Assessment of AC Protection in weakening system

09th September 2021 | Webcast

Bharath Ponnalagan & Benjamin Marshall, The National HVDC Centre.
&
Karl Dirks & Lalin Kothalawala, Manitoba Hydro International.

The National HVDC Centre

We are expecting a large number of participants to join, so the session will start a couple of minutes late.

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Welcome to our Network Protection Webcast

Due to large audience, please turn off video & put microphone on mute

Please direct interactive discussions and questions to the speakers in MS Teams chat.

This webinar may be recorded. Link to slides will be shared after the webcast.

Considering a lot of participants are expected, all questions or comments may not be addressed during the webcast. A briefing note with summary of questions, answers and technical discussions will be published and circulated to all participants after the webinar.

Agenda

Time	Description
15.00 - 15:10	Welcome and Influential factors
15.10 - 15:45	Assessment of AC protection in weakening network
15:45 – 15:50	Subsequent Projects of Protection Testing
15:50 – 16:00	Q&As

Project Partners

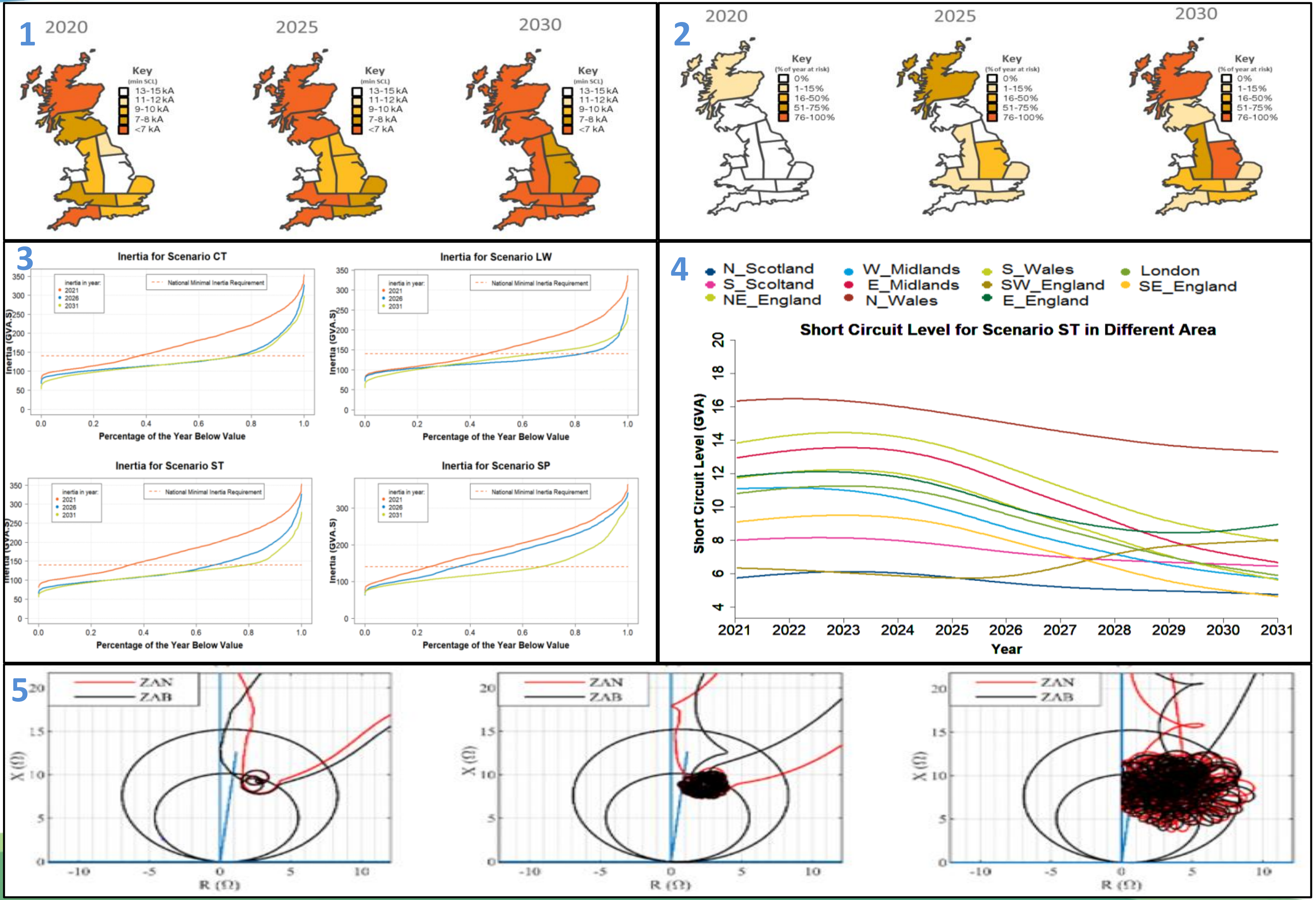
The National HVDC Centre

Manitoba HYDRO INTERNATIONAL

SP ENERGY NETWORKS

Background

The National HVDC Centre



Impact of declining Short circuit level (A System Operability Framework Document), National Grid ESO, download (nationalgrideso.com)

1. Phase Locked Loop Risk
2. Declining Short-circuit level
3. Mean Short Circuit Level for scenario System Transformation in different areas
4. Annual distribution of the inertia- where this is influences performance- not just the fault current, but its predictability!
5. Worsening Protection Performance on decreased Short-circuit level and increased converter penetration

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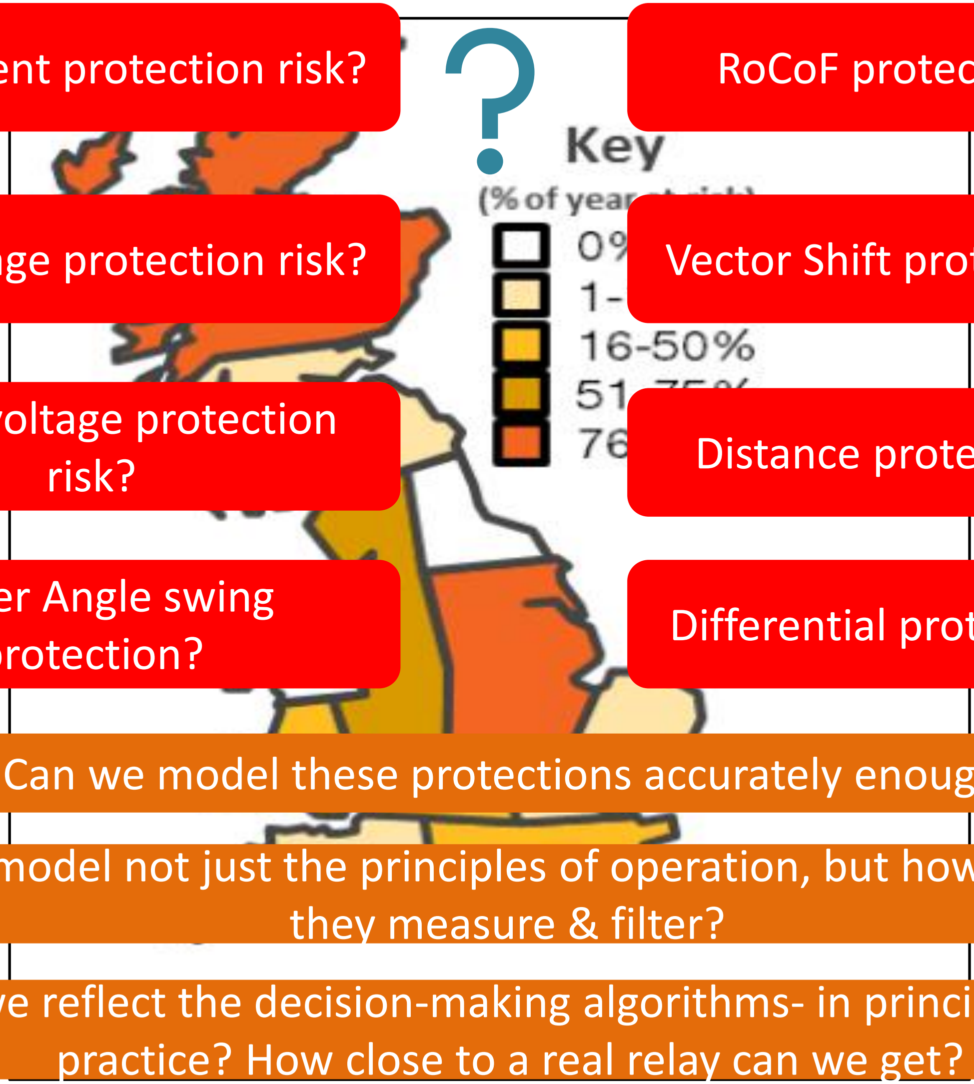
Project objectives...

The National HVDC Centre



Overcurrent protection risk?

RoCoF protection risk?

Overvoltage protection risk?

Vector Shift protection risk?

Under-voltage protection risk?

Distance protection risk?

Power Angle swing protection?

Differential protection risk?

Problem

Can we model these protections accurately enough?

Can we model not just the principles of operation, but how and what they measure & filter?

Can we reflect the decision-making algorithms- in principle or in practice? How close to a real relay can we get?

Solution

1. Protection performance challenges can emerge across a range of protection assets- how many & in what forms?
2. To what extent can these be screened for/ understood in off-line simulation?
3. What are the limitations of the available models?
4. Can these be addressed within improved models?

Assessment of AC Protection Systems Performance in a Weakening System

September 9th , 2021

Karl Dirks EIT
Lalin Kothalawala M.Sc. P.Eng.

What is the purpose of this work…

- The UK is undergoing a significant switch from traditional power sources (Coal, Nuclear, Gas) to new renewable plants and transmission techniques (Wind, Solar, HVDC)
- Traditional power sources have certain characteristics during a fault:
  - Around 10 times rated current for short period
  - Significant negative and zero sequence fault current for unbalanced faults

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What is the purpose of this work…

- Current in inverter-based generation (IBG) is thermally limited so will only produce slightly over the rated current during a fault

  ↓ Fault Current

- Negative and zero sequence current contribution is significantly less than synchronous machines (dependent on control scheme)

  ↓ Negative and Zero Sequence

- Typically, IBG is not a supplier of system inertia (though this is currently a topic of research)

  ↓ System Inertia

What is the purpose of this work…

- Existing transmission protection algorithms are based on:
  - AC generation and transmission system
  - Classical behaviours of synchronous machines

- New fault current envelope/characteristics no longer guaranteed to meet the algorithm assumptions

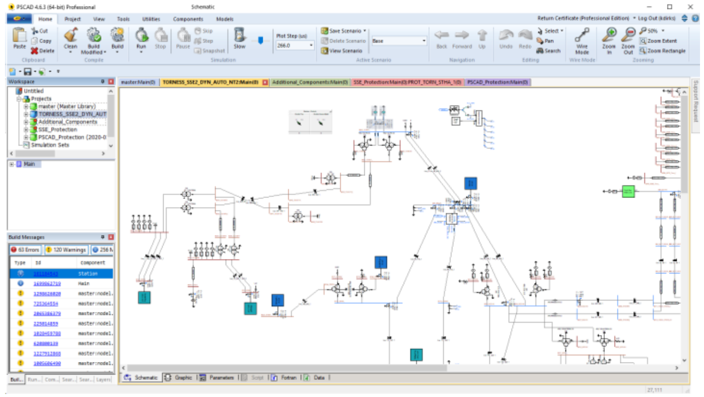
What is the purpose of this work…

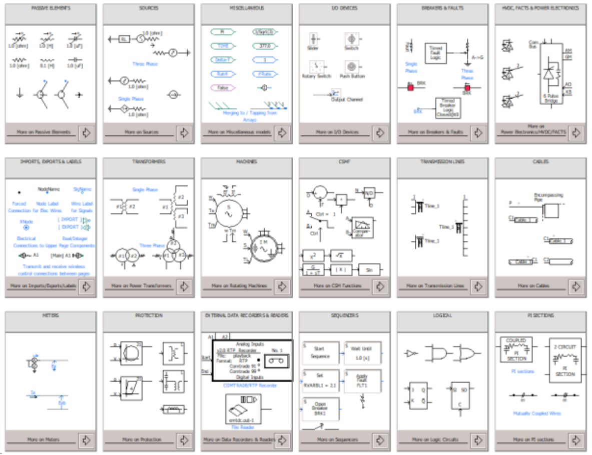
- This work considers the effect on AC transmission protection algorithms in a weakening system due to integration of IBG and retirement of traditional generation (based on PSCAD™ studies)
- Primary focus on Distance Protection algorithms
- Uses a representative portion of the UK grid (Area around Torness Nuclear Power Station) with different contingencies to capture future loss of network strength
- Preliminary investigation (has potential for further development)
- All studies performed in the industry standard software **PSCAD™**

What is PSCAD™?

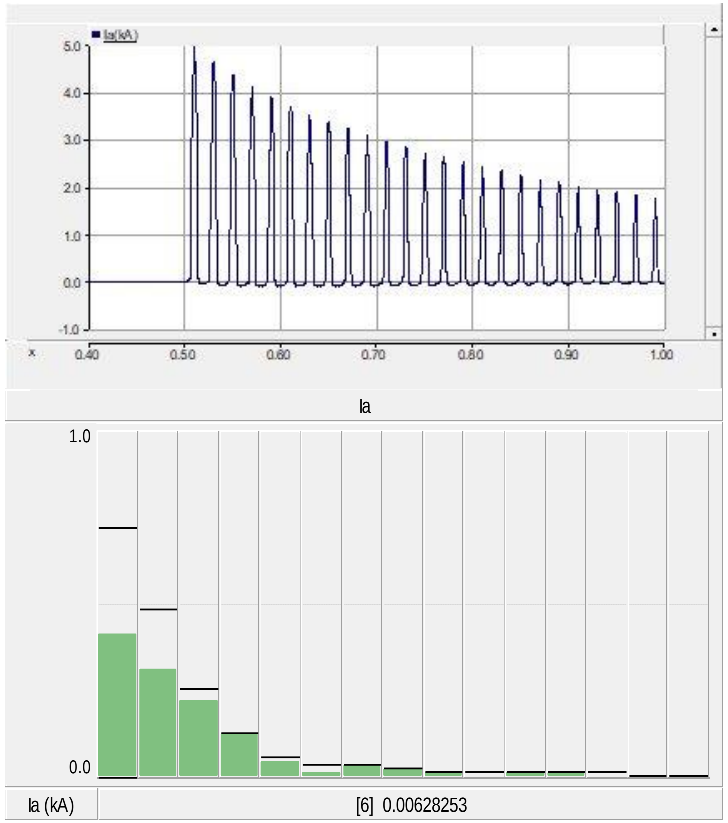
PSCAD™ (Power Systems Computer Aided Design)

- Allows the simulation of complex models in the electromagnetic domain (EMT Domain)
- Model interface is provided so that users can create endless options outside of the in-built libraries
- Captures unbalanced and chaotic interactions that are not possible in RMS type simulations (control interactions, transformer ferro-resonance, fault current DC offset)

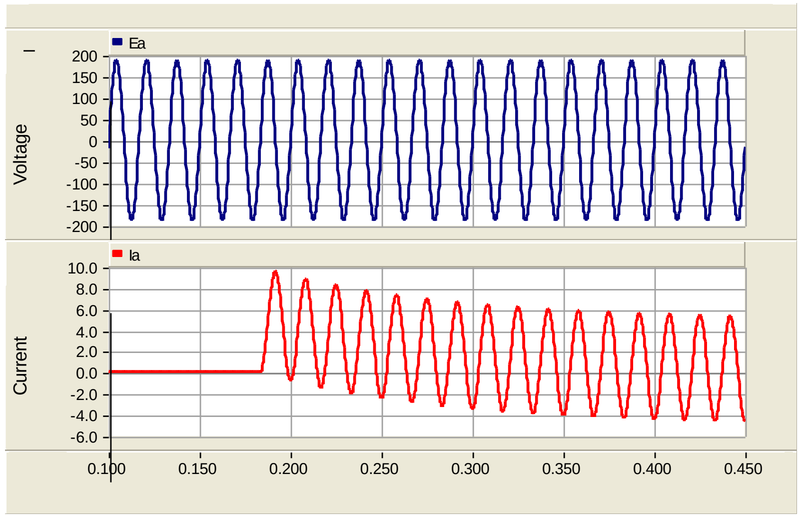




Transformer Inrush Current



Fault Current DC Offset



For more information and examples please see: https://www.pscad.com/knowledge-base

What level of detail is included…

- Power Plants
  - Wind Farms (full converter models)
  - Synchronous Machines (differential machine equations)
- Transmission lines
  - Bergeron Model (travelling wave, lines longer than about 10 km)
  - Coupled Pi-Section (short lines)
- Transformers
  - Detailed EMT model

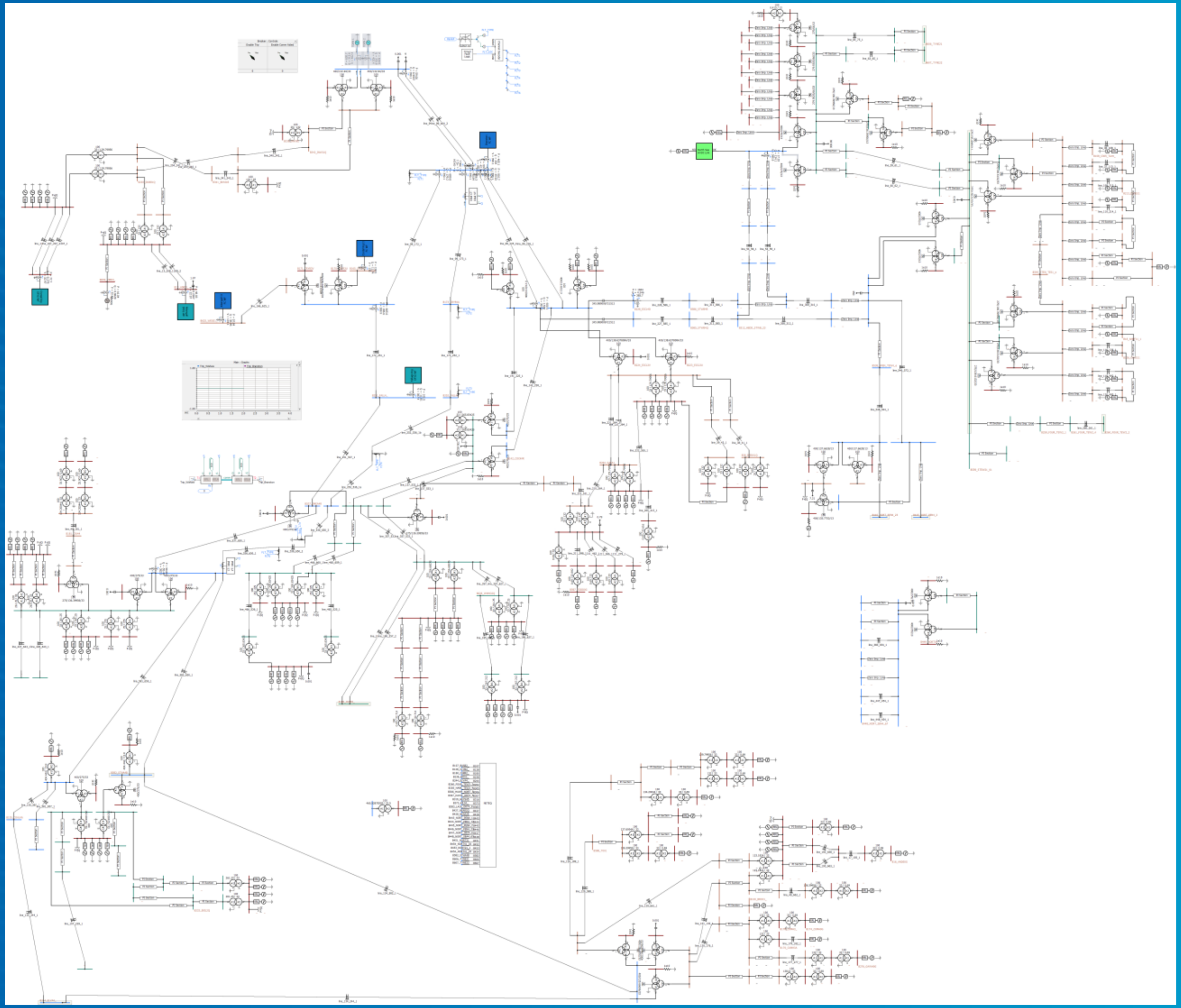
What level of detail is included...

- Protection Relays
  - Detailed generic protection models (new PSCAD™ protection library)

A high level of detail is required in the PSCAD™ model to represent the in-fault behaviour of the converter-based generation.

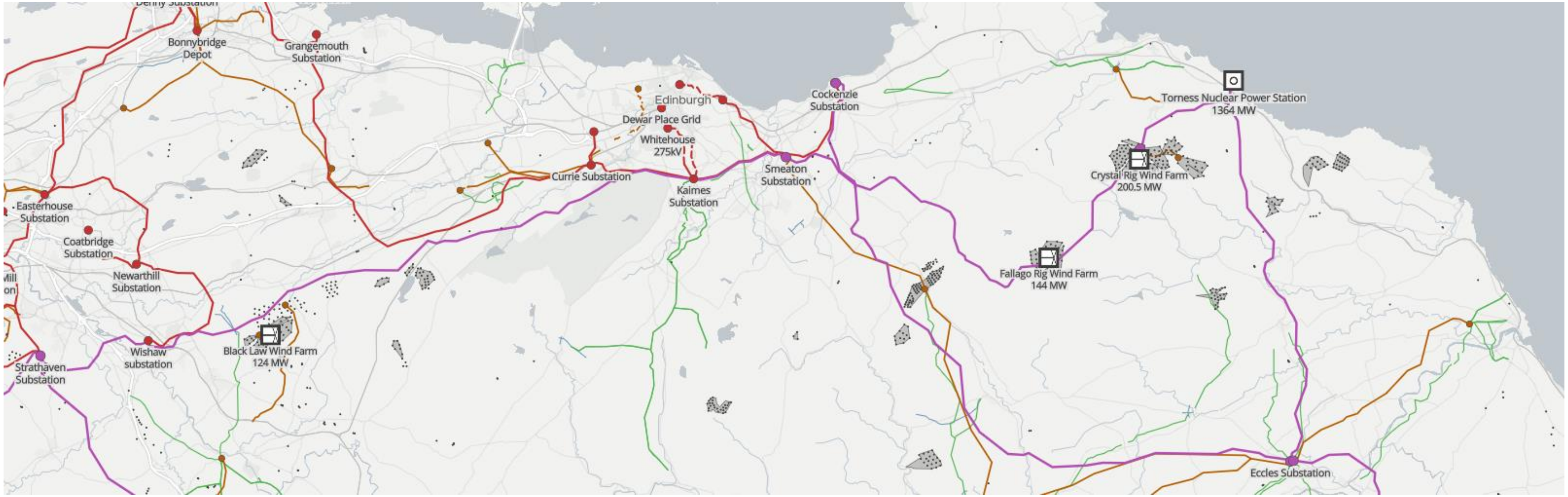
As more information is made available the model can be continuously updated and upgraded

Study Model



Area of Interest

- Area around Torness Nuclear Power Station

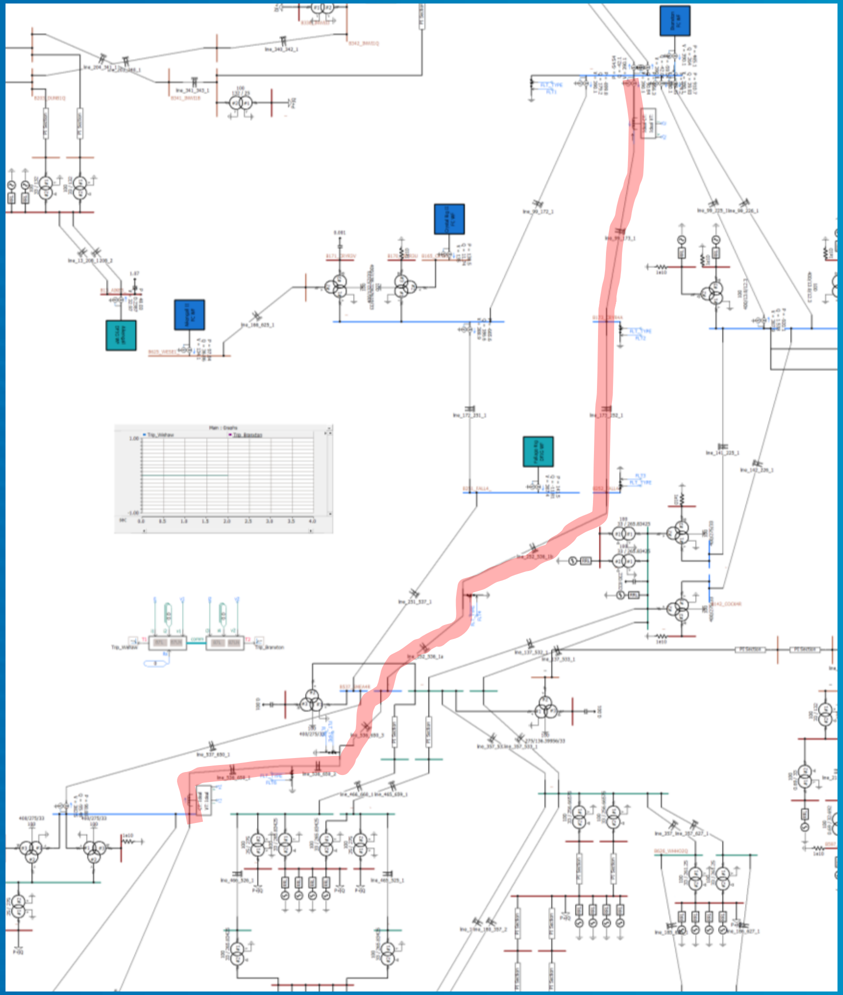


Transmission Lines Considered

- 400 kV Branxton to Wishaw (currently Torness to Strathaven)
- 132 kV Innerwick to Dunbar

Both lines represented as Bergeron travelling-wave models with RXB data extracted from the provided PowerFactory™ model

400 kV Branxton to Wishaw



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Synchronous Machines

Parameter	Unit
Rated RMS Line-to-Neutral Voltage	kV
Rated RMS Line Current	kA
Base Angular Frequency	Hz
Inertia Constant	s
Armature Resistance [Ra]	pu
Potier Reactance [Xp]	pu
D: Unsatured Reactance [Xd]	pu
D: Unsatured Transient Reactance [Xd_]	pu
D: Unsatured Sub-Transient Reactance [Xd__]	pu
D: Unsatured Transient Time (Open) [Td_]	s
D: Unsatured Sub-Transient Time (Open) [Td__]	s
Q: Unsatured Reactance [Xq]	pu
Q: Unsatured Transient Reactance [Xq_]	pu
Q: Unsatured Sub-Transient Reactance [Xq__]	pu
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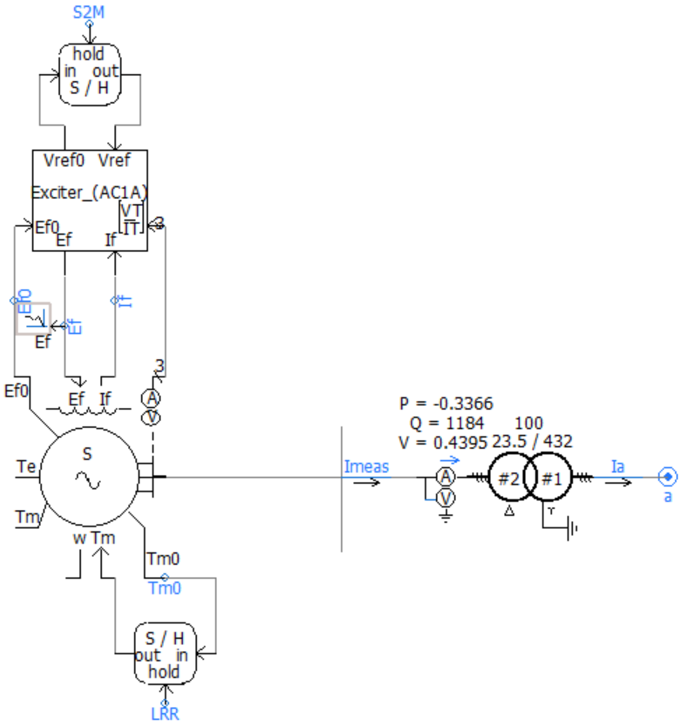

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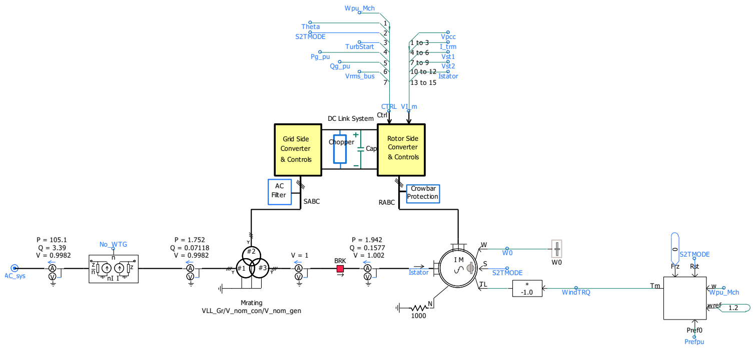
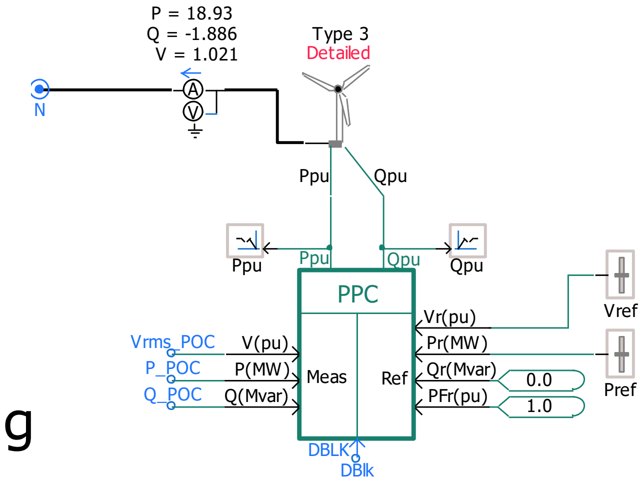
Type 3 Generic Windfarms

- Mechanical System
  - Induction Machine (Also Electrical)
  - Simple PI Torque Controller
- Electrical System
  - Grid-side Converter and Controls
  - Rotor-side Converter and Controls
  - DC-link Chopper Protection
  - Crowbar Protection
  - Low Pass Filter
  - 3-Winding Grid Transformer
  - Power Scaling Component

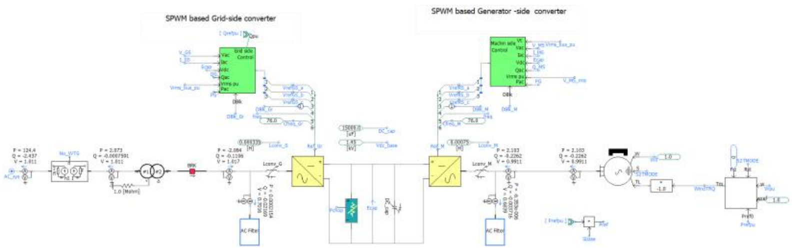


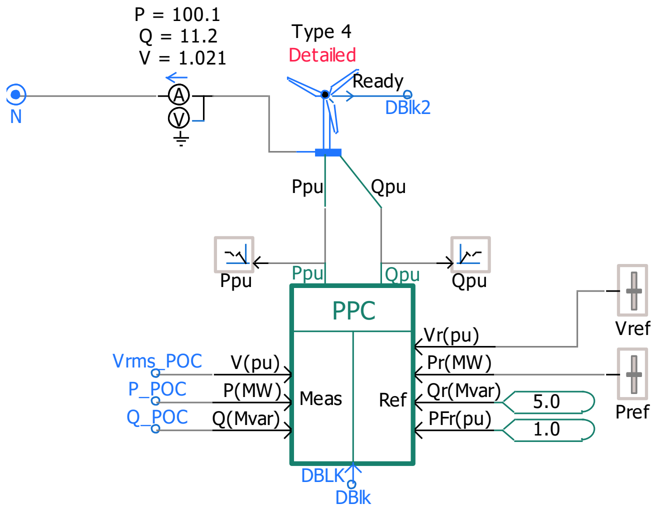


Aikengall I, Crystal Rig I, Fallago Rig

Type 4 Generic Windfarms

- Mechanical System
  - Permanent Magnet Machine (Also Electrical)
  - Simple PI Torque Controller
- Electrical System
  - Grid-side Converter and Controls
  - Machine-side Converter and Controls
  - DC-link Chopper Protection
  - Low Pass Filter
  - LV/MV Power Transformer
  - Power Scaling Component

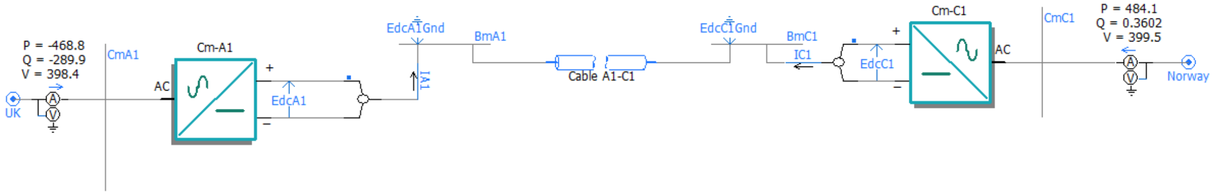




Aikengall II, Branxton, Crystal Rig II, NNGB

HVDC – Future North Sea HVDC Link

- Terminals are represented using a generic Modular Multilevel topology (MMC) with decoupled current controllers
- UK end (Blyth) holds reactive power and DC voltage steady
- Representative cable and topology use



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Network Equivalent

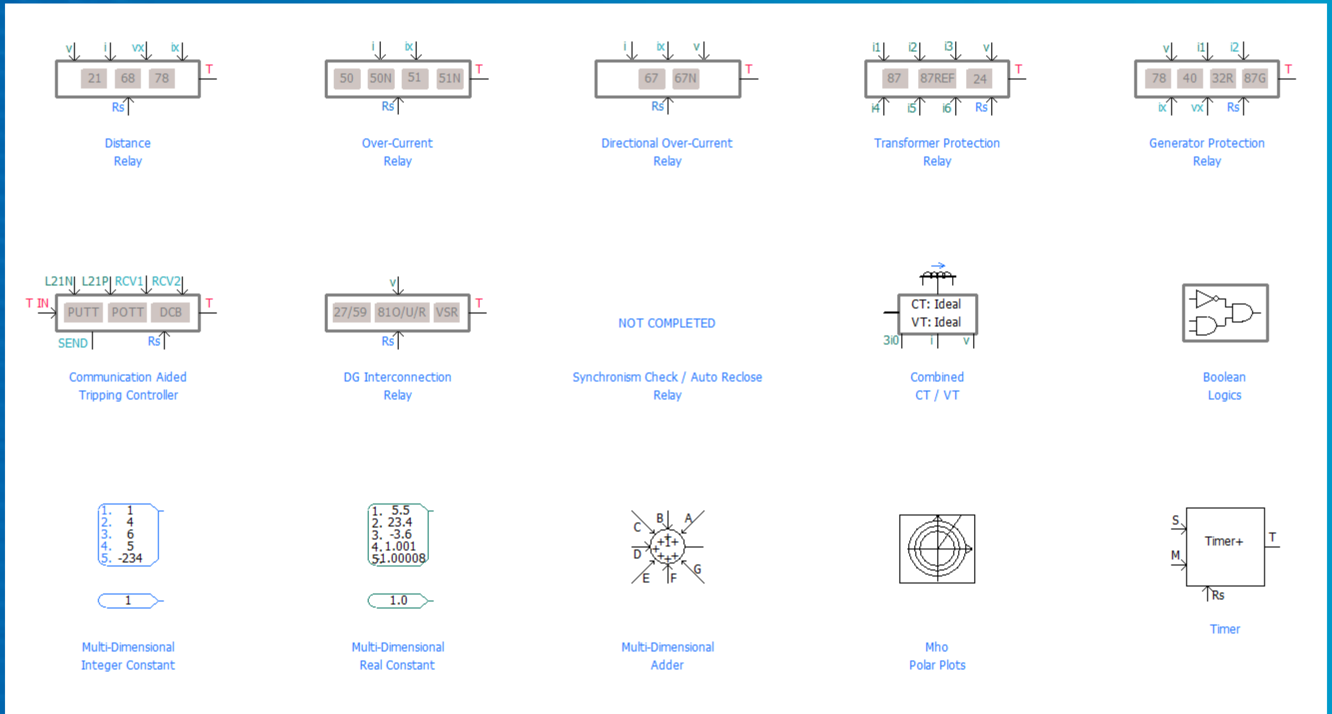
- Network components beyond the identified study area need to be considered but not included
  - Kron Reduction -> numerically reduce the admittance matrix to create equivalent impedances between boundaries
  - Ensures load flow and short circuit levels from rest of network are maintained
- Carried out by SPT in PowerFactory™ prior to the network information being provided to MHI

Assumptions and Limitations

- The model presented in this work is only for demonstration purposes and cannot be used to make detailed policy decisions
- Specific manufacturer models are needed to fully model true dynamic behaviour

Protection Elements

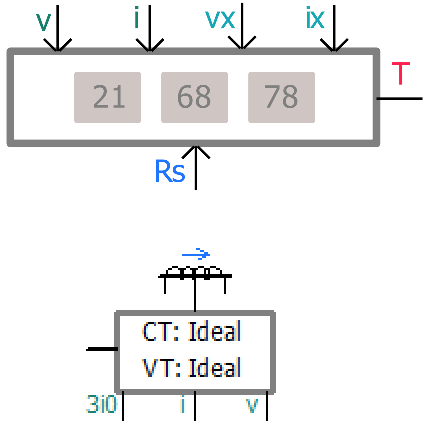
New protection library for PSCAD™ (Currently in BETA, expected to be officially released in 2022)



Transmission Differential Relay not pictured. BETA available for evaluation through PSCAD™ support.

PSCAD™ Distance Protection Model

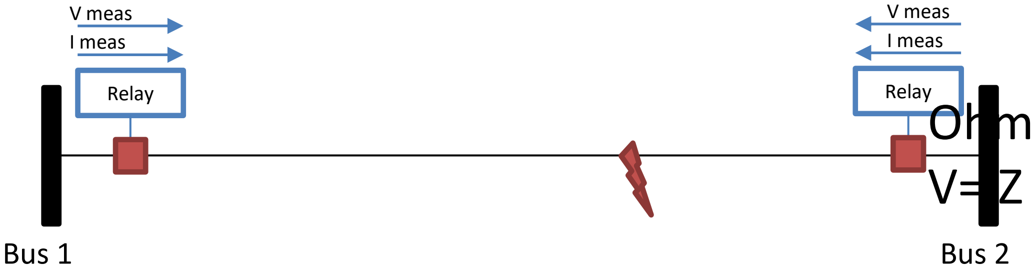
- Up to four mho/quadrilateral protection zones
- User selectable sampling rate
- Supervisory functions
  - Out-of-Step Blocking
  - Directional Supervision
  - Fault Type Identification
  - Load Encroachment



Distance Relay Theory

Normal Operation

Faulted Operation



Ohm's Law

$V=IZ \therefore Z=V/I$

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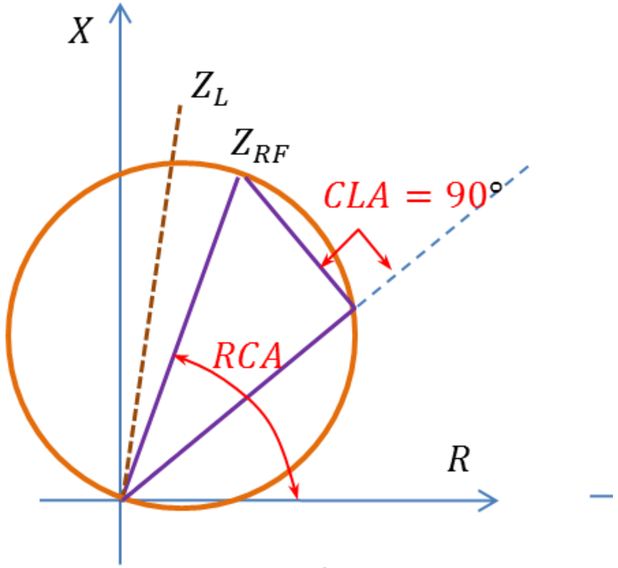
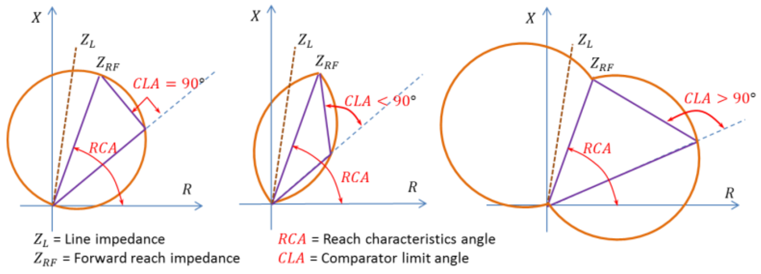
Distance Relay Theory



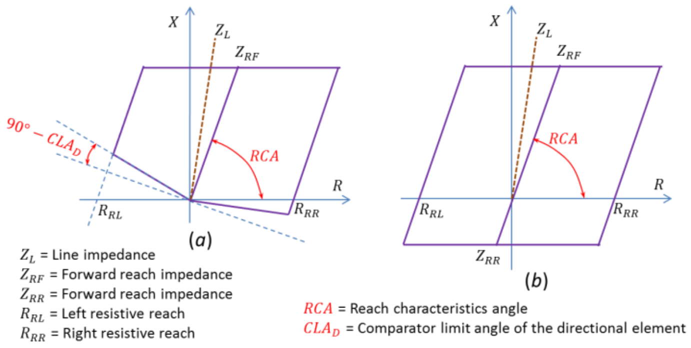
Z_L = Line impedance
Z_{RF} = Forward reach impedance

- Impedance measured during fault
- Check if impedance falls within zone -> if so, wait for trip to be issued

Distance Relay Theory



Mho Characteristic



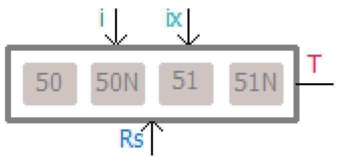
Quadrilateral Characteristic

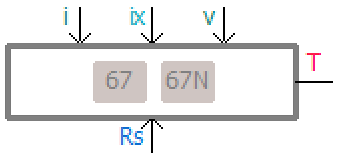
Distance Relay – Initial Potential Issues

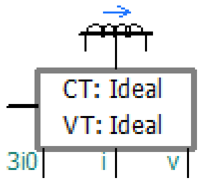
- Decreased Short Circuit Level
  - Require a certain ratio of the source impedance to line impedance (SIR) to operate within error limits (National Grid requires SIR < 30)
  - Some relays have a minimum fault current threshold
- Reduced System Inertia
  - Power swings are more likely across lines. Impedance may swing into zone
- Voltage Polarization
  - Uses a bit of pre-fault voltage if the measured voltage falls below threshold
  - Introduces an error in the impedance calculation. Can be large if source impedance is large and in-fault phase shift is large. (Will discuss more in upcoming section)

PSCAD™ Over-current Protection Model

- Up to three elements of each type (ANSI 50,50N,51,51N)
- Directional supervised version also available (ANSI 67,67N)
  - Definite Time Over-Current
  - Inverse Time Over-Current







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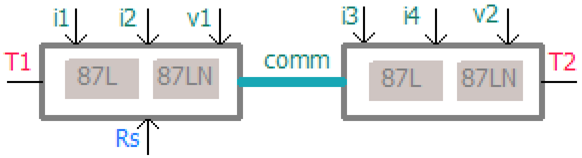
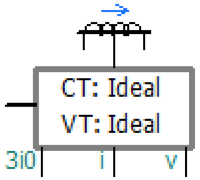
Over-Current Relay – Initial Potential Issues

- Decreased Short Circuit Level
  - Relies on sufficient fault level to operate
  - Most susceptible of transmission protection relays to reduced current
- Reduced Negative Sequence Current
  - Many directional decision algorithms (used in ANSI 67,67N) depend on the angles between sequence currents/voltages
  - These assumptions may no longer hold true

PSCAD™ Differential Protection Model

- Uses KCL to determine if fault is within protected zone
- Two current elements from each side
- Differential and Fast Differential characteristics supported
- Supervisory Functions:
  - CT Saturation Detection
  - Delta Phase Protection
  - Harmonic Blocking





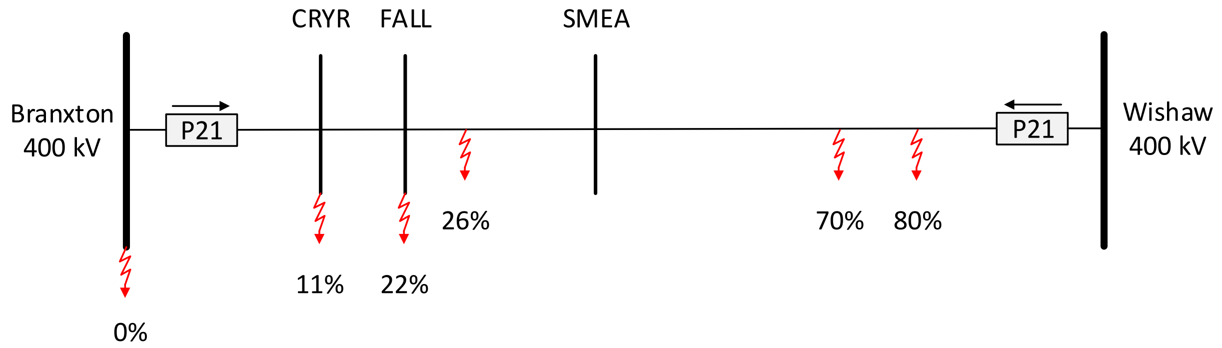
Differential Relay – Initial Potential Issues

- Generally resistant to low fault current
- Disturbance Detection Function
  - Used to block spurious trips from data corruption in communication
  - Very manufacturer dependent but often depends on sequence currents or voltages
- Decreased Short Circuit Level
  - If it drops by a large margin, it may become close to the bias setting (minimum differential current to allow trip)

Fault Studies

- 400 kV Branxton to Wishaw (currently Torness to Strathaven)
- 132 kV Innerwick to Dunbar

Branxton to Wishaw 400 kV



Line Info

Total Line Impedance	38.1∠85.1° Ω
VT Ratio	3636
CT Ratio	2000
Secondary Impedance	20.96∠85.1° Ω
Zone 1	75%
Zone 2	117%
Zone 3	140%

- Simple Mho Elements (CLA = 90 degrees -> Circle)
- Zone distances based on previous configuration

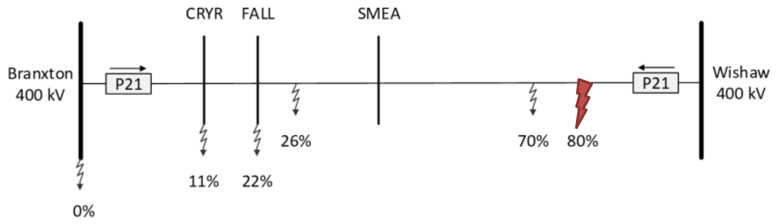
Branxton to Wishaw 400 kV

- Network Contingencies Pre-Fault

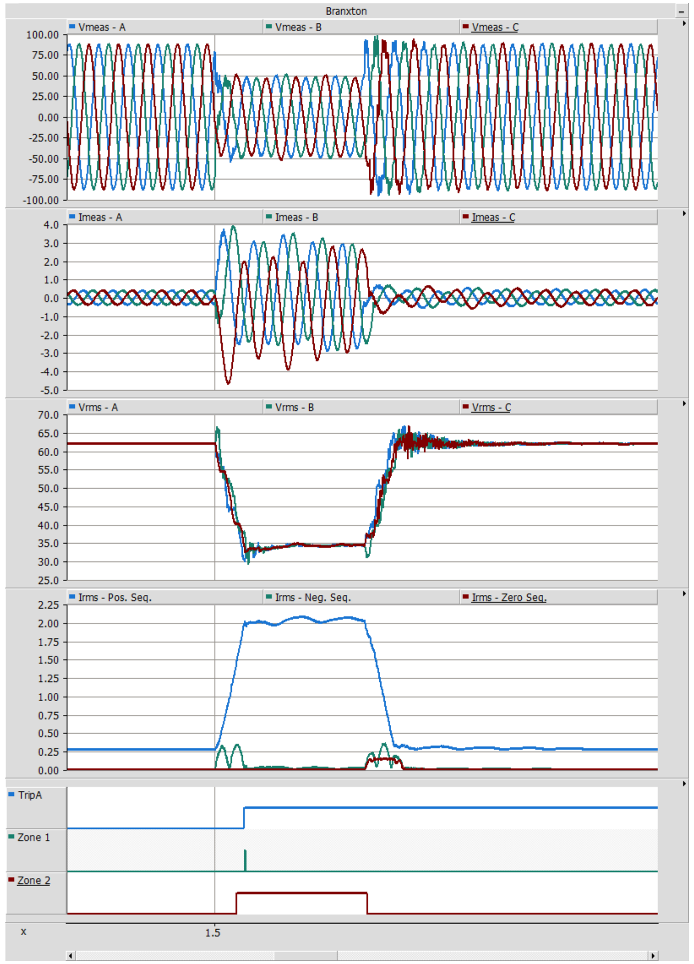
1. System normal, all power plants in service
2. System normal, Torness 1/2 out-of-service
3. N-1 one Branxton to Eccles line out, Torness 1/2 out-of-service
4. N-2 both Branxton to Eccles line out, Torness 1/2 out-of-service
5. N-2 both Branxton to Eccles line out, Torness 1/2 out-of-service, all WF out-of-service

Decreasing Fault Levels

Branxton to Wishaw 400 kV



- Spurious Zone 1 Pickup -> Instantaneous trip (Mal-operation)
- Zone 2 Pickup is correct
- Need to look at impedance plot in detail as reason is not obvious



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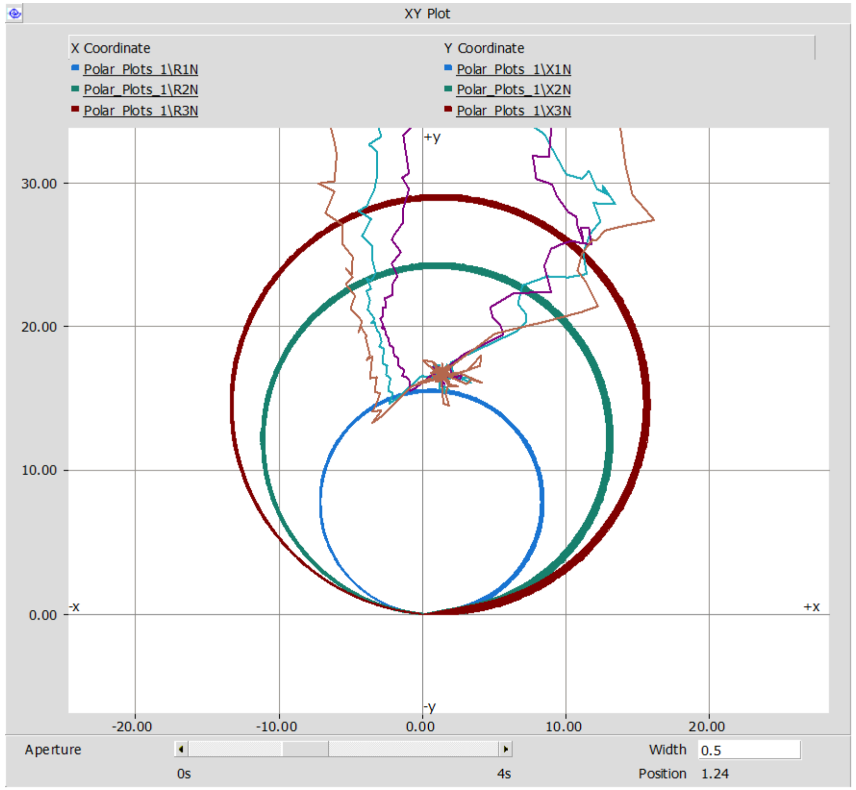
Branxton to Wishaw 400 kV

- Measured impedance swings around the true impedance during the fault
- Temporarily crosses into Zone 1
- Whether this will issue a trip in real relay will depend on manufacturer algorithm (proprietary design)



- System normal, all power plants in service
- System normal, Torness 1/2 out-of-service
- N-2 both Branxton to Eccles line out, Torness 1/2 out-of-service, all WF out-of-service

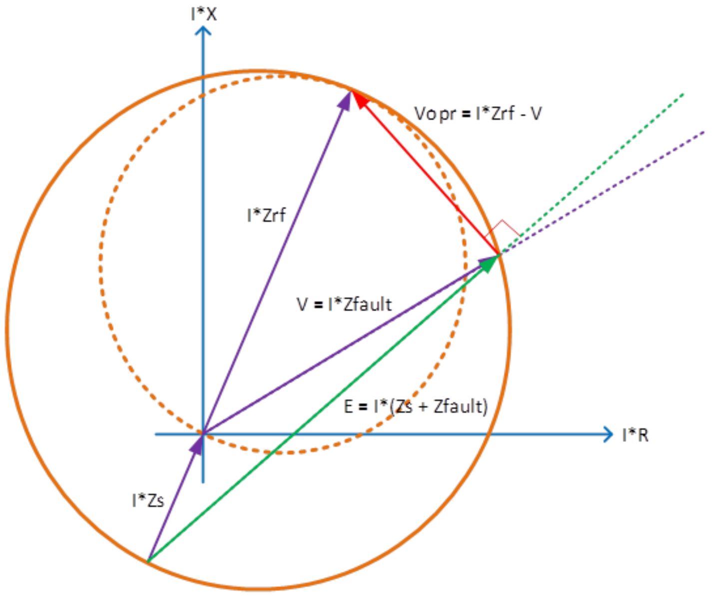
Innerwick to Dunbar 132 kV

Line Info

Total Line Impedance	3.82∠67.6° Ω
VT Ratio	1200
CT Ratio	2000
Secondary Impedance	6.38∠67.6° Ω
Zone 1	80%
Zone 2	120%

- Simple Mho Elements (CLA = 90 degrees -> Circle)
- Zone distances based on industry practice

Expanding Dynamic Characteristic



Z_{rf} = Forward reach impedance
Z_{fault} = Fault impedance + line impedance to the fault
Z_s = Source impedance
V_{opr} = Operating voltage. Characteristic voltage – measured voltage
V = Measured voltage vector
E = Combination of measured voltage and prefault polarized voltage
I = Measured line current
θ = Angle between operating voltage and E

- Occurs with certain types of memory polarization
- Effective measured voltage is combination of pre-fault (source impedance) and during fault (line impedance) voltages
- Creates an expansion of the zone to capture potential maloperations
- Can expand too far

Effect of Differential Protection

- Replaced the distance protection relays with generic differential protection
- All observed mal-operations were eliminated

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Additional Considerations

Time Permitting:

- Power Angle Swings
- Impact on Negative Sequence Functions
- Impact on Rate-Of-Change-Of-Frequency (ROCOF) Relay

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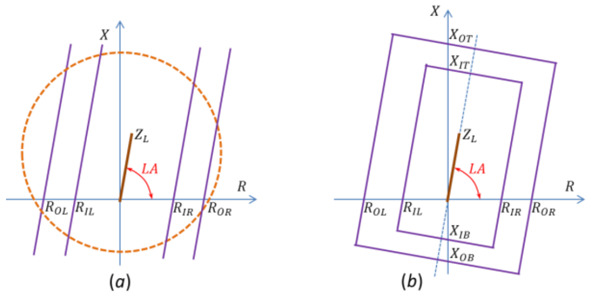
Power Angle Swings

- Occur when generators temporarily lose synchronism during disturbance
- Sustained low frequency voltage and current oscillations can swing through distance protection zone
- Out-of-step (OOS) function detects this condition and modifies the output trip (can block or issue depending on use case)
- No power angle swings detected in studied scenarios



Z_L = Line impedance
R_{IL} = Inner zone left resistance reach
R_{IR} = Inner zone right resistance reach
R_{OL} = Outer zone left resistance reach
R_{OR} = Outer zone right resistance reach

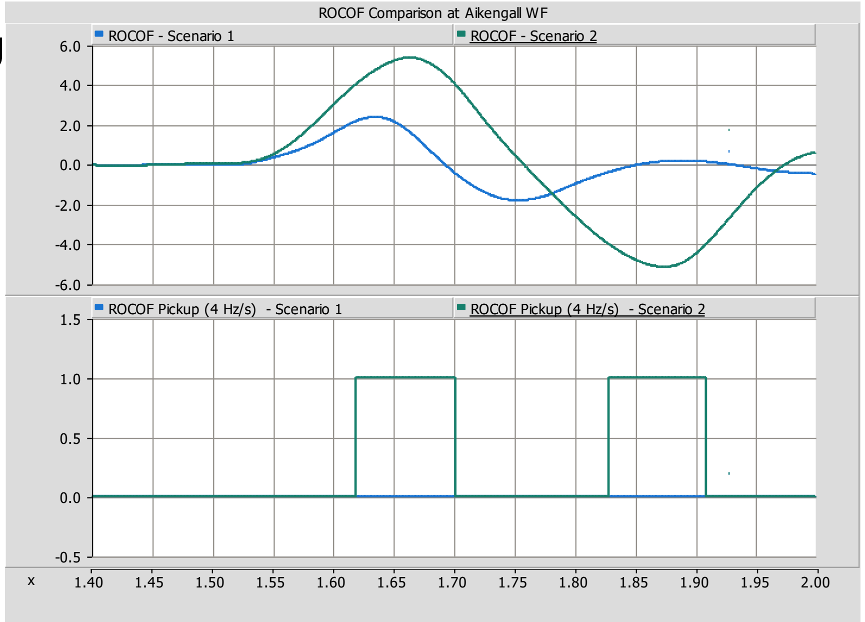
LA = Line impedance angle
X_{IT} = Inner zone top reactance reach
X_{IB} = Inner zone bottom reactance reach
X_{OT} = Inner zone top reactance reach
X_{OB} = Inner zone top reactance reach

Impact on Negative Sequence Functions

- Inverter based sources inject significantly less (or none depending on control scheme) negative sequence current than synchronous machines
- Some common protection functions which use negative sequence current:
  - Directional blocking
  - Fault type identification
  - Disturbance Detection
  - Some algorithm specific impedance estimation
- No mal-operations due to these issues were observed in this study

Impact on Rate-Of-Change-Of-Frequency

- Reduced system inertia allows faster local frequency swings during and post disturbance
- Distributed generation often has anti-islanding ROCOF relays
- Significant risk of disconnection in the future which requires revised settings and/or frequency support devices



Conclusions

Basic assumptions built into the fabric of protection algorithms may no longer be valid in the new system paradigm.

The required level of detail to simulate these complex bahaviours has increased.

In the future a greater emphasis on non-traditional protection studies may be required ensure proper operation.

Next Steps

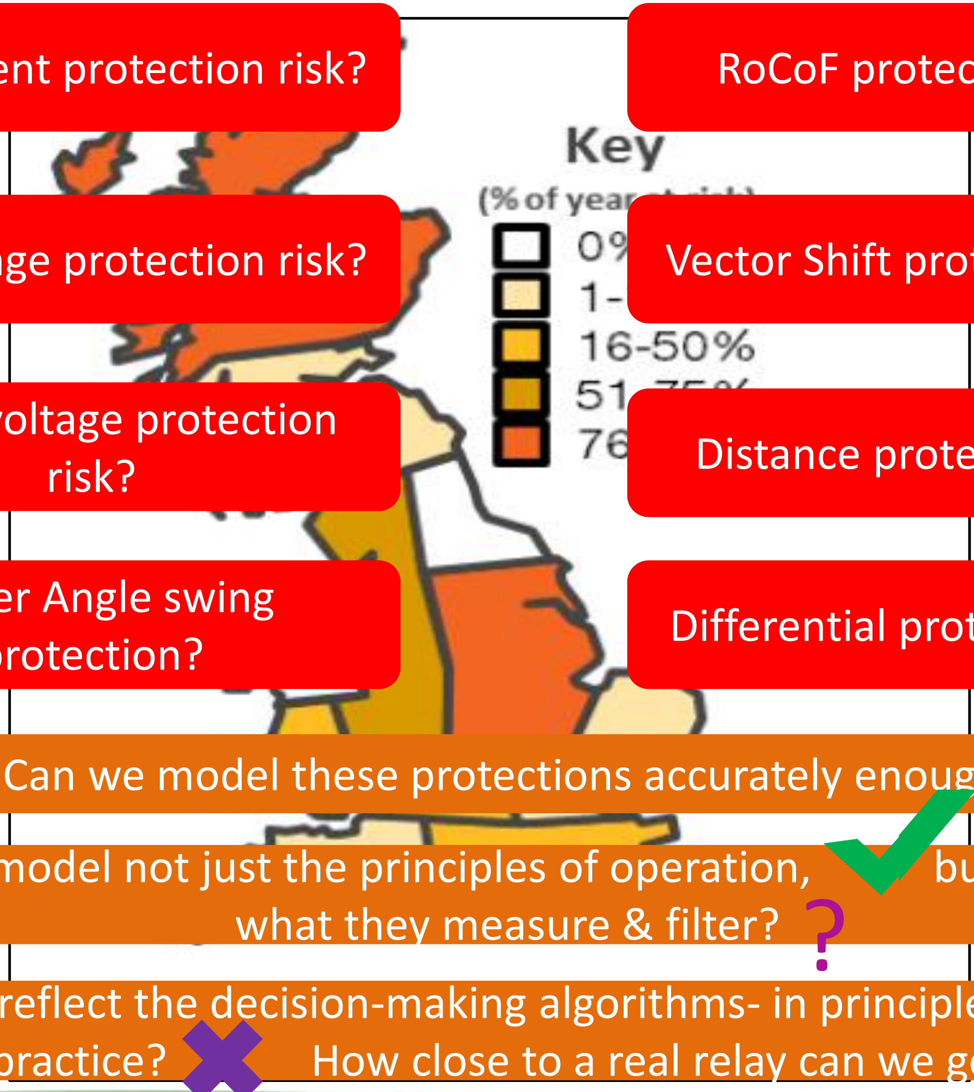
The presented model has been created as a representative basis. Some potential issues are identified but sufficient detail is not present to make decisions about specific pieces of protected equipment.

Further studies must be undertaken with an increased level of detail:

- Using manufacturer provided models
- Including CT/VT saturation data
- Include Bus, Transformer, and Generator protection relays

Additional avenues of simulation, such as Hardware-in-the-Loop (HIL) and Comtrade playback, may also be required.

Project outcomes...



Problem

- ! Overcurrent protection risk?
- ? Overvoltage protection risk?
- ? Under-voltage protection risk?
- ! Power Angle swing protection?
- RoCoF protection risk? !
- Vector Shift protection risk? !
- Distance protection risk? !
- Differential protection risk? ?

Solution

- Can we model these protections accurately enough? ✗
- Can we model not just the principles of operation, ✓ but how and what they measure & filter? ?
- Can we reflect the decision-making algorithms- in principle? ? or in practice? ✗ How close to a real relay can we get? ✗

1. Protection performance challenges can emerge across a range of protection assets- how many & in what forms? ?
2. To what extent can these be screened for/ understood in off-line simulation? ✗
3. What are the limitations of the available models? ✓
4. Can these be addressed within improved models? ?

Key

- ✓ Has been answered in project
- ? Requires further investigation
- ! Has been highlighted in project
- ✗ Not practicable at this time, via off-line simulation.

The Future of Protection System Testing

09th September 2021 | Webcast

Bharath Ponnalagan, The National HVDC Centre

The National HVDC Centre

We are expecting a large number of participants to join, so the session will start a couple of minutes late.

Scottish & Southern Electricity Networks

TRANSMISSION

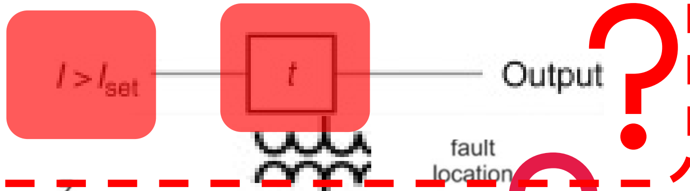
Low fault level and Converter related risks for Protection

The National HVDC Centre

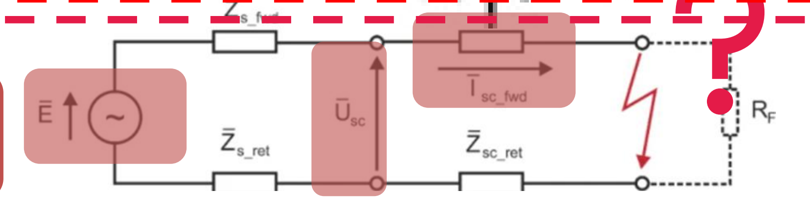
- Convertor fault current injection is limited and non-linear in magnitude.
- Low fault level would reduce the transient and sub transient fault current
- Convertor fault injection is initially chaotic in angle, stabilising differently for different faults
- Low fault level would will change the impedance trajectory
- Converter based compensation like STATCOM, Virtual Synchronous machines could help
- Synchronous compensation can help, but needs to be carefully sized and distributed
- Control changes can help but need to be considered against a range of required functions.

?

Overcurrent protection risk

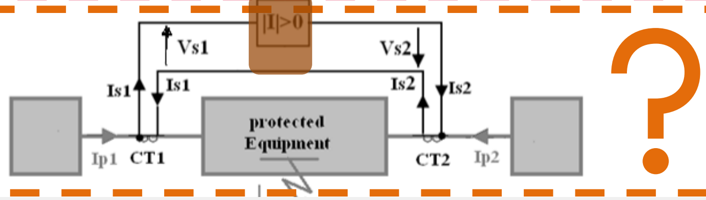


Distance Protection risk



Current Measuring Relay

Differential Protection risk



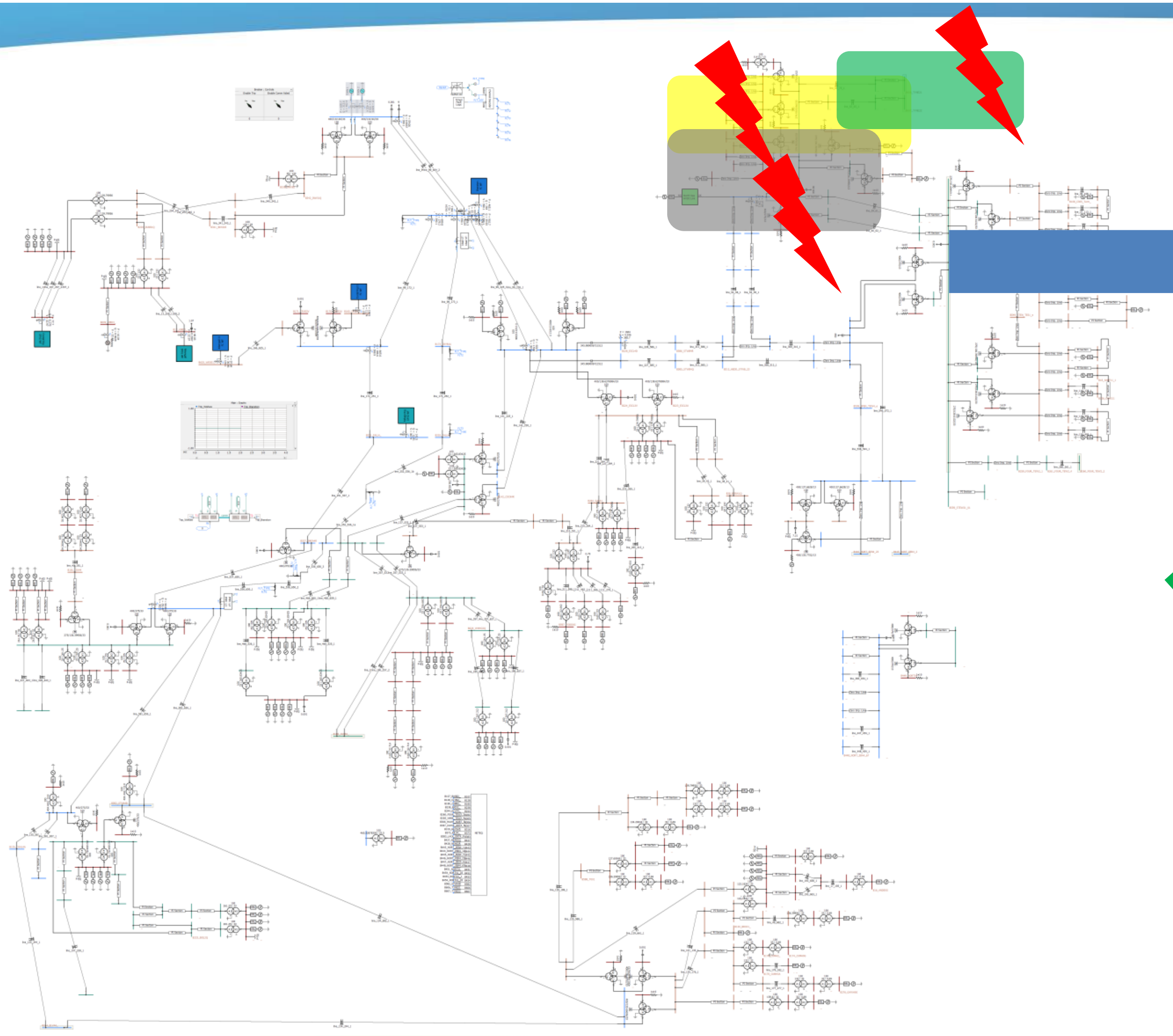
Combines with Other stability need areas

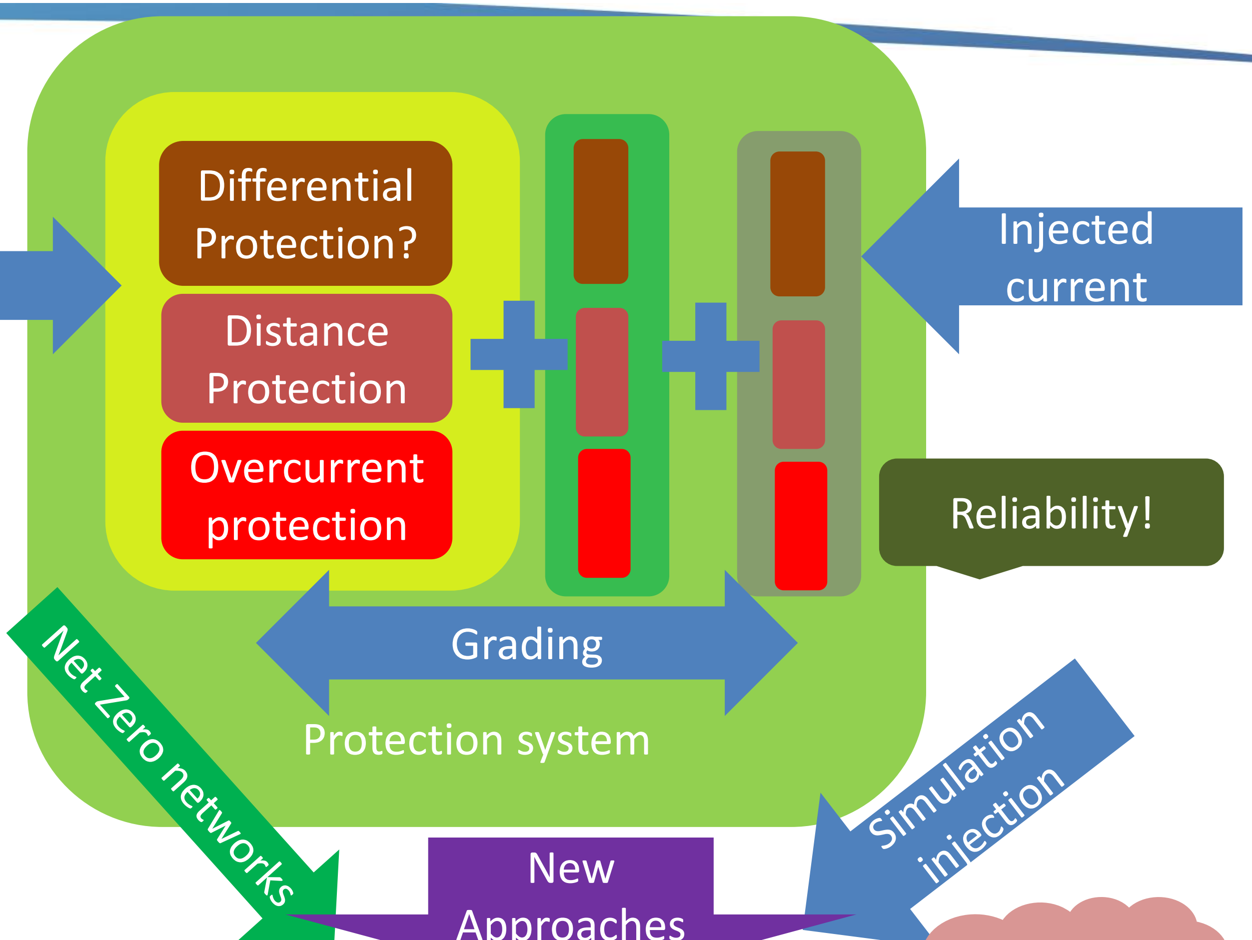
NOA Stability Pathfinder – Phase 2 (ongoing)

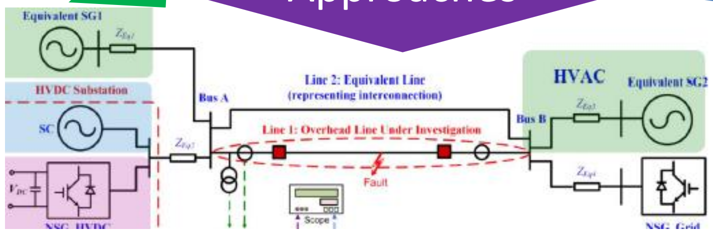
Phase 2 is looking for the most cost effective way to increase both stability and inertia (stored energy) in Scotland.

- **All forms of Protection used today are potentially compromised in convertor dominated areas.**
- **Synchronous compensation is a “Hammer” to crack a protection “Nut”**
- **Code and standard review is an imperfect instrument without more information.**
- **<u>New Protection systems could address these issues more effectively</u>**

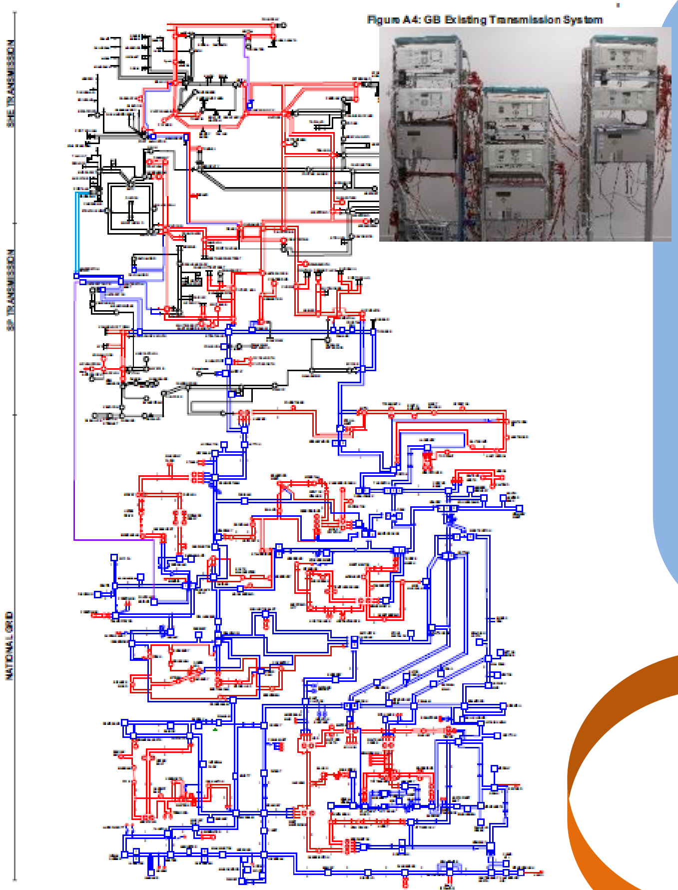
Protection systems today- how they work & how we know that.





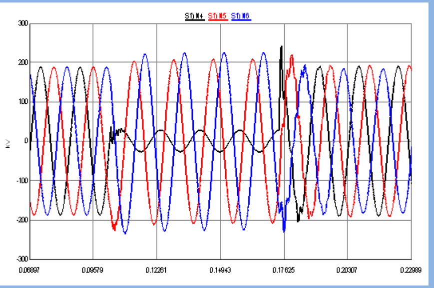


NIA project- New Protection system verification and testing



Real protections in Real time simulation environment HIL studies

Real protections in the real system- "open loop"

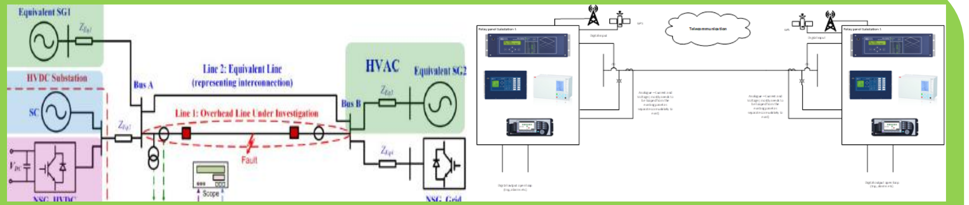


Fault recorder data, pseudo-operation logs

Reliability evidence across a range of new vendor approaches

- WAPS?
- Negative Seq. Diff.?
- Neutral Diff.?
- Travelling wave?

Review experience



Defining reliability requirements, testing and verifying these

- New testing approaches & processes
- New Protection System Options
- New reliability indexes

Thanks for listening.

Any questions, please?

- For further information, please visit www.hvdccentre.com ; OR email: info@hvdccentre.com

The National HVDC Centre

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