequence source impedance



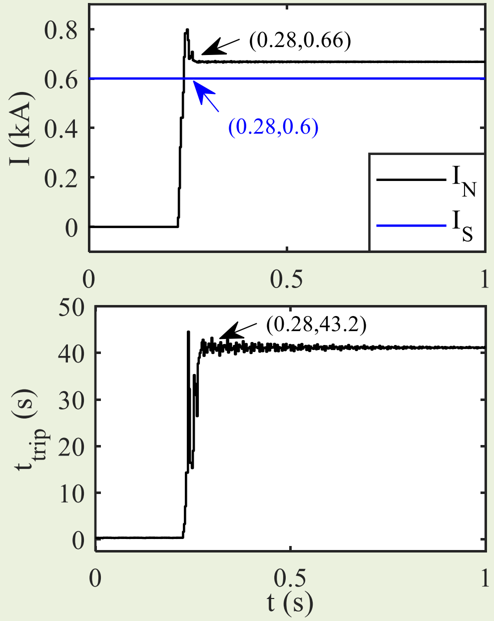
No remote-end infeed

Calculated Required Minimum Fault Level

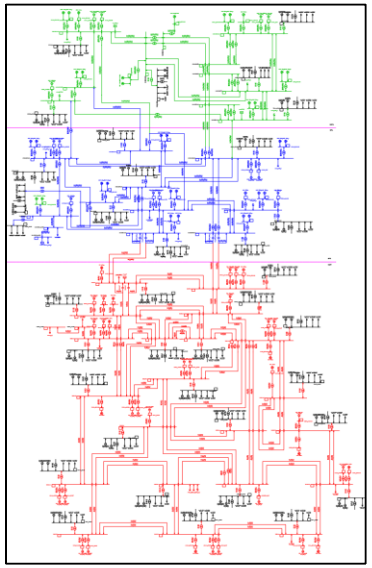
$$FL_{min} = 318.3\ MVA$$

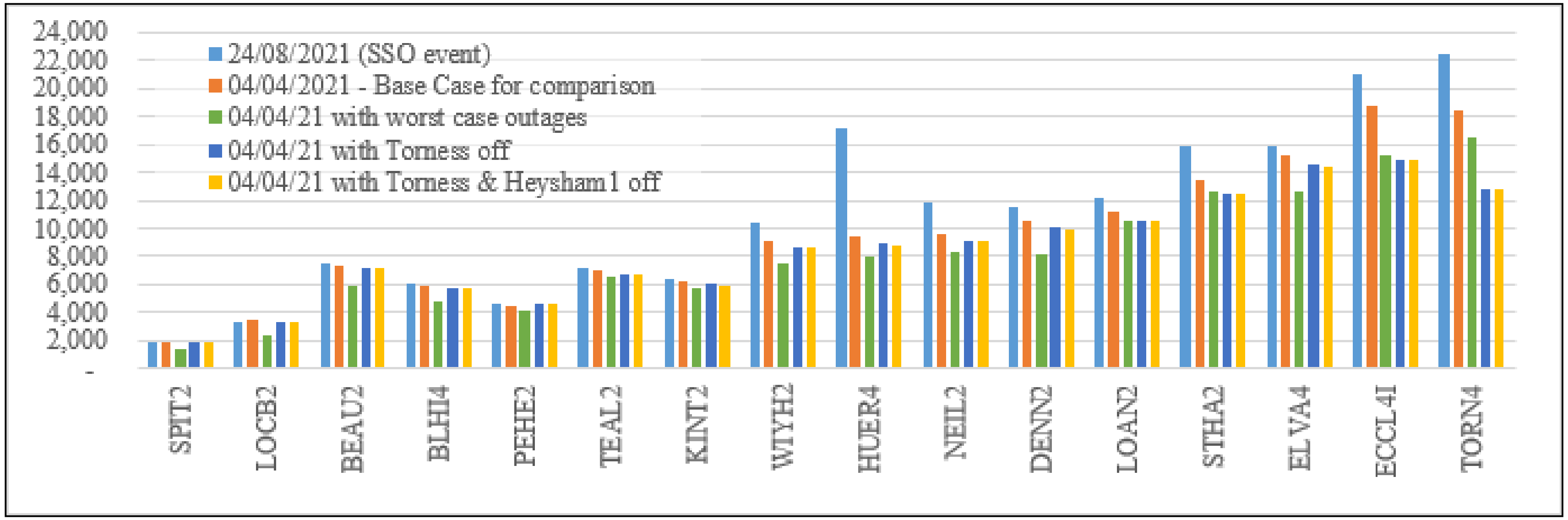
Key findings:
Earth fault protection can maintain dependability at very low fault level (i.e. 318.3 MVA @275kV).

RTDS Results



Modelling and understanding future trend of fault level (FL) in Scotland





Key findings

- Scotland already experienced very low FL.
- SGs closure in Scotland does not appear to have major impact FL – locational effects
- Equipment outages can reduce the FL - implications for system outage planning

What are the true system needs?

- FL is probably not the main issue (or the only issue), at least from protection perspective?
- FL needed for avoiding wide spread of voltage depression or other considerations?

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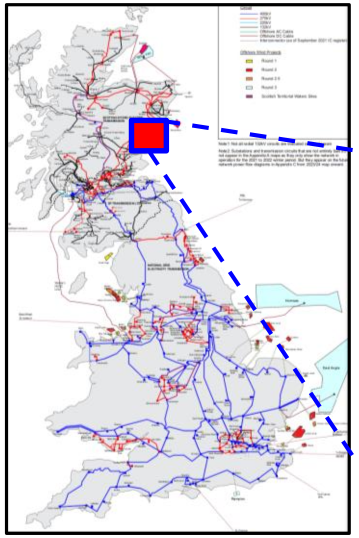
Impact of Converter Control on Distance Protection Performance

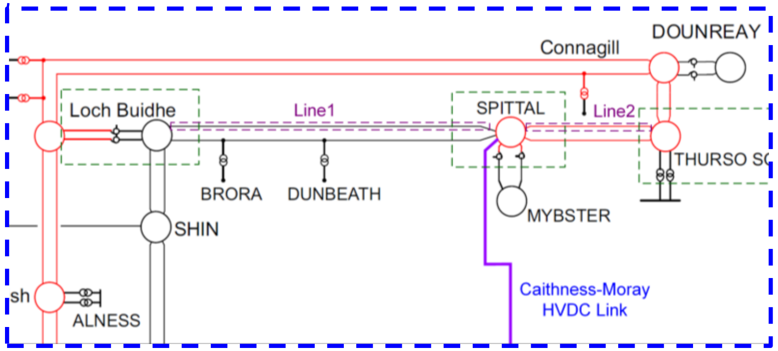
Protection of Future Power Networks – Phase I

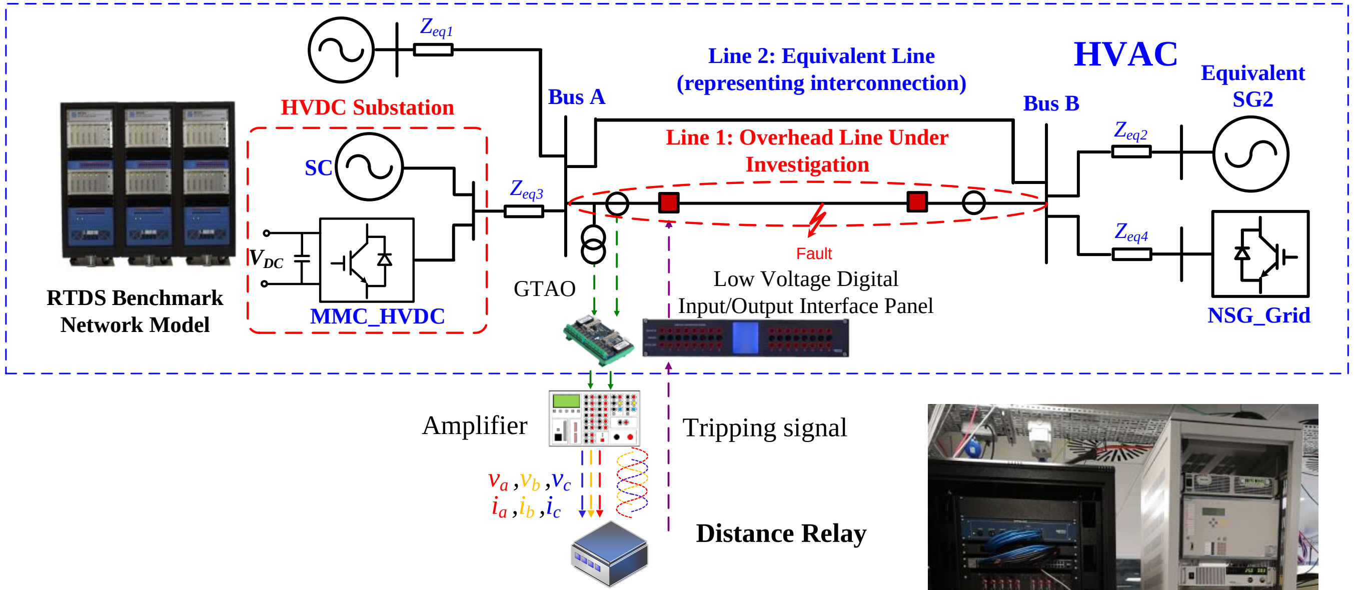
University of Strathclyde Engineering

- Evaluation of inverters' impact on distance protection
- Closed-loop testing of physical relay performance under a wide range of conditions



Case study: AC network near Caithness-Moray HVDC Link





D. Liu, **Q. Hong***, et al., Evaluation of HVDC System's Impact and Quantification of Synchronous Compensation for Distance Protection, *IET Renewable Power Generation*, 2022

Funded by:

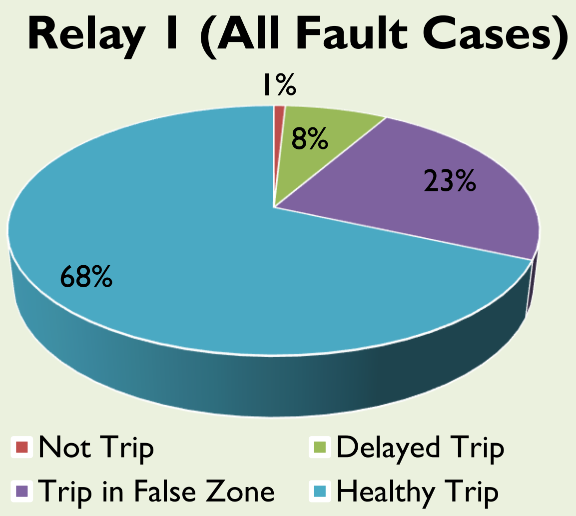
The National HVDC Centre

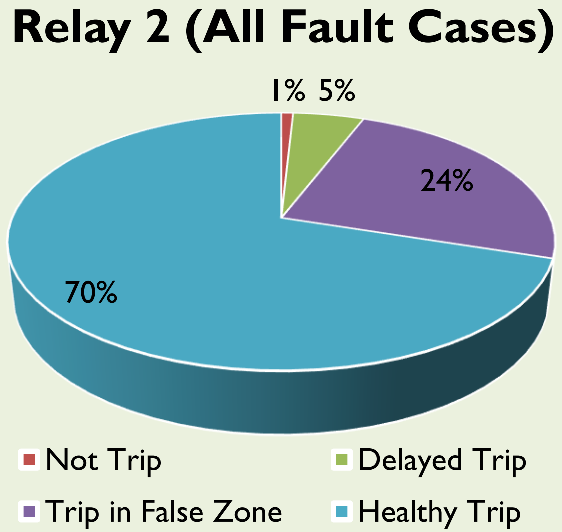
Scottish & Southern Electricity Networks

Impact of Local and Remote-end Fault Level

Current fault level

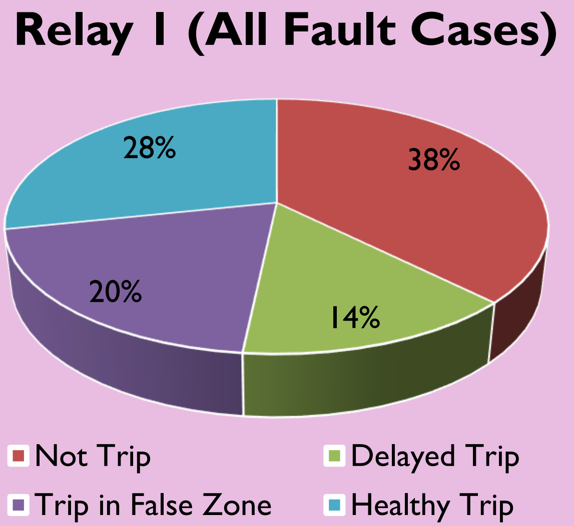
$FL_{SG1} = 1832\ MVA, FL_{SG2} = 1372\ MVA$

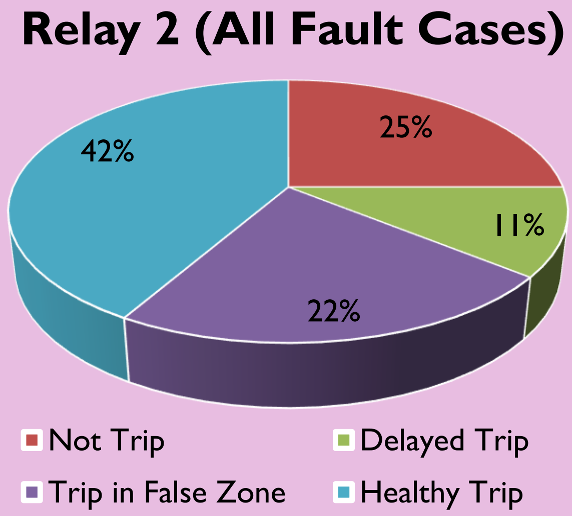




Potential future extreme scenario

$FL_{SG1} = 0\ MVA, FL_{SG2} = 3000\ MVA$





- 🟦 **Healthy Trip (<90ms)**
- 🟩 **Delay Trip (>90ms)**
- 🟪 **Trip in False Zone**
- 🟥 **No Trip**

Observations:

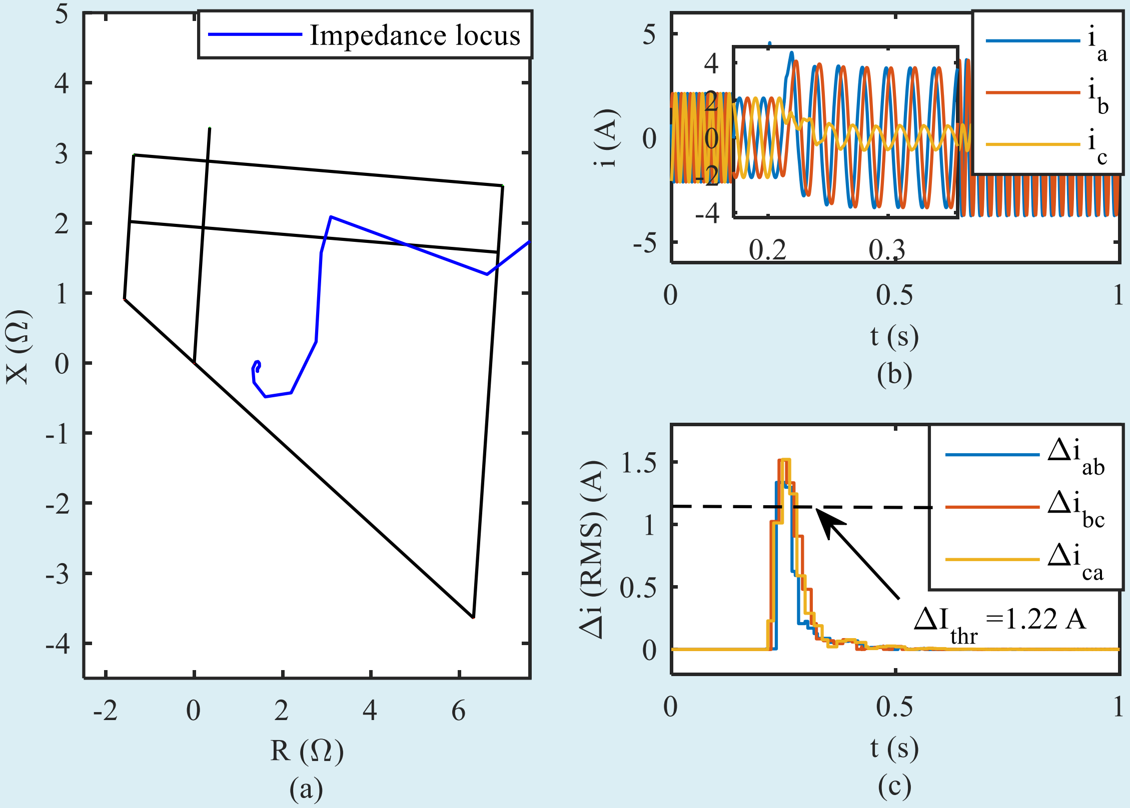
- Current fault level – relay responds correctly in majority of the cases.
- Small number of cases with delay and no trip – due to specific HVDC control deployed.
- When local fault infeed from SG1 drops to 0MVA, i.e. only HVDC feeding the fault, clear change of protection performance.

Detailed investigation of studied cases

Issues of faulted phase selection (Relay 1):

Cases	FL_{SG1}	FL_{SG2}	HVDC Mode	Fault Condition	Relay 1	Relay 2
4	0 MVA	3000 MVA	BI	AG, 15 %, 2 ohm	No	Yes (100 ms)

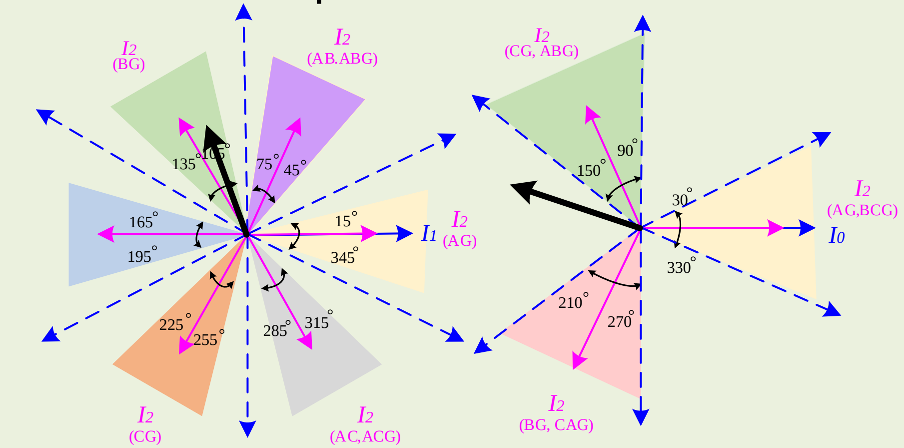
Relay 1 (Superimposed currents - based):



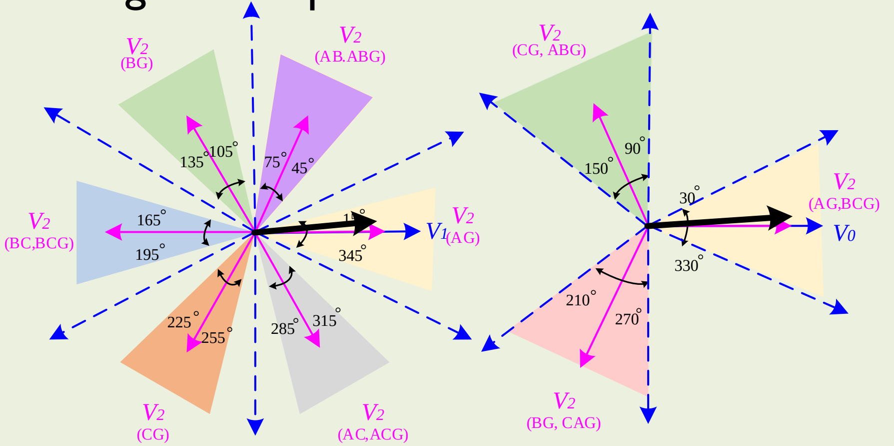
(a) impedance locus, (b) GTAO input currents, (c) Ph-Ph superimposed currents

Relay 2 (Sequence currents/voltages - based):

Sequence current-based phase selector:



Sequence voltage-based phase selector:

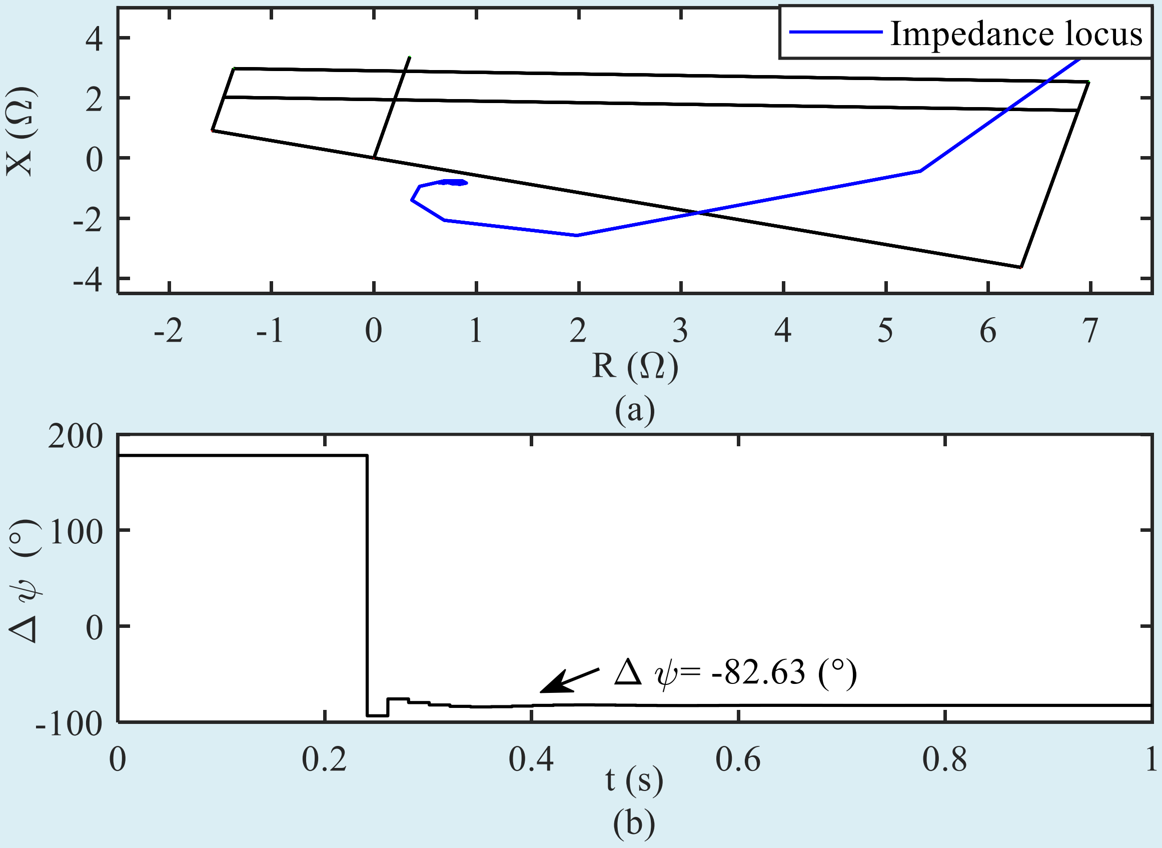


Detailed investigation of studied cases

Issues of over-reach:

Cases	FL_{SG1}	FL_{SG2}	HVDC Mode	Fault Condition	Relay 1	Relay 2
7	0 MVA	3000 MVA	BI	AB, 15 %, 2 ohm	No	Yes (43 ms)

Impedance locus measured by distance relays:



(a) impedance locus, (b) GTAO input currents, (c) phase-to-phase superimposed currents

Analysis of Case 7:

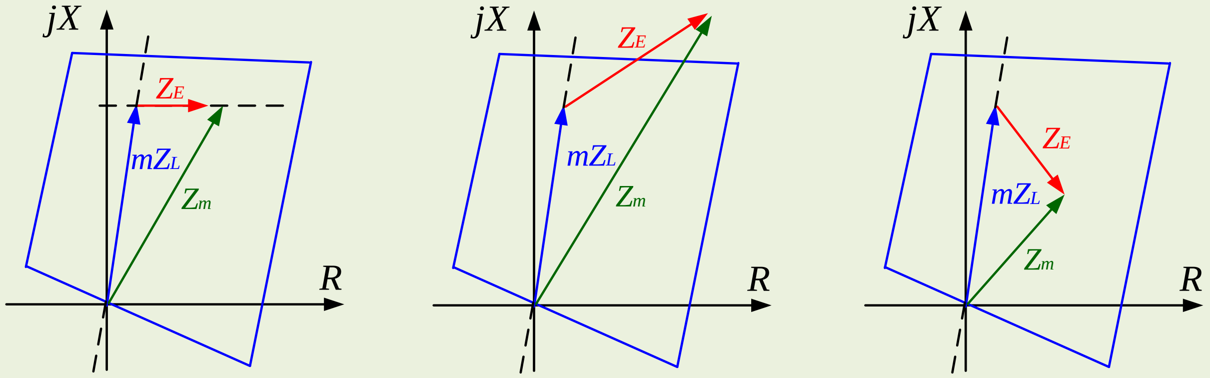
Phase currents from the converter with BI controller [1]:

$$i_p(t) = \sqrt{{i_d^+}^2 + {i_q^+}^2}\;sin\left(\omega t + arctan\left(\frac{i_q^+}{i_d^+}\right) + \theta_{vd}^+ + \theta_p\right)$$

Impedance measured by distance relays:

$$Z_m = mZ_L + \left(1 + \boxed{\overbrace{\left(\frac{i_{SG2}}{i_{HVDC}}\right)}^{A\angle\Delta\psi}}\right)R_F$$

With different values of $\angle\Delta\varphi$:



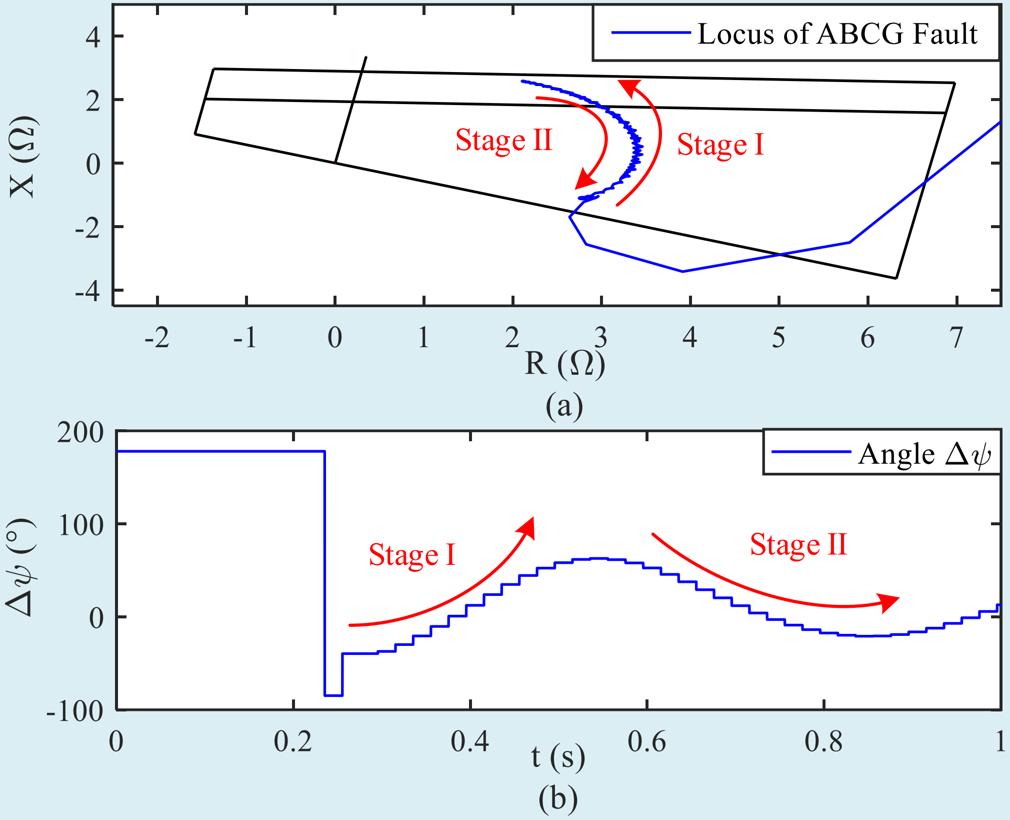
Y. Fang, K. Jia, Z. Yang, Y. Li and T. Bi, "Impact of Inverter-Interfaced Renewable Energy Generators on Distance Protection and an Improved Scheme," in *IEEE Transactions on Industrial Electronics*, vol. 66, no. 9, pp. 7078-7088, Sept. 2019.

Detailed investigation of studied cases

Issues of oscillating impedance locus:

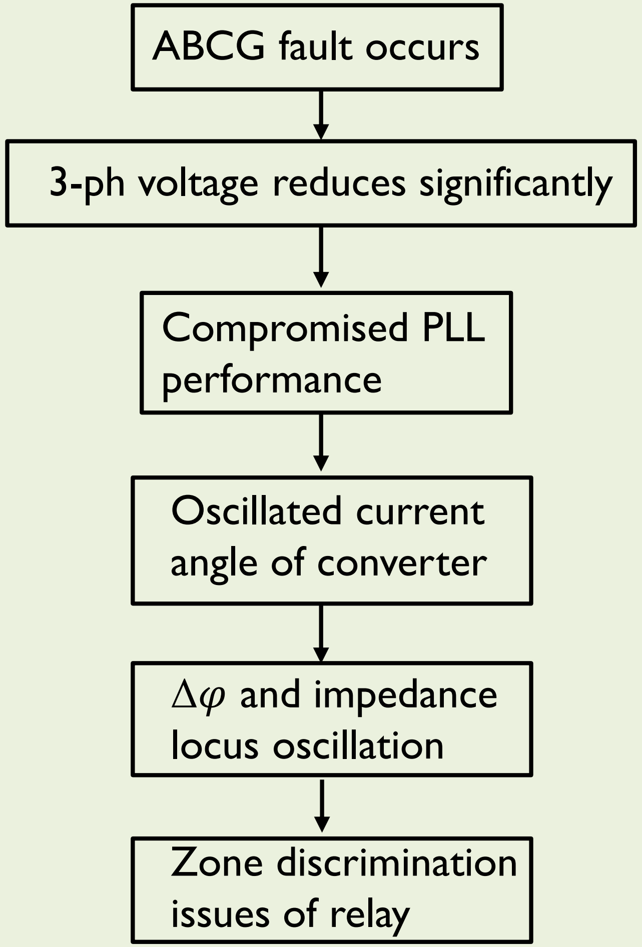
Cases	FL_{SG1}	FL_{SG2}	HVDC Mode	Fault Condition	Relay 1	Relay 2
9	0 MVA	3000 MVA	BI	ABCG, 15 %, 2 ohm	Yes (468 ms)	Yes (50 ms)

Impedance locus measured



(a) impedance locus, (b) angle difference of current infeed from both ends of the protected line

Analysis of Case 9:



ABCG fault occurs

3-ph voltage reduces significantly

Compromised PLL performance

Oscillated current angle of converter

$\Delta\varphi$ and impedance locus oscillation

Zone discrimination issues of relay

Emerging Protection Solutions:

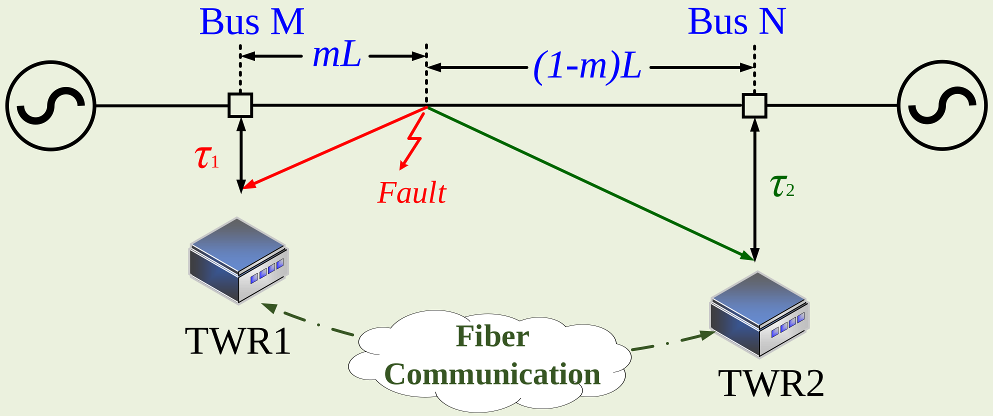
Travelling Wave

Revised Distance Protection

Travelling Wave (TW) – based Differential Protection

- **TW-based protection provides a promising solution for CBR-dominated power systems:**
  - Largely unaffected by converter control/converter type
  - Largely unaffected by the variation of system fault level
  - Fast operating speed

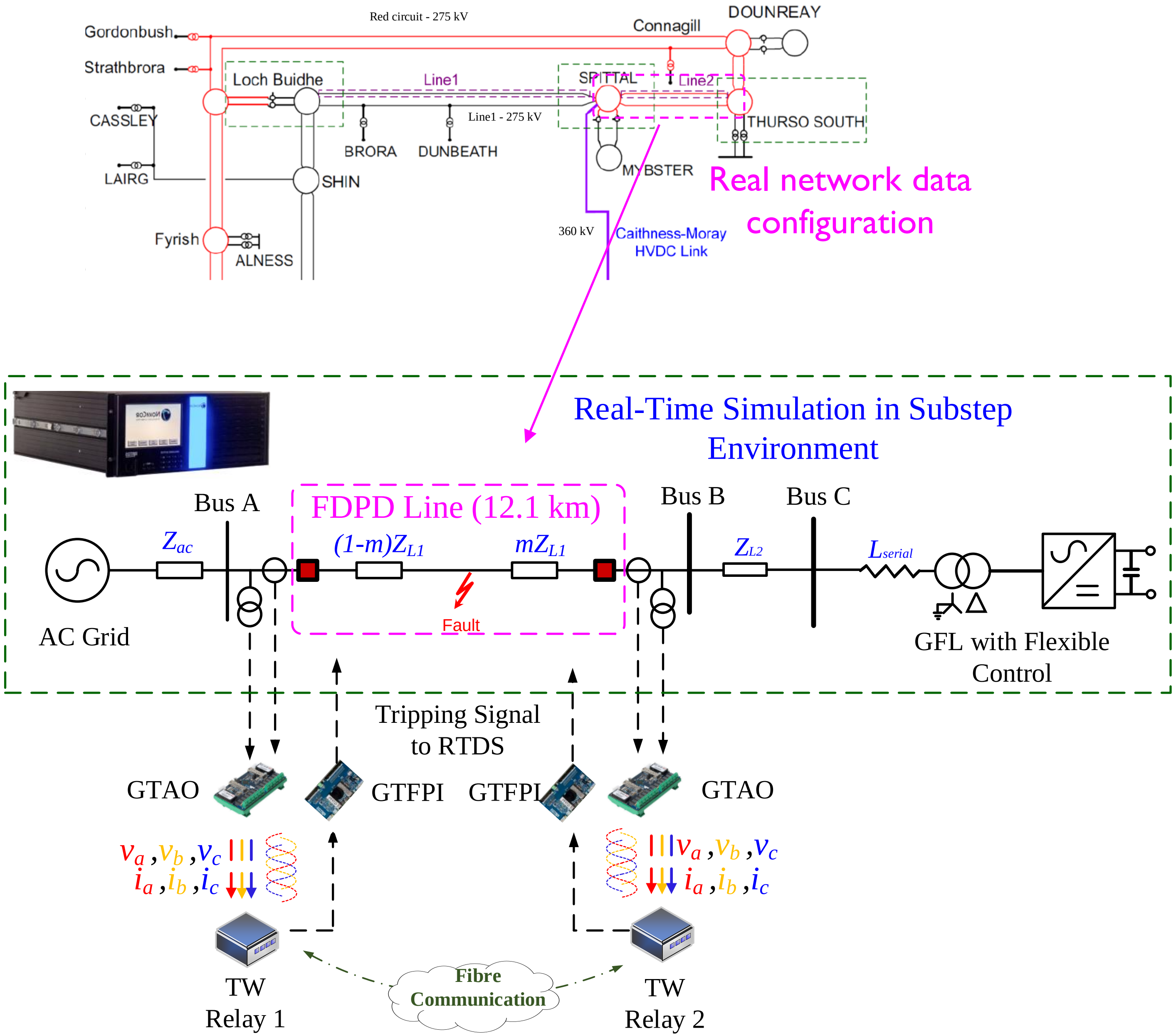
- **TW-based differential protection:**



For internal faults :

- ○ Initial current TWs of TWR1 and TWR2 have same polarity
- ○ $|\tau_2 - \tau_1| <$ Time threshold

Network Model for Travelling Wave Relay Tests



Model Explanation

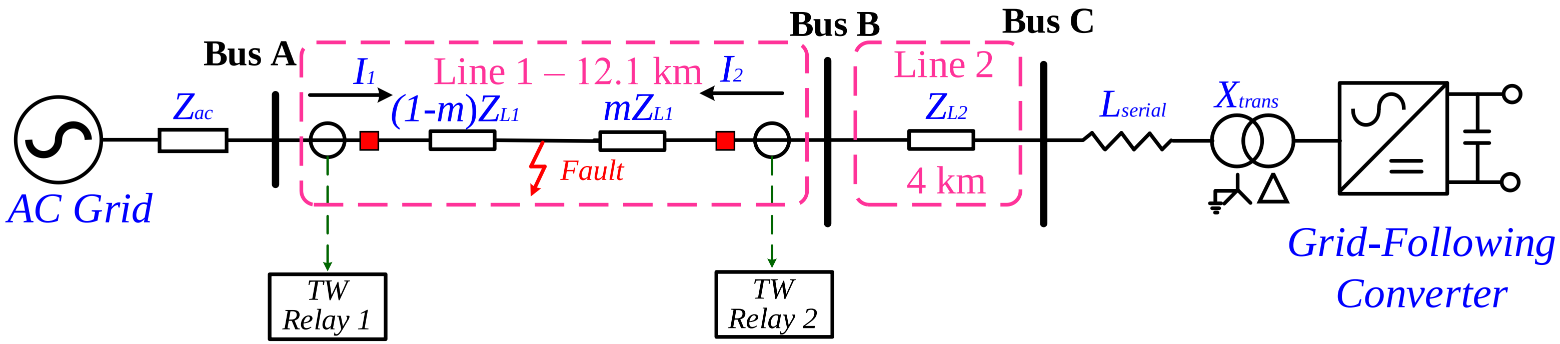
1. The model is developed in sub-step environment with 4 μs step by NovaCor RTDS rack.

2. The transmission line is modelled using Frequency-Dependent Phase-Domain (FDPD) Line.

3. The serial inductor, L_{serial}, is to emulate the impacts of the transformer.

4. The length of adjacent line L_2 can be flexible tuned to emulate different scenarios.

Hardware in the Loop-based Systematic Tests



HiL systematic tests

- ❑ 300 cases in total
- ❑ Scripts and MATLAB codes developed for relay injection and results analysis

• Minimum Fault Inception Angles (FIAs)

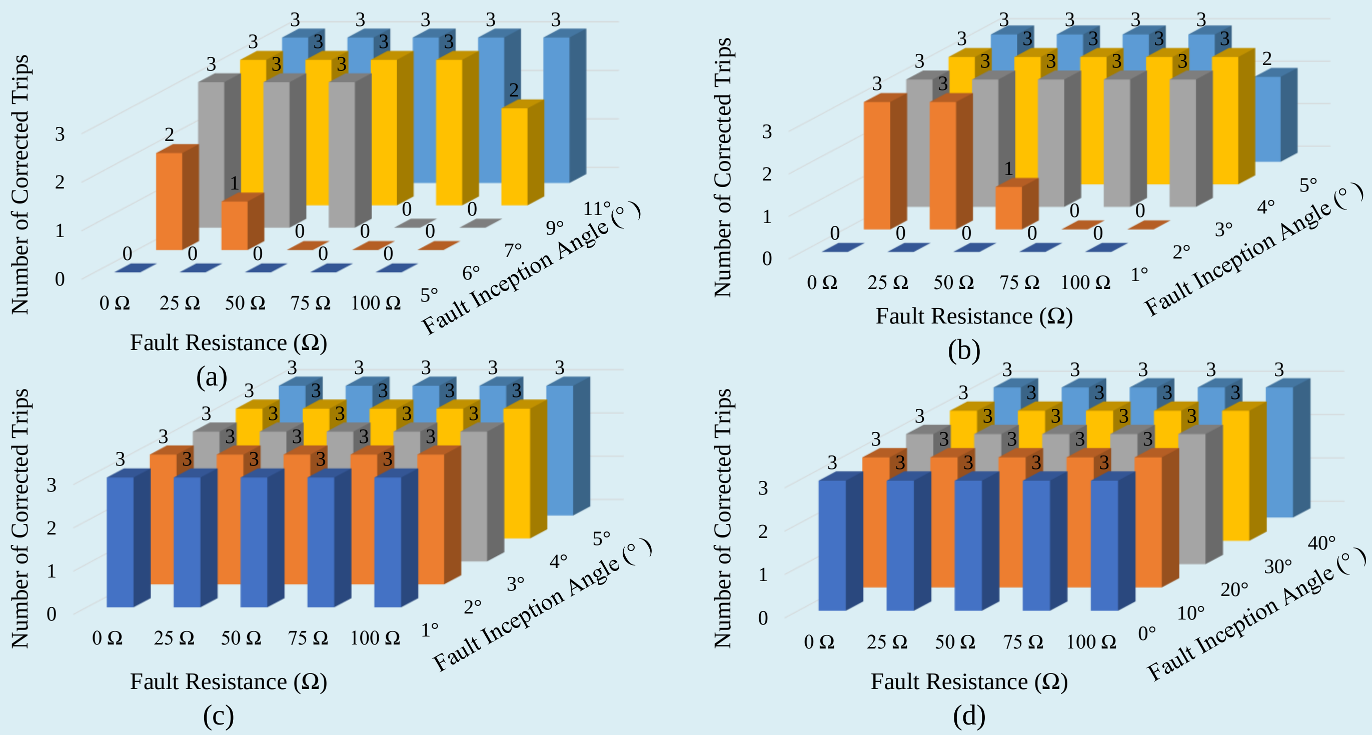
Fault Type	Fault	Minimum FIA (°)
AG	10%, 0 Ω	6
	10%, 100 Ω	9
AB	10%, 0 Ω	2
	10%, 100 Ω	3
ABG	10%, 0 Ω	2
	10%, 100 Ω	3
ABCG	10%, 0 Ω	0
	10%, 100 Ω	0

• Cases in systematic tests

Fault Parameters	Settings
Faulted line	Line 1
Fault positions	10%, 50%, 90%
Fault types and fault inception angles	AG: 5°, 6°, 7°, 9°,11°; AB: 1°, 2°, 3°, 4°, 5°; ABG: 1°, 2°, 3°, 4°, 5°; ABCG: 0°, 10°, 20°, 30°, 40°;
Fault resistance	0 Ω, 25 Ω, 50 Ω, 75 Ω, 100 Ω

Systematic Travelling Wave Relay Tests

- **Statistics of all tested cases:**

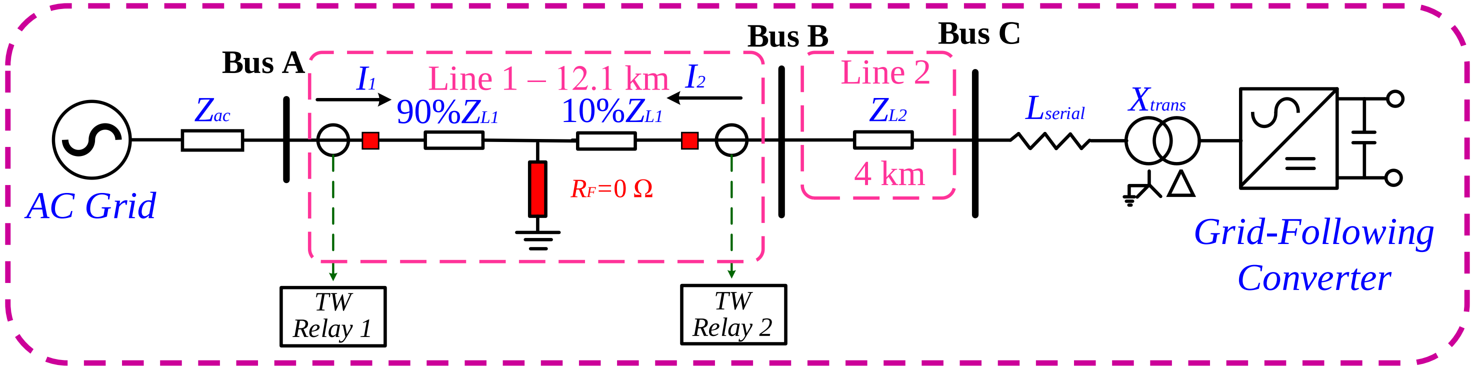


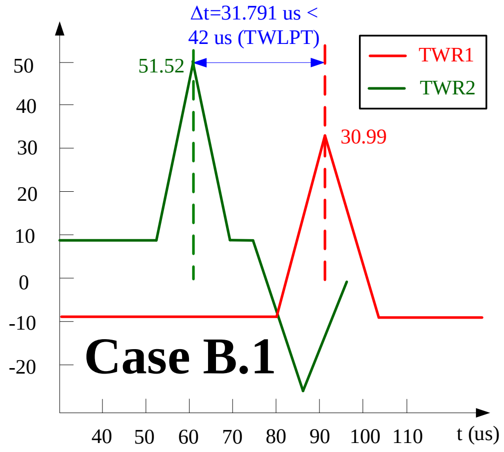
(a) AG faults, (b) AB faults, (c) ABG faults, (d) ABCG faults

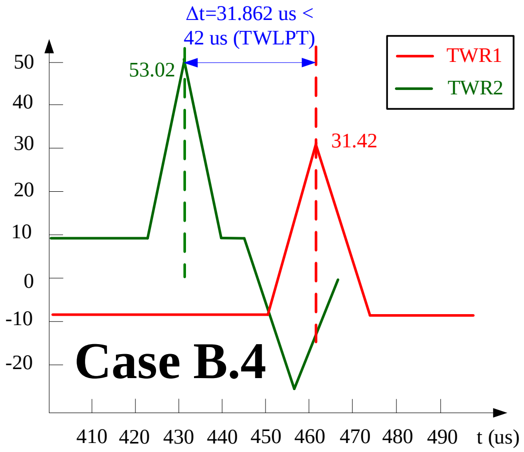
Observations:

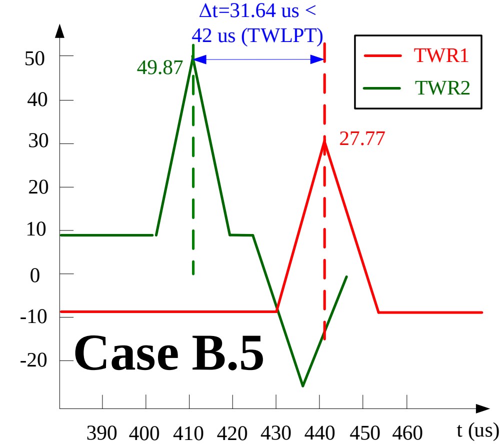
- The minimum FIAs of AG and AB faults are 6° and 2° (faults tends to occur in large FIAs).
- Protection sensitivity increases as fault resistance decrease and fault inception angle increase.
- Trip in all cases in ABG and ABCG faults

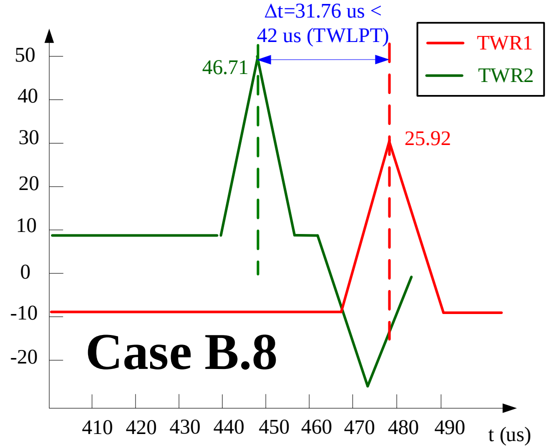
Impact of Fault Level











Fault Level Impact

1. Minimum FIAs (AG)

$SCR_{Grid} = 2.5\ (FIA_{min} = 6^{\circ})$

$SCR_{Grid} = 3\ (FIA_{min} = 6^{\circ})$

$SCR_{Grid} = 4\ (FIA_{min} = 6^{\circ})$

$SCR_{Grid} = 5\ (FIA_{min} = 6^{\circ})$

2. Minimum FIAs (AB)

$SCR_{Grid} = 2.5\ (FIA_{min} = 2^{\circ})$

$SCR_{Grid} = 3\ (FIA_{min} = 2^{\circ})$

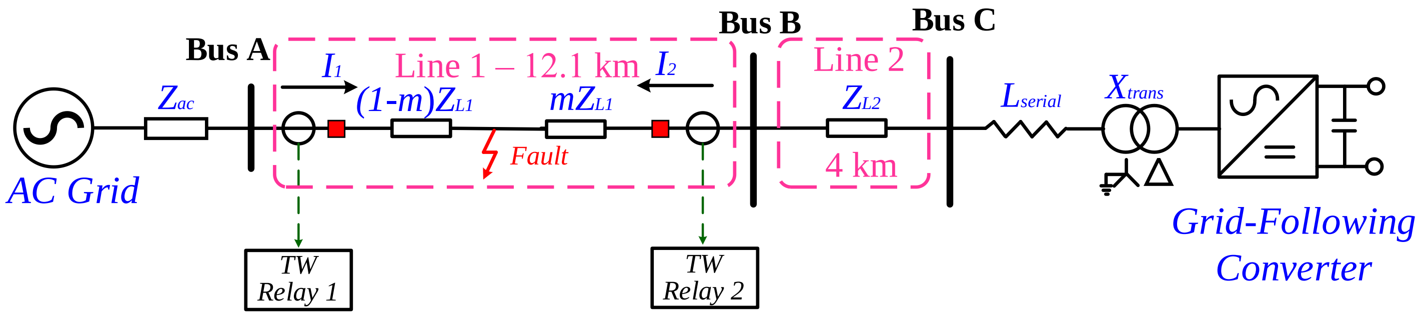
$SCR_{Grid} = 4\ (FIA_{min} = 2^{\circ})$

$SCR_{Grid} = 5\ (FIA_{min} = 2^{\circ})$

Studied Cases:

Case	SCR_{Grid}	Fault Type	FIAs (°)	TWs Trip?
B.1	2.5	AG	6°	Yes
B.2	3	AG	6°	Yes
B.3	4	AG	6°	Yes
B.4	5	AG	6°	Yes
B.5	2.5	AB	2°	Yes
B.6	3	AB	2°	Yes
B.7	4	AB	2°	Yes
B.8	5	AB	2°	Yes

Impacts of Converter Control



Control Mode Impact

1. Minimum FIAs

$$FIA_{CP}^{AG} = 6^{\circ} \qquad FIA_{CP}^{AB} = 2^{\circ}$$

$$FIA_{CQ}^{AG} = 6^{\circ} \qquad FIA_{CQ}^{AB} = 2^{\circ}$$

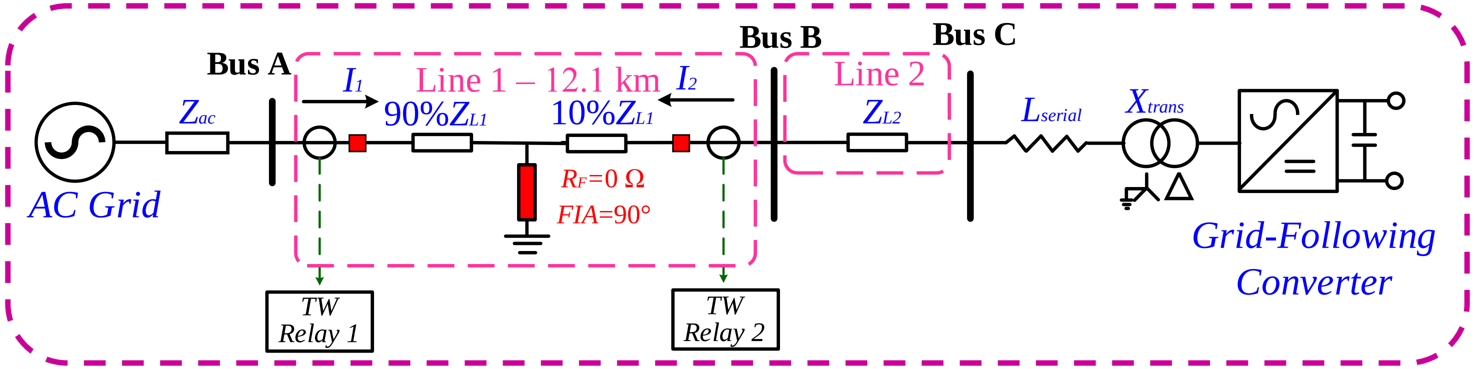
$$FIA_{BI}^{AG} = 6^{\circ} \qquad FIA_{BI}^{AB} = 2^{\circ}$$

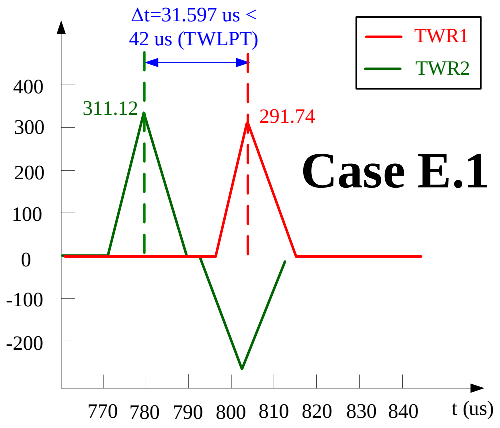
2. TW relay performance is largely unaffected by the converter control.

Testing Results

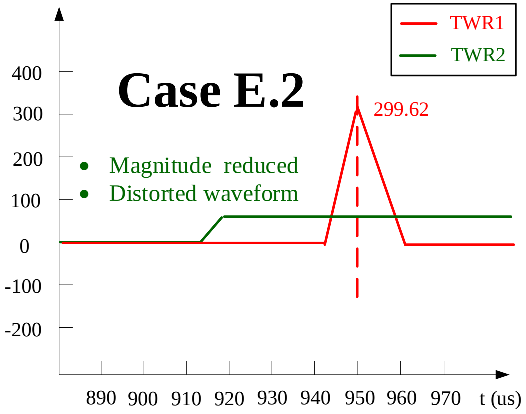
Case	SCR_{Grid}	Control Mode	Fault Type	Fault Resistance (Ω)	FIAs (°)	Fault Position (%)	Trip
B.1	3	CP	AG	0 Ω	6°	10 %	Yes
B.3	3	CQ	AG	0 Ω	6°	10 %	Yes
B.4	3	BI	AG	0 Ω	6°	10 %	Yes
B.5	3	CP	AB	0 Ω	2°	10 %	Yes
B.7	3	CQ	AB	0 Ω	2°	10 %	Yes
B.8	3	BI	AB	0 Ω	2°	10 %	Yes

Impact of Transformer



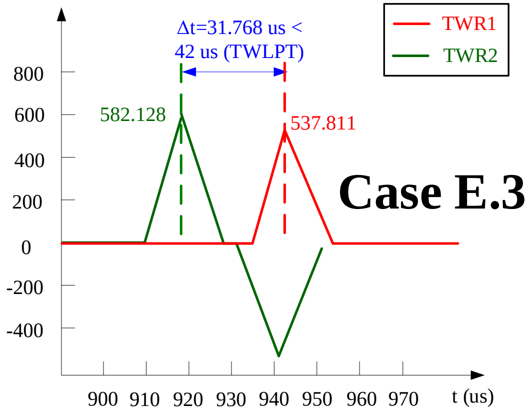


Case E.1

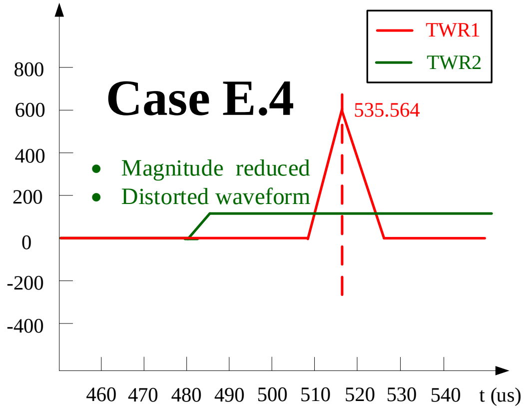


Case E.2

- Magnitude reduced
- Distorted waveform



Case E.3

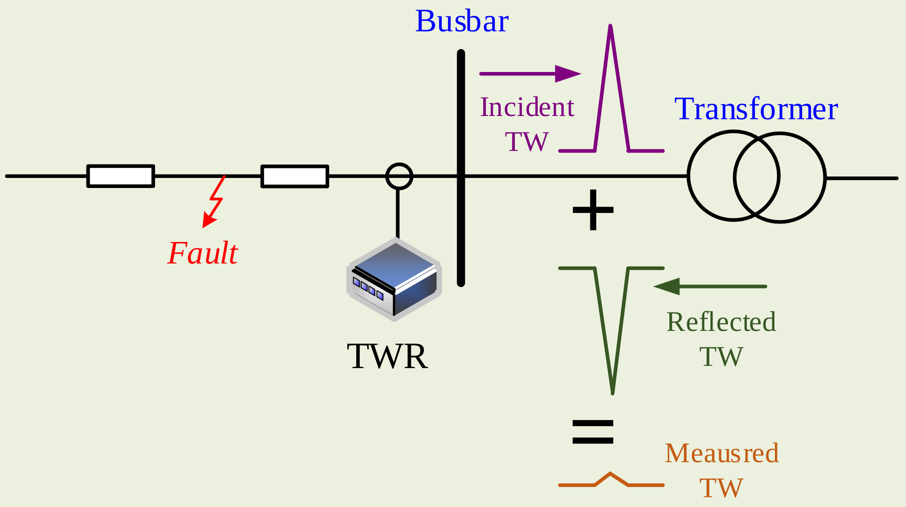


Case E.4

- Magnitude reduced
- Distorted waveform

Studied Cases:

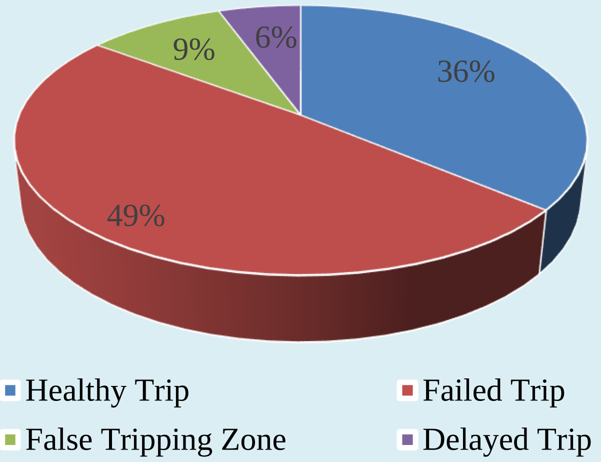
Case	Line 2 Length	Fault Type	TWs Trip?
A.1	4 km	AG	Yes
A.2	0 km	AG	No
A.3	4 km	AB	Yes
A.4	0 km	AB	No



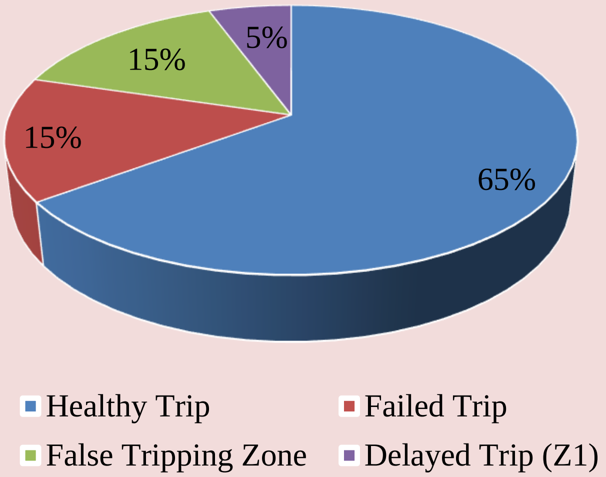
Fault occurs → transformer characteristic impedance increases significantly → $\Gamma_I = \frac{I_{re}}{I_{in}} = \frac{Z_C - Z_T}{Z_C + Z_T} \approx -1$ → TWs cancellation

Performance of the Refined Distance Protection Algorithm

Conventional Sequence Current-based Faulted Phase Selection Algorithm:



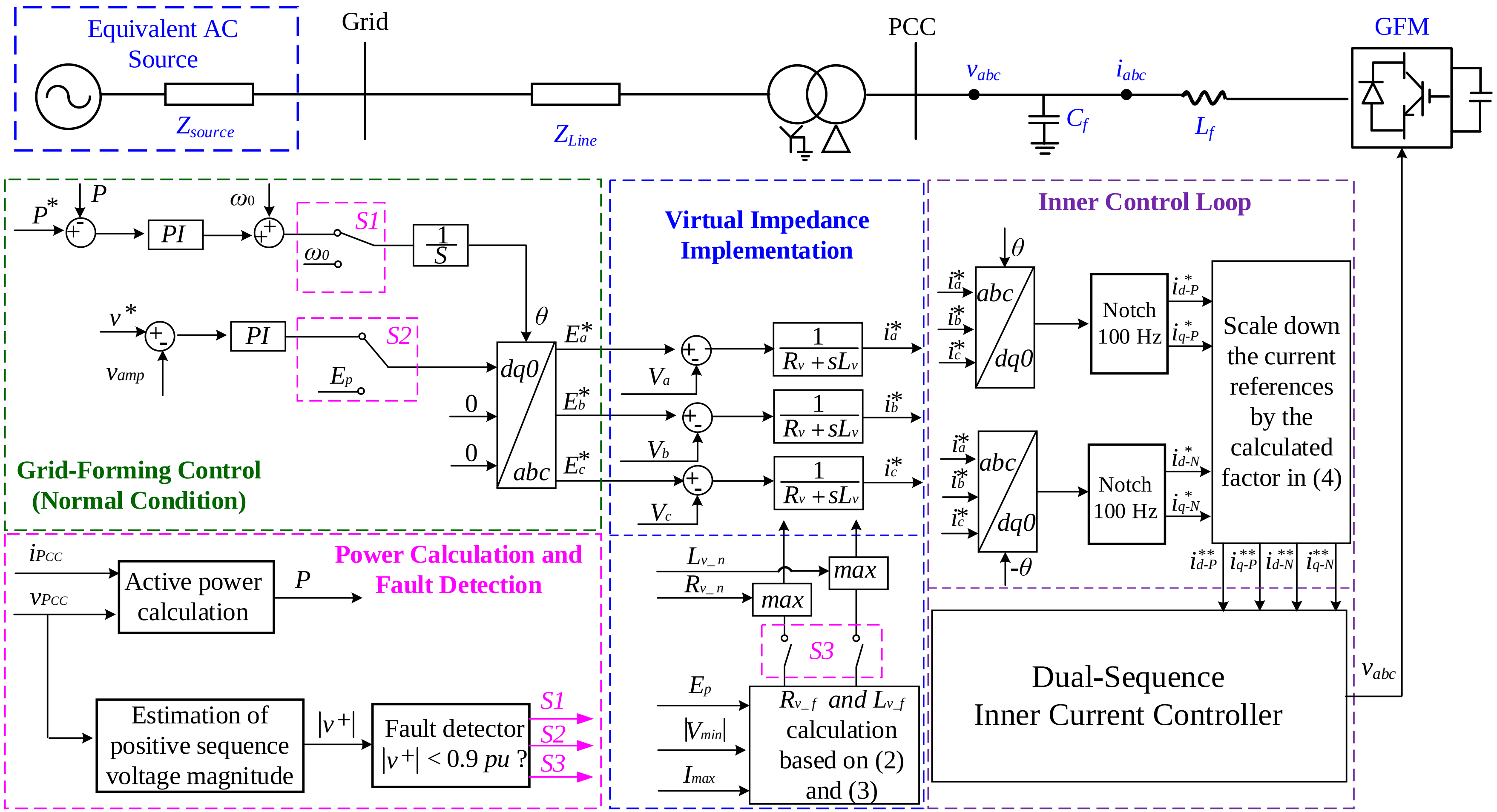
Revised Faulted Phase Selection Algorithm:



Performance of Converter Control Assisted Protection

Virtual Impedance-based Grid-Forming Control

❑ GFM with virtual impedance-based FRT – Revised version based on [3]



Normal condition:
Control voltage angle and magnitude at PCC

Fault detector:
Control signal 'S1', 'S2' and 'S3'

Virtual impedance FRT
Calculation the virtual impedance during faults by (1) to (3):

$$Z_{v\_f} = \frac{E_p - |V_{min}|}{I_{max}} \quad (1)$$

$$R_{v\_f} = \frac{Z_{v\_f}}{\sqrt{XR_{ratio}^2+1}} \quad (2)$$

$$L_{v\_f} = \frac{(XR_{ratio} \cdot R_{v\_f})}{\omega_0} \quad (3)$$

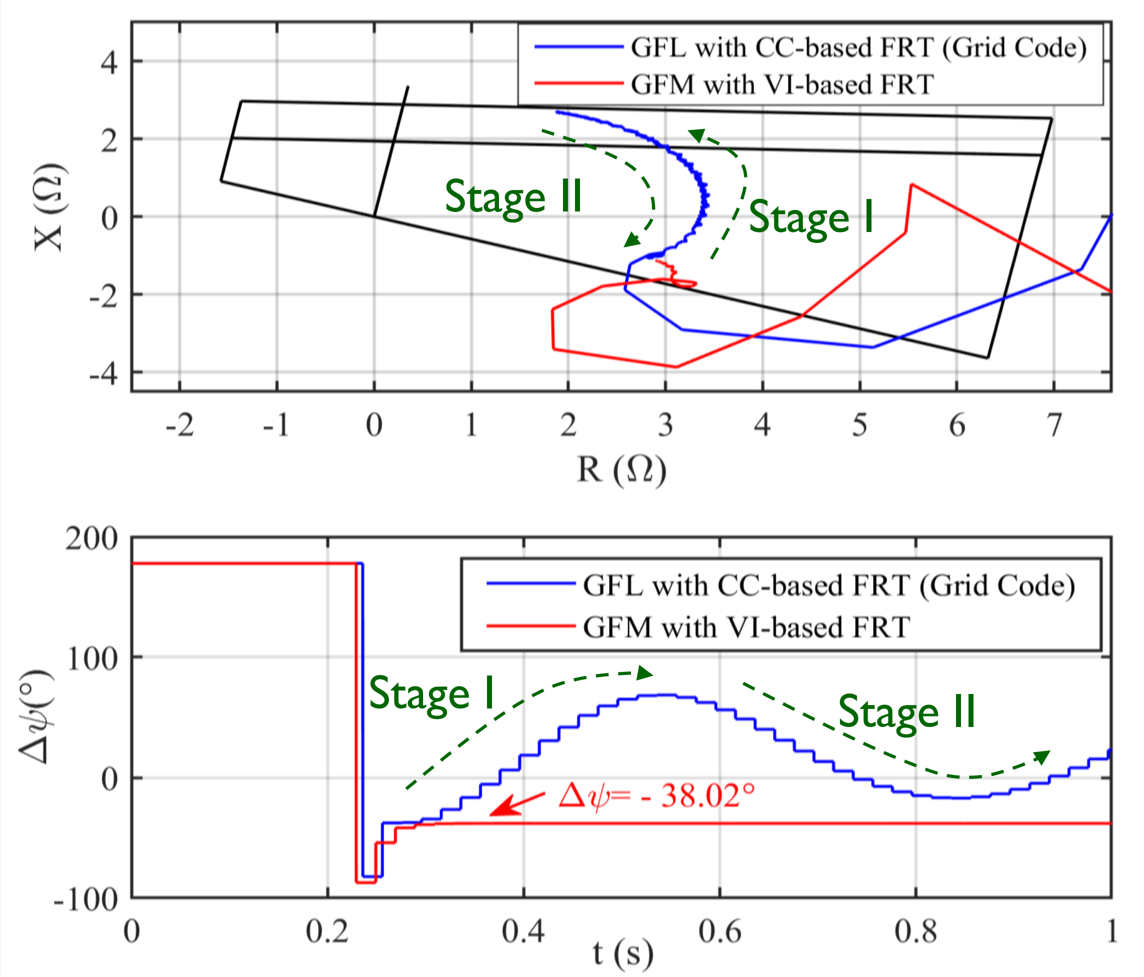
Inner control loop:
Largely suppress the initial transient currents during faults

$$SF = \frac{\sqrt{\left(i_{d-P}^*\right)^2+\left(i_{q-P}^*\right)^2}+\sqrt{\left(i_{d-N}^*\right)^2+\left(i_{q-N}^*\right)^2}}{I_{max}} \quad (4)$$

[3] R. Rosso et al., "On The Implementation of an FRT Strategy for Grid-Forming Converters Under Symmetrical and Asymmetrical Grid Faults," in *IEEE Trans. on Industry Applications*, vol. 57, no. 5, pp. 4385-4397, Sept.-Oct. 2021.

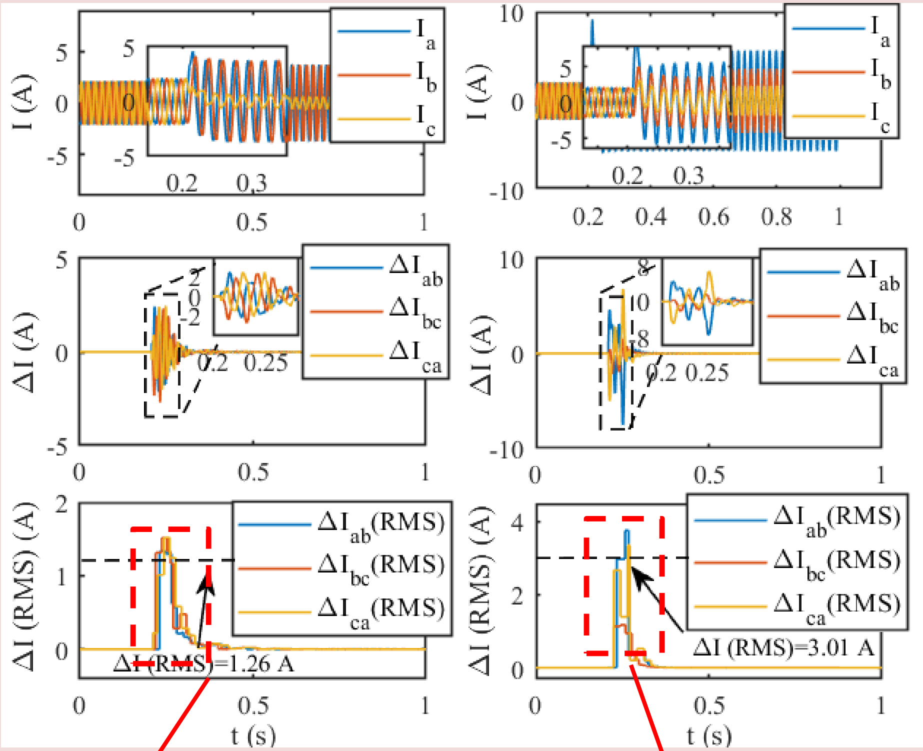
Distance Protection with VI-based GFM

Oscillating Impendence Locus Issue:



As no PLL was used in VI-based GFM, the oscillating impedance locus disappears with VI-based GFM

- ## Faulted Phase Selection Issue:

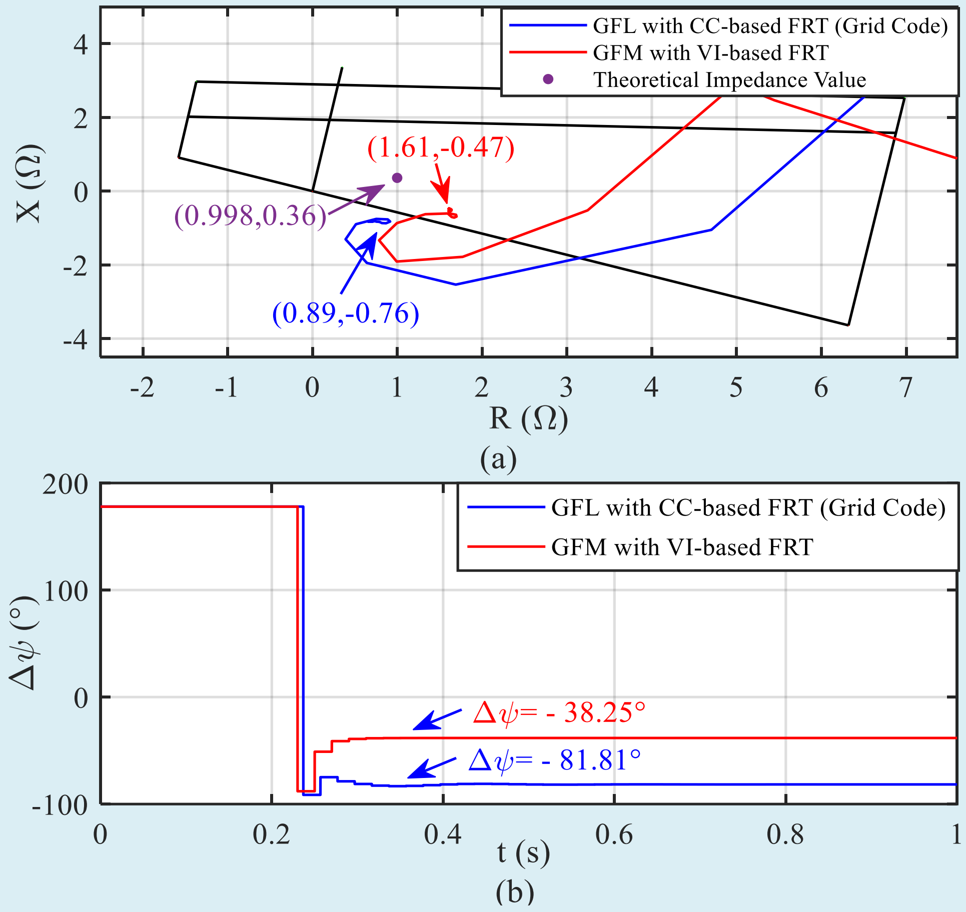


AG fault detected as a ABCG fault with GFL

AG fault detected correctly with VI-based GFM

Distance Protection with VI-based GFM

- **Under/Over-reach Issue:**



Compared to GFL, the VI-based GFM can reduce the impedance measurement error

QUESTION?

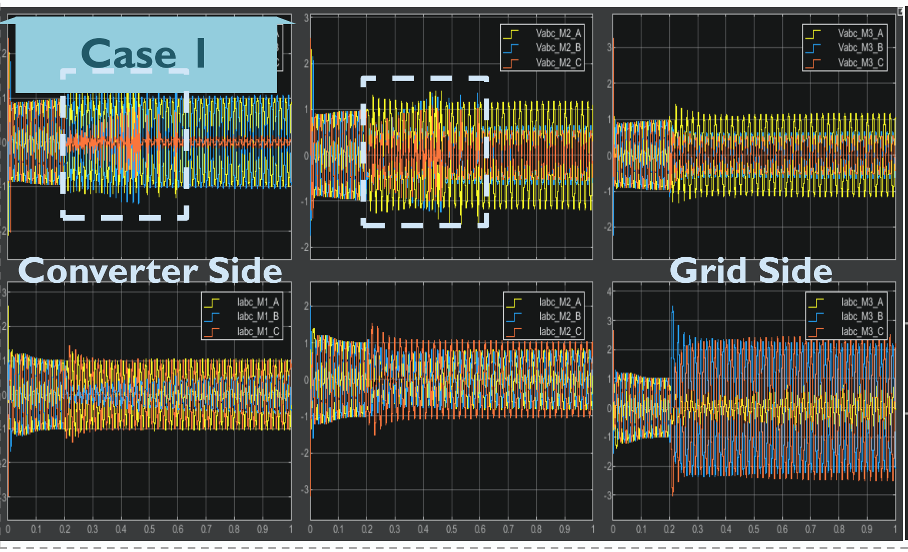
Can we further control the angle difference $\Delta\Psi$ to 0° to fully remove the under/reach issues of distance relay?

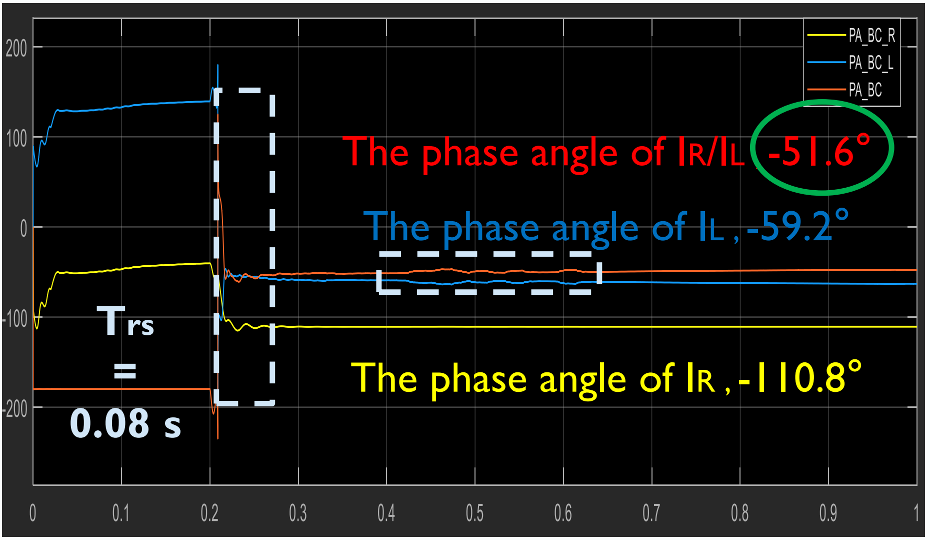
Answer: Yes !

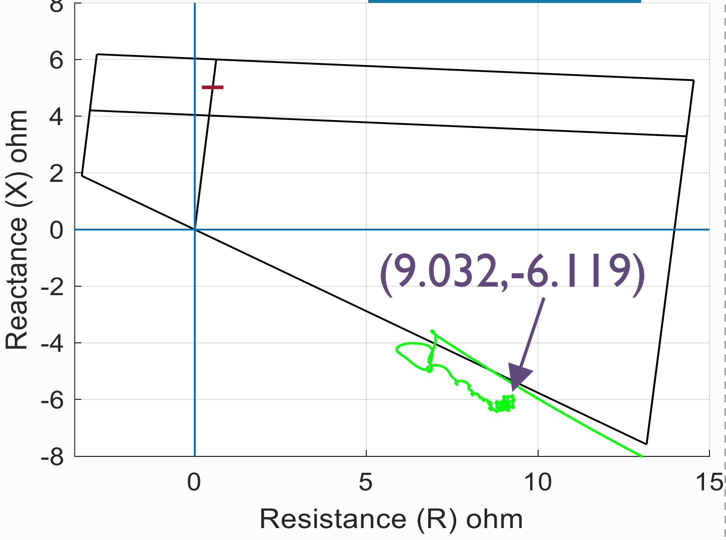
D. Liu, Q. Hong, A. Khan, A. Dyśko, A. Alvarez and C. Booth, Evaluation of Grid-Forming Converter's Impact on Distance Protection Performance, *IET 16th International Conference on Developments in Power System Protection*, 2022

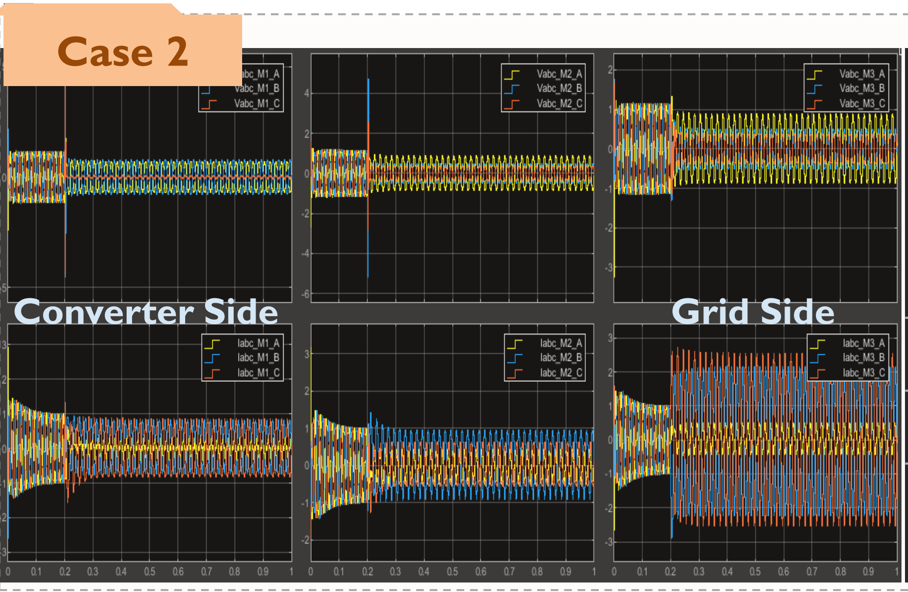
Performance Validation

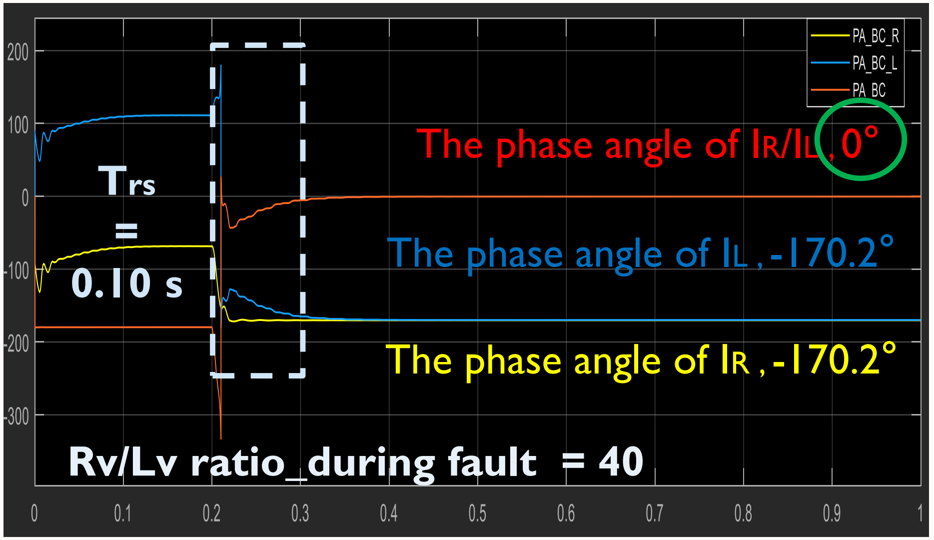
Cases	Types of converter control schemes	Fault conditions	Fault types
1	VI-FRT-based GFM	6 Ω, 15%, BC	Zone 1
2	The proposed VI-based GFM	6 Ω, 15%, BC	

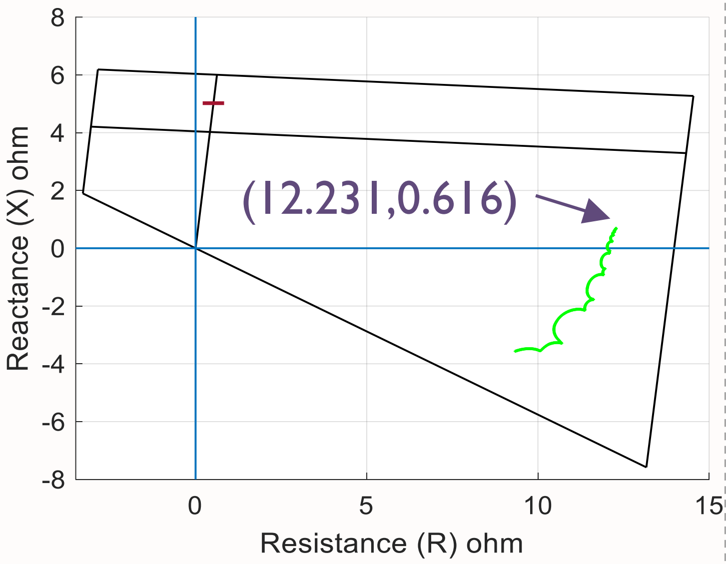












Conclusions

❑ Reduced fault level:

- Fault level in Scotland already low, and do not seems to get significantly lower.
- The fault characterise (determined by CBR control) seems to have larger impact than magnitude

❑ CBR control on protection performance:

- Existing control does not consider protection, can lead to risks of various protection failure.
- Impact on protection should be considered as part of control design.

❑ Emerging solutions for protection of CBR dominated networks

Travelling Wave:

- Fast, largely unaffected by CBR control and fault level
- Need to consider transformer impact, communications etc.

Revised distance protection

- No need to replace existing relays
- Performance dependent on CBR control strategy

Protection Assisted by Revised CBR Control

- No need to replace existing relays
- Required coordination with different converter control objectives

Thank you!

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