Challenges to Control and Protection of Future Power Systems

Dr Campbell Booth
University of Strathclyde

May 18th 2015

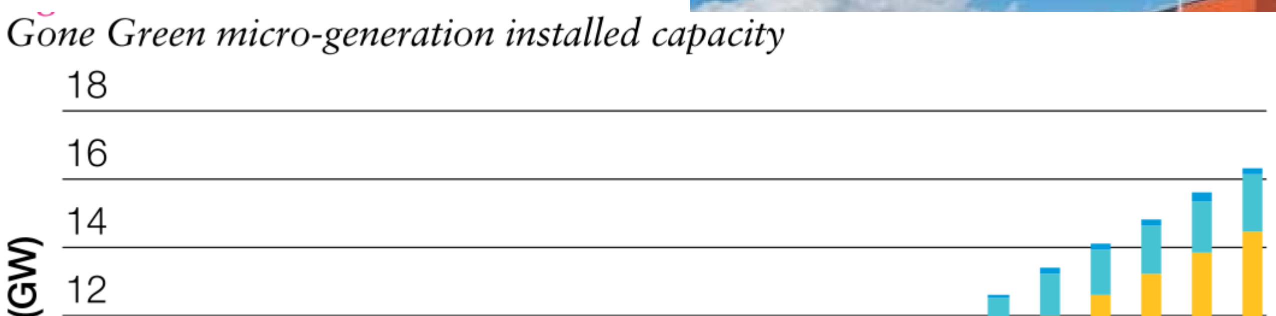
1st International Symposium on Smart Grid Methods, Tools and Technologies, Shandong University, China

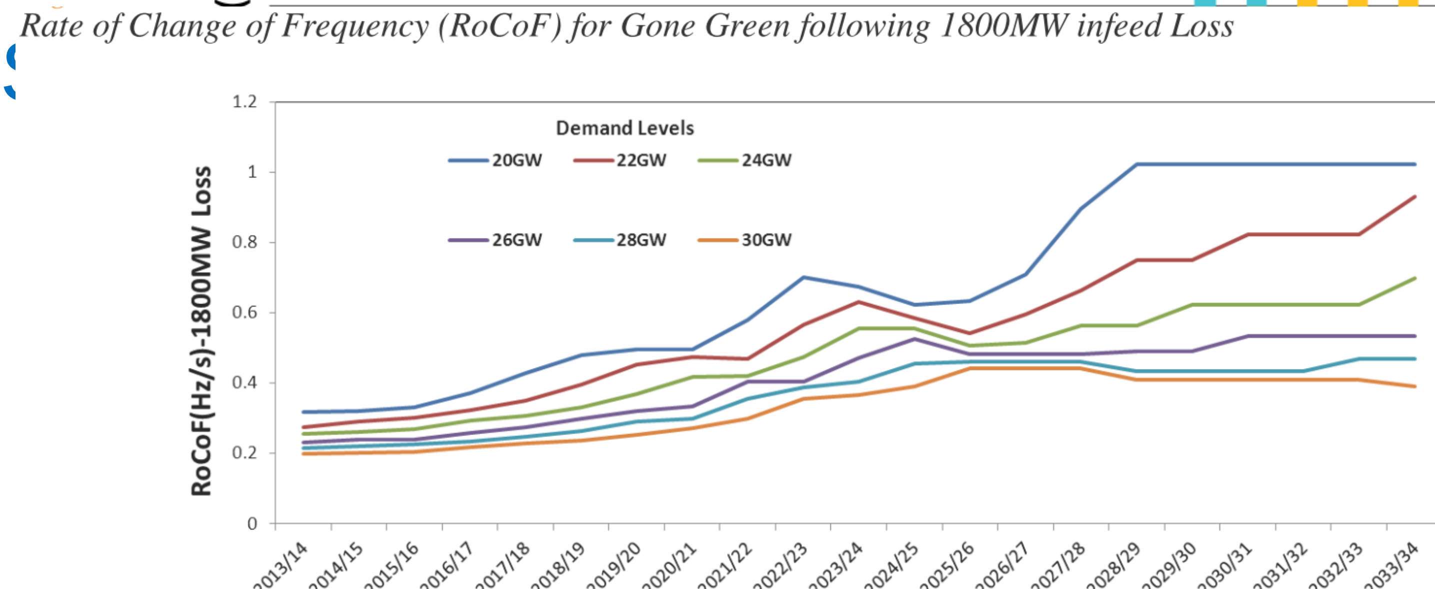
University of Strathclyde

Strong links with China

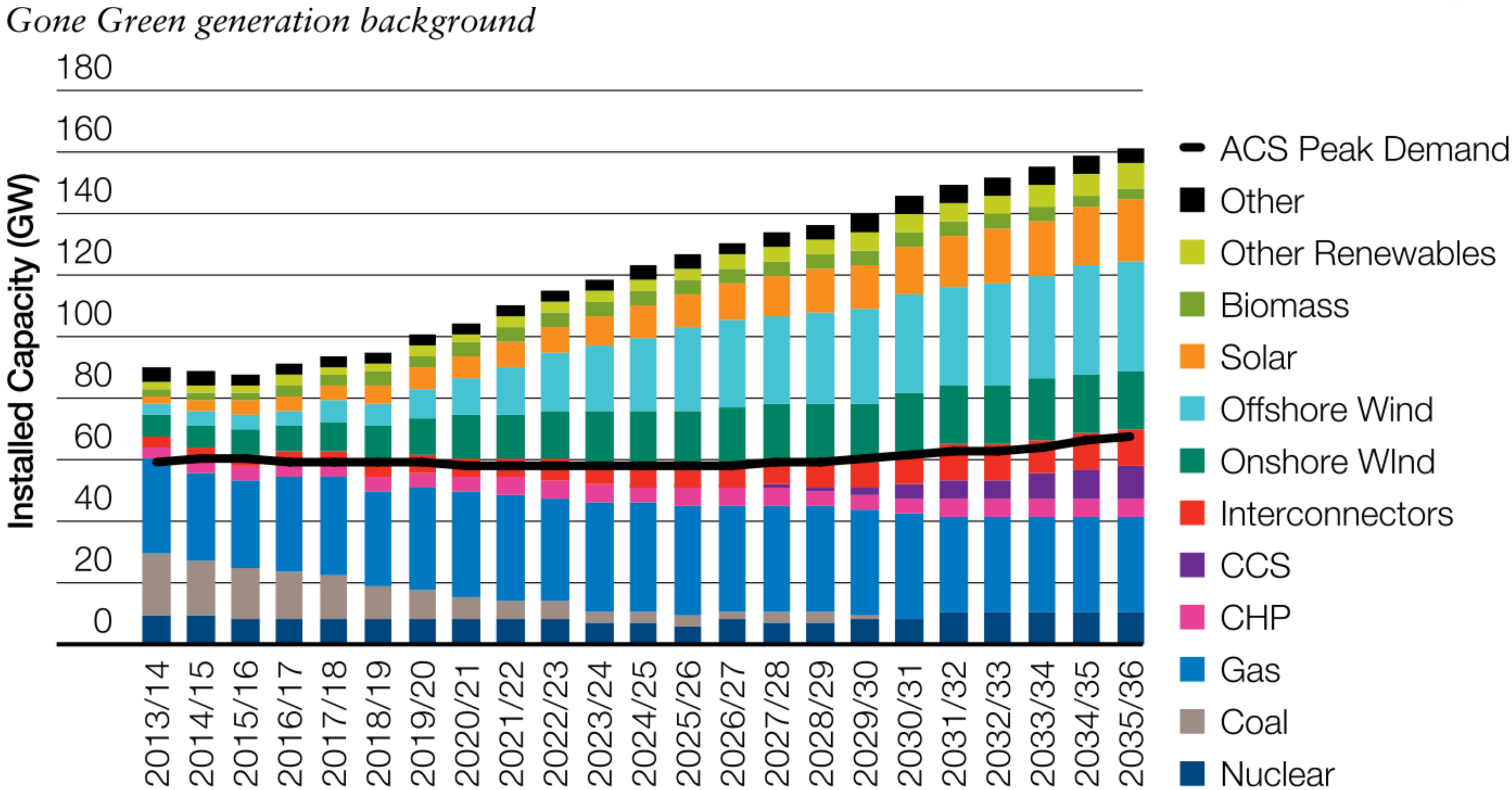
Outline and objectives

- Present and future power system in Great Britain (GB)
- Chall
  - Wea
  - Ope
- S





Future energy mix



http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=34301

Future energy mix

University of Strathclyde Engineering

Gone Green

	2013	2020	2035
Electricity			
Peak demand/GW	60.5	59.3	68.1
Annual demand/TWh	345	338	366
Total capacity/GW	91	106	163
Low carbon capacity/GW	28	50	109
Interconnector capacity/GW	4	6	11
Residential HPs/Millions	0.1	1.2	10
EVs number/Millions	0.01	0.6	5.4

GB Power System: Today

http://media.indiatimes.in/media/content/2012/Dec/bullet_train_china_1356523039_540x540.jpg

GB System: Tomorrow?

http://www.hasebikes.ro/2-media_slide_shows.html

System Operability - Future

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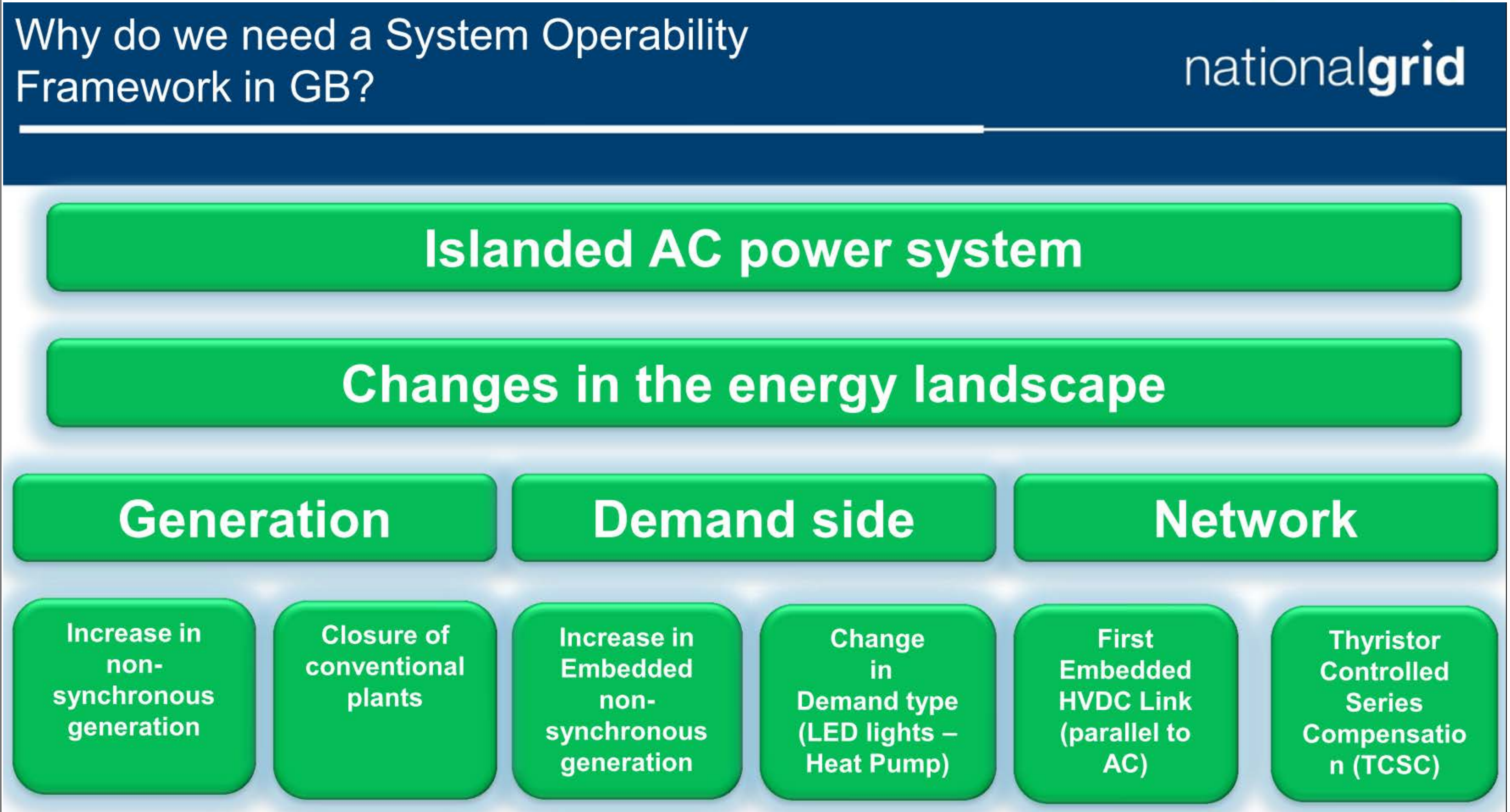

http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/

System Operability - Future

University of Strathclyde

Change	Affected Subjects
System Inertia	RoCoF Frequency Containment Generation Withstand Capability System Stability
Short Circuit Level	Protection Voltage Dips Voltage Management Resonance and Harmonics LCC HVDC Commutation
Reduction on Controlability	Supply and Demand Predictability
Distributed Generation Increases Electrification of Heating and Transportation Demand Side Response	DNO-TSO Interaction
Conventional Generation Closure New Nuclear Power Plant	Emergency System Restoration
Increased Reliance on External Power Networks	System Resilience
Series Compensation New CSC HVDC Links	Sub-synchronous Resonance
New VSC HVDC Links	Control Systems

http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/

Operating the system in 2020-30

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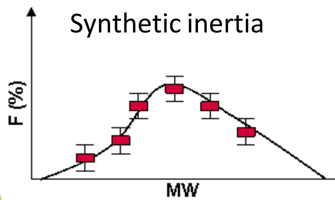
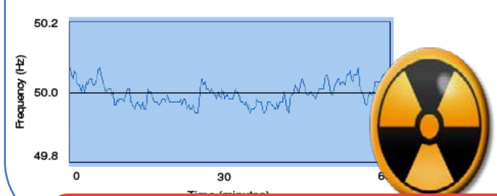
Variable generation

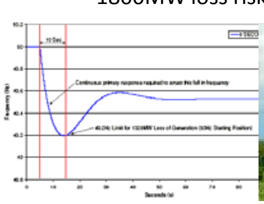


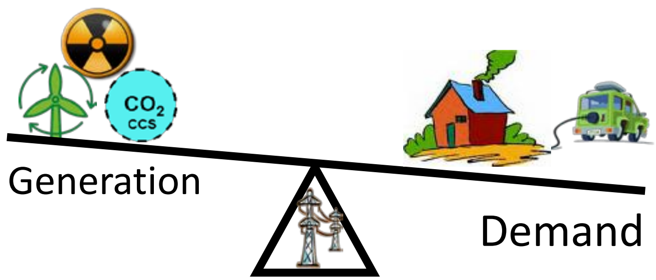
Inflexible generation



Large generation

1800MW loss risk





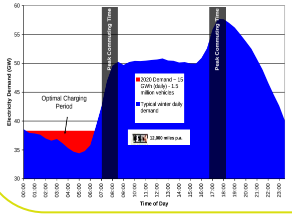
Active Distribution Networks

Smart Grids & meters

Distributed generation

ROCOF & Robustness issues

Active Demand



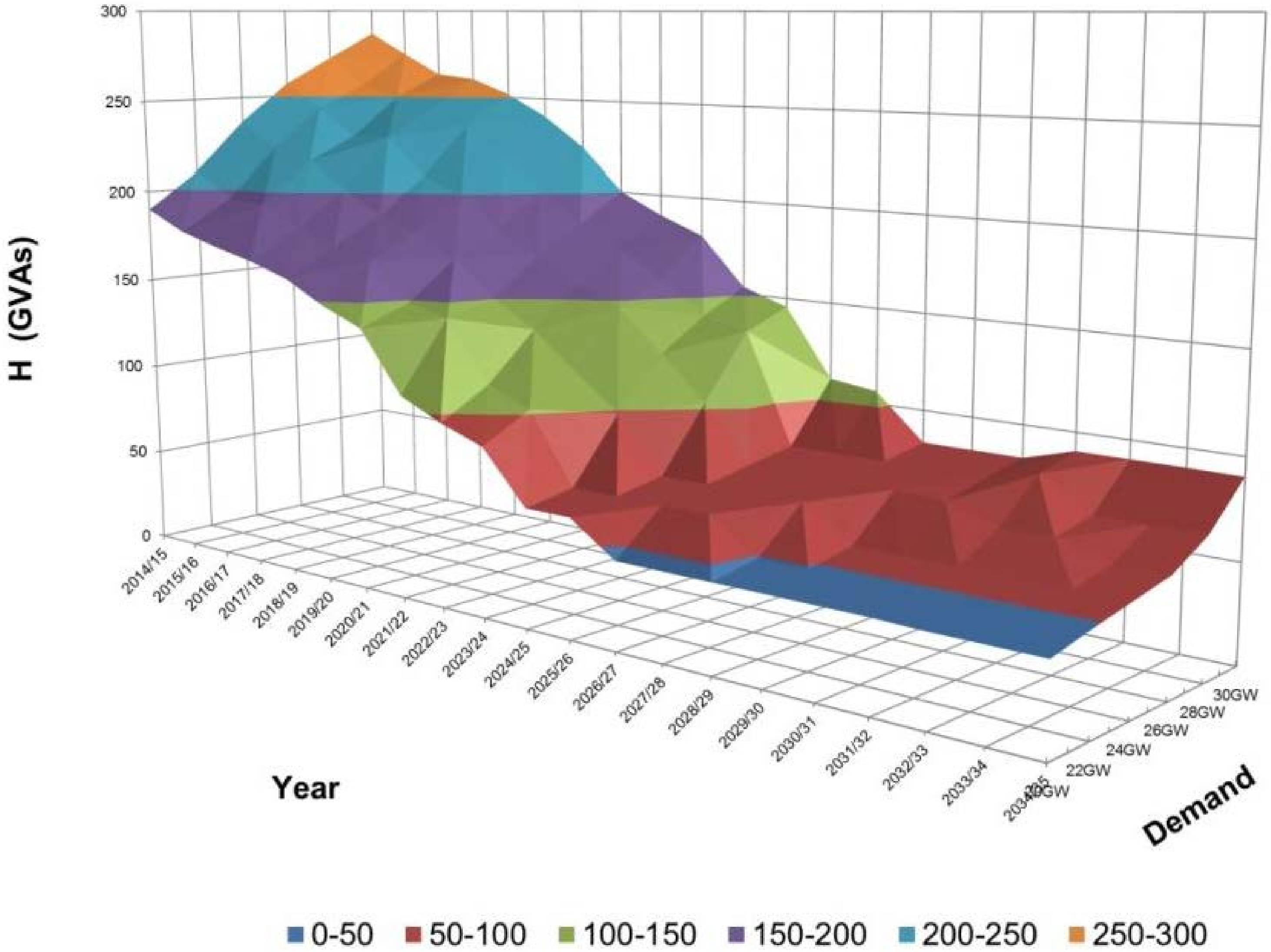
Time of use tariffs

nationalgrid

Weak systems

- Challenges:
  - Higher frequency dynamics and voltage/reactive power issues
  - Potential for maloperation of frequency-based protection
  - Constraints on renewables
  - Low fault levels, delayed (or maybe too fast?) converter fault responses?
- Solutions:
  - Enhance/emulate inertia – stored energy
  - Effective grid codes to drive technical innovation
  - Enhanced/novel protection and control – including frequency-responsive loads, sources, storage

Future low inertia systems

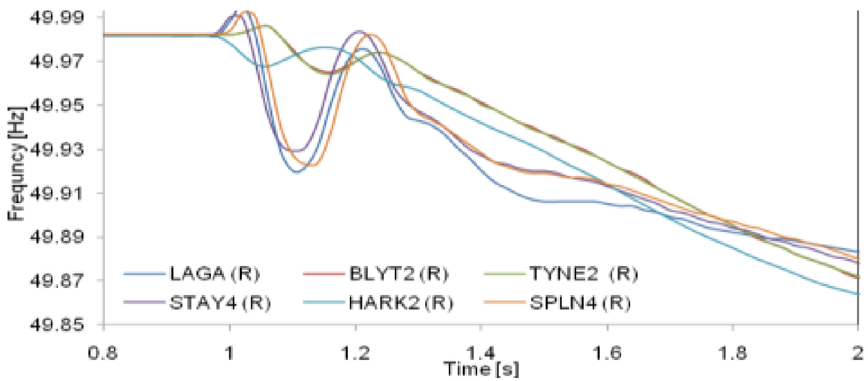


http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/

Project

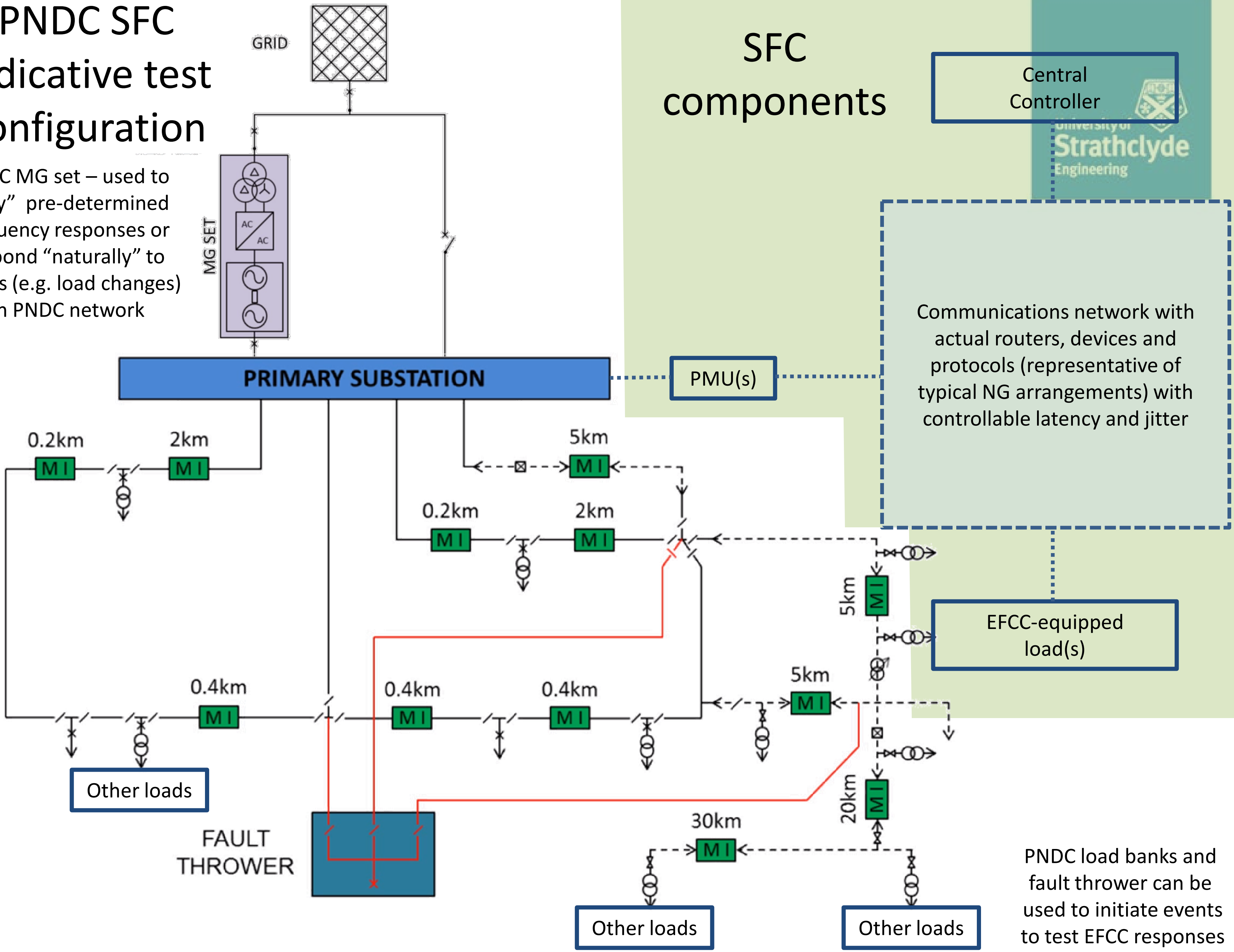
Smart Frequency Control

- £9m+ project led by National Grid
- Investigation of fast regional RoCoF-triggered response using PMUs– loads, storage, generation
- Save £100s m in future
- PMUs and distributed controllers
- Testing at PNDC



PNDC SFC indicative test configuration

PNDC MG set – used to "play" pre-determined frequency responses or respond "naturally" to events (e.g. load changes) on PNDC network



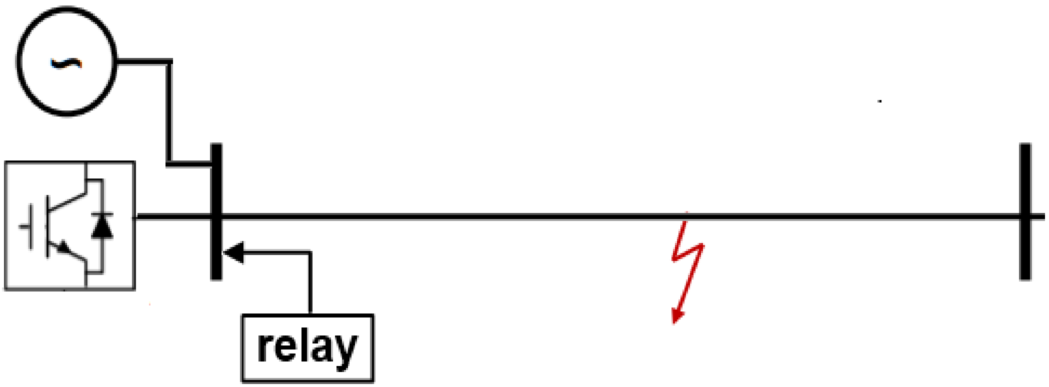
PNDC load banks and fault thrower can be used to initiate events to test EFCC responses

MI – "mock impedance" to electrically emulate feeder lengths

Project

Protection of converter-dominated systems

- Challenges:
  – Reduced AC network short-circuit levels?
  – Converters’ responses to short circuits?
- Solutions:
  – Quantification and demonstration of problems
  – Elimination of overcurrent-based protection?
  – Adaptive/new methods of protection?
  – Do we still need fast protection in an inverter-dominated AC system?



Project

Protection of converter-dominated systems

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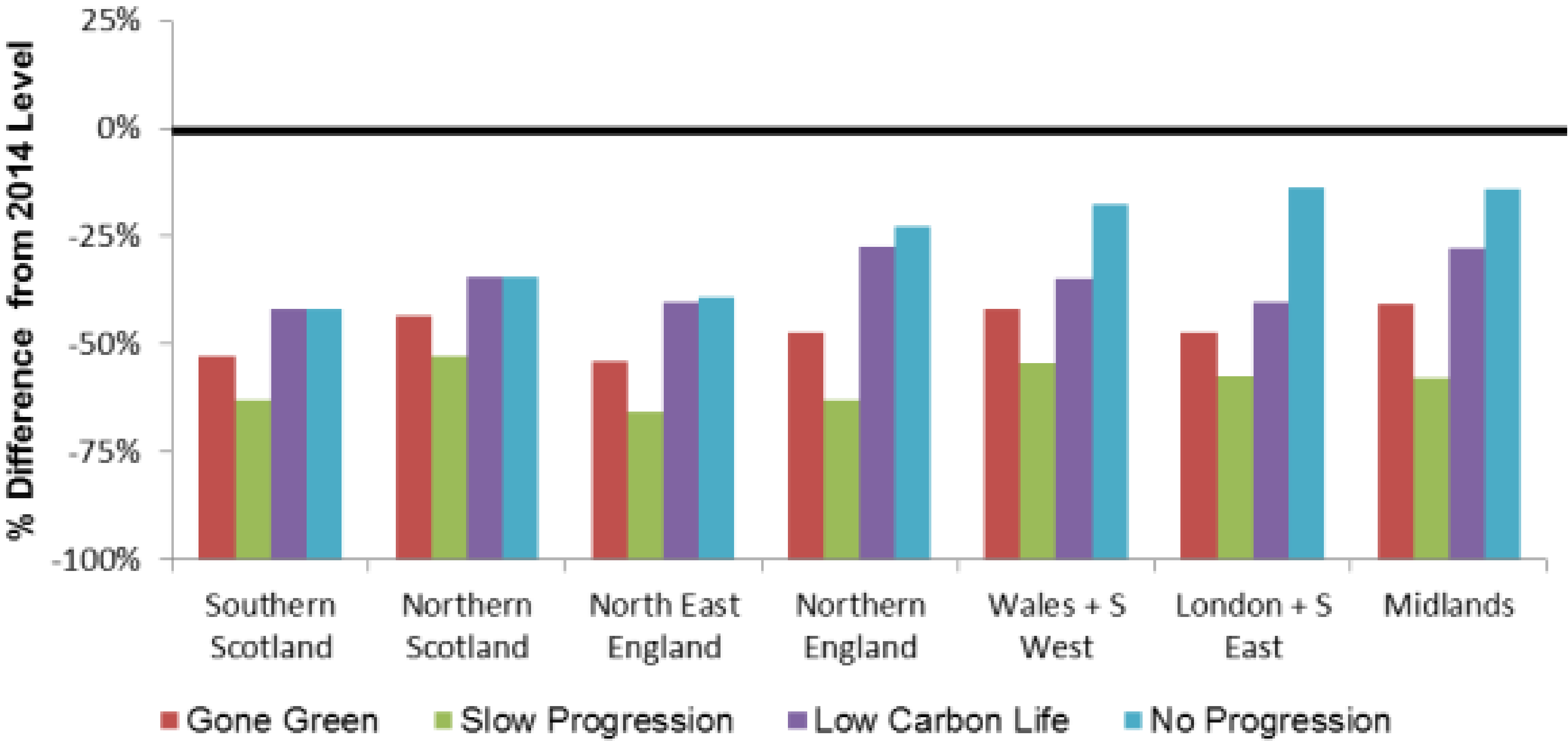
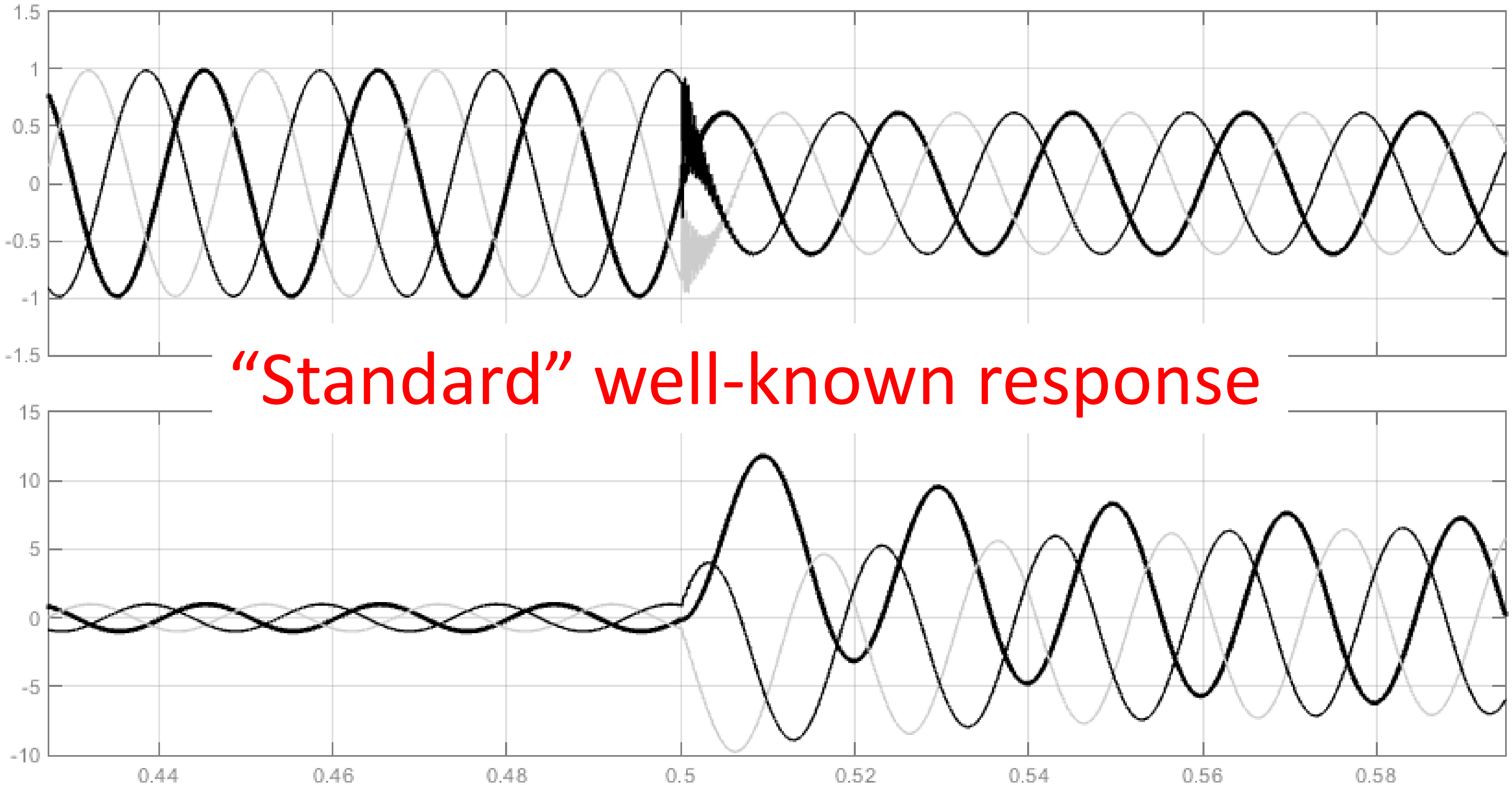


NG System Operability Framework

Figure 22 Minimum Short Circuit Level Relative to 2014/15 Level (2034/35)

Project

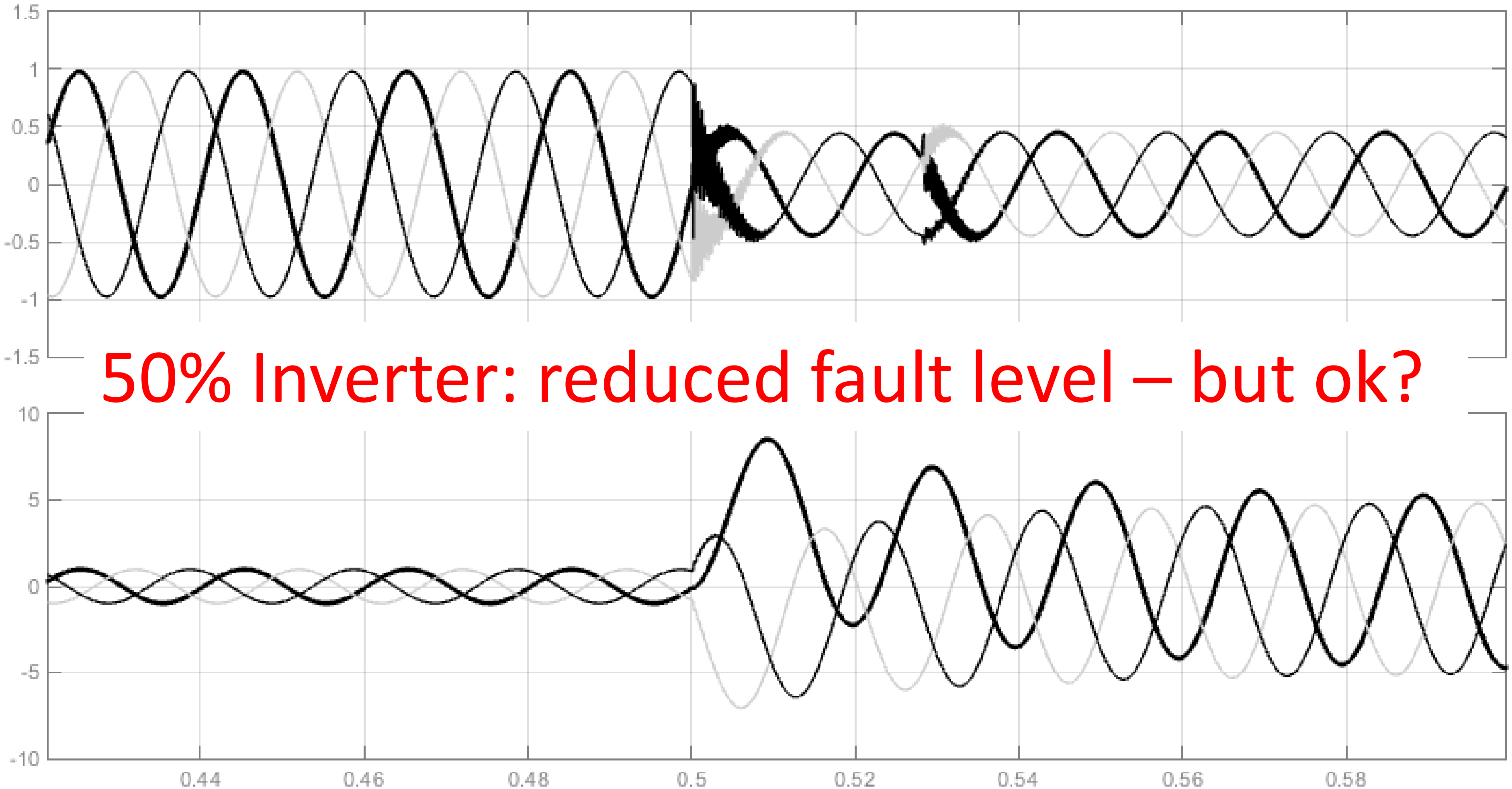
Protection of converter-dominated systems



VI(pu value) wave form measured at Grendon station(with 0% converter penetration level)

Project

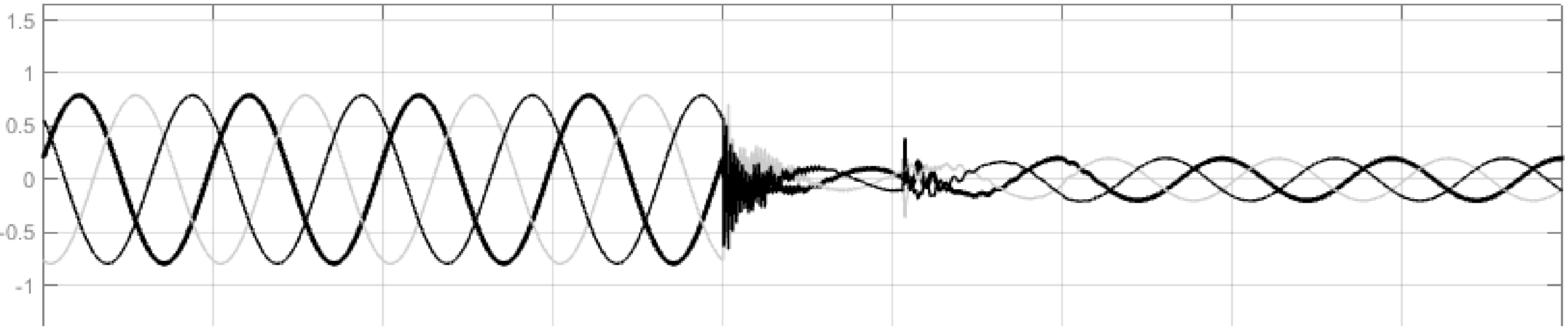
Protection of converter-dominated systems



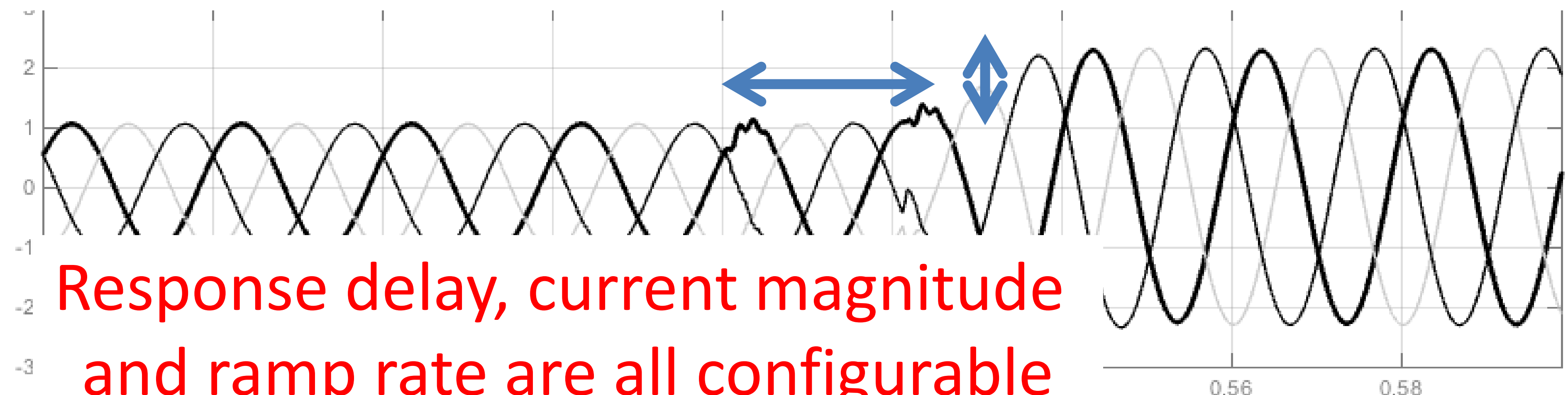
VI(pu value) wave form measured at Grendon station(with 50% converter penetration level)

Project

Protection of converter-dominated systems



100%: OK? Delay in response, waveform distortion…?



Response delay, current magnitude and ramp rate are all configurable

VI(pu value) wave form measured at Grendon station(with 100% converter penetration level)

Measured inverter responses

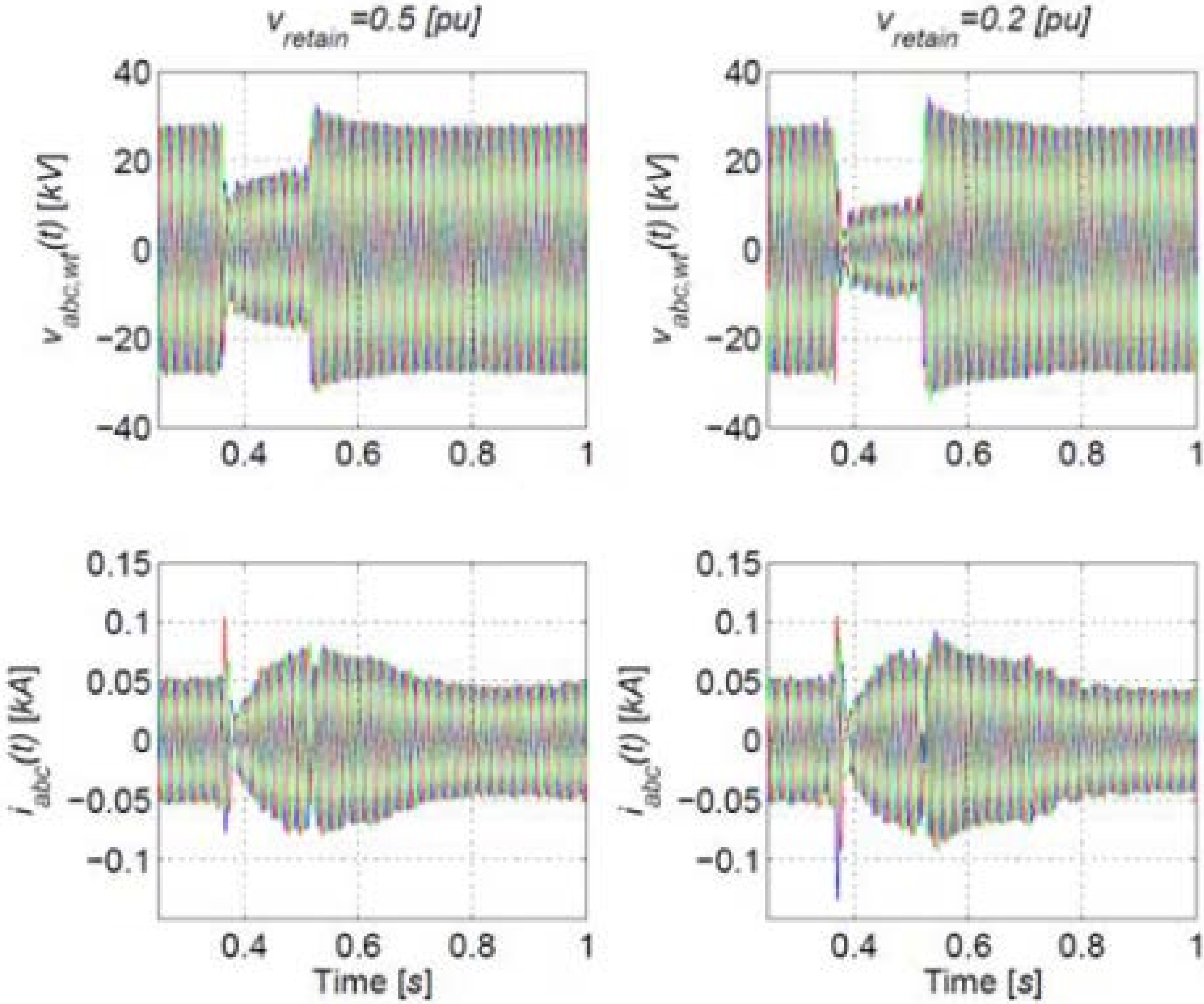
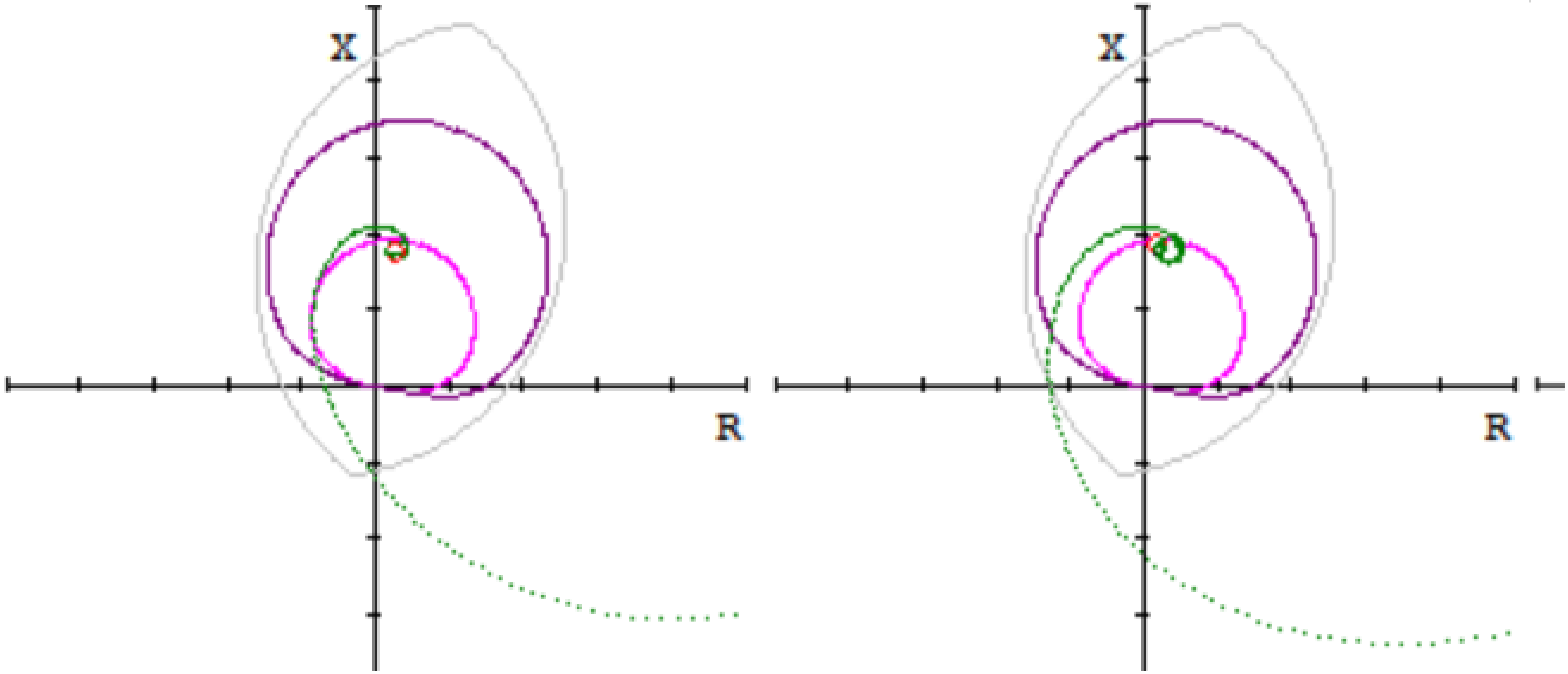


Fig. 4 Measured voltage and current at the HV of the WTG transformer during the PHIL test

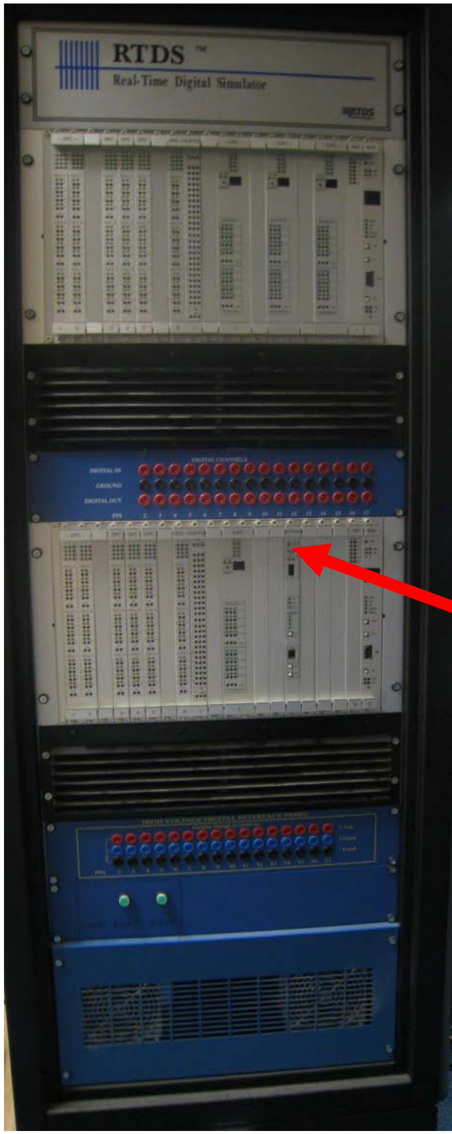
Power Hardware In The Loop Validation of Fault Ride Through of VSC HVDC Connected Offshore Wind Power Plants Ranjan Sharma, Qiuwei Wu(□), Seung Tae Cha, Kim H. Jensen, Tonny W. Rasmussen, Jacob Østegaard J. Mod. Power Syst. Clean Energy DOI 10.1007/s40565-

Distance protection responses



Next steps….

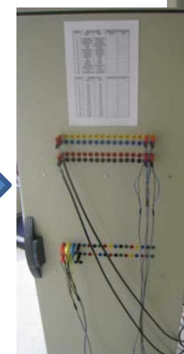
Injection tester

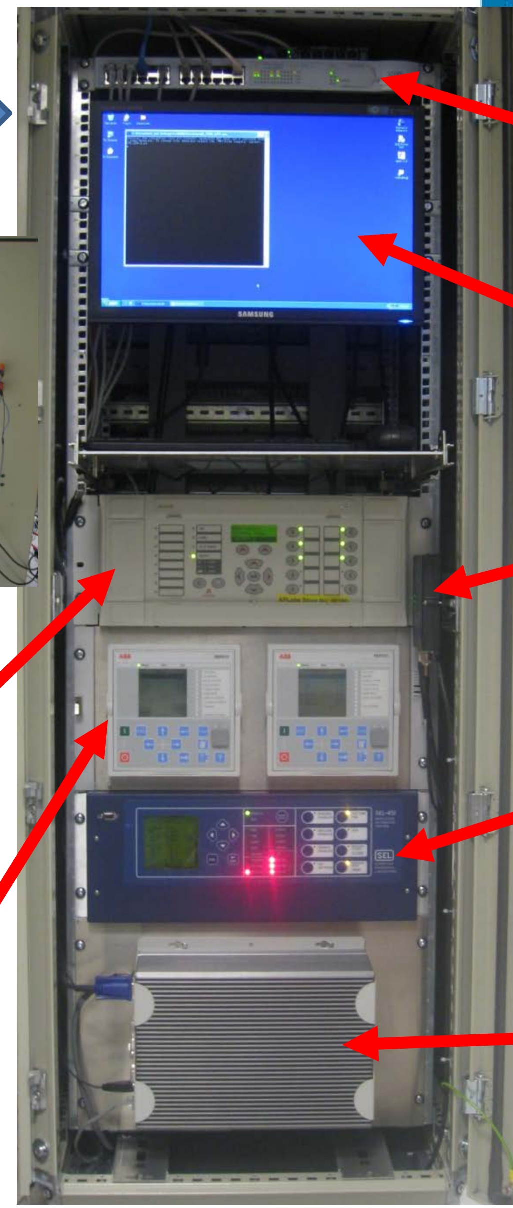


RTDS LAN Interface

RTDS/AMP D&A Interface

GTNET Card (GOOSE/SV/DNP3)





Local/ External LANs

HMI

GPS Receiver

PMU

Transmission Protection

Distribution Protection

Substation Gateway

https://www.entsoe.eu/major-projects/network-code-development/high-voltage-direct-current/Pages/default.aspx

ENTSO-E Draft Network Code on High Voltage Direct Current Connections and DC-connected Power Park Modules

30 April 2014

Notice
This document reflects the work done by ENTSO-E in line with ACER's framework guidelines on electricity grid connections published on 20 July 2011 and the EC mandate letter received by ENTSO-E on 29 April 2013.

HVDC grid codes
ENTSO-E doc

Article 17 **Short circuit contribution during faults**

1. HVDC Systems shall fulfil the following requirement referring to Voltage stability:

(a) The Relevant Network Operator in coordination with the Relevant TSO shall have the right to require while respecting the provisions of Article 4(3) the capability of a HVDC System to provide Fast Fault Current at a Connection Point in case of symmetrical (3-phase) faults.

(b) The Relevant Network Operator in coordination with the Relevant TSO shall while respecting the provisions of Article 4(3) specify

– how and when a Voltage deviation is to be determined as well as the end of the Voltage deviation,

– the characteristics of the Fast Fault Current,

– the timing and accuracy of the Fast Fault Current, which may include several stages.

(c) With regard to the supply of Fast Fault Current in case of asymmetrical (1-phase or 2-phase) faults the Relevant Network Operator in coordination the Relevant TSO shall have the right to introduce while respecting the provisions of Article 4(3) a requirement for asymmetrical current injection.

HVDC grid codes
ENTSO-E doc

Article 10 **Synthetic inertia**

1. With regard to the capability of providing Synthetic Inertia in response to a rate of change of Frequency:

   (a) The Relevant TSO shall have the right to require that a HVDC System shall be capable of providing Synthetic Inertia in response to Frequency changes, activated in low and/or high Frequency regimes by rapidly adjusting the Active Power injected to or withdrawn from the AC Network in order to limit the rate of change of Frequency, while respecting the provisions

   of Article 4(3) of this Network Code and at least accounting for the results of the studies as specified in Article 15(8)c) of [NC OS].

   (b) The principle of this control system and the associated performance parameters shall be agreed between the Relevant TSO and the HVDC System Owner while respecting the provisions of Article 4(3).

HVDC grid codes
ENTSO-E doc

Article 11 **Frequency Sensitive Mode (FSM)**

1. When operating in Frequency Sensitive Mode (FSM),the following shall apply:

   (a) The HVDC System shall be capable of responding to Frequency deviations in each connected AC Network by adjusting the Active Power transmission as indicated in Figure 1 and in accordance with the parameters specified by each TSO within the ranges shown in Table 2. This specification shall be subject to notification to the National Regulatory Authority. The modalities of that notification shall be determined in accordance with the applicable national regulatory framework.

   (d) As a result of a Frequency step change, the HVDC System shall be capable of adjusting Active Power to the Active Power Frequency response defined in Figure 1, such that the response is

      i. as fast as inherently technically feasible; and

Transmission protection

Summary of future issues

- **No major issues in near term…**
- **In future – when converters “dominate”?**
  - Slow operation due to delayed response of converters?
  - Weaker system – healthy generator ride-through issues?
  - Variable infeed levels – back up protection?
  - Waveform shape – will protection be confused?
  - Will converters be able to ride through remote faults (especially during slow/backup operations)?
  - LOM and overall system frequency control issues

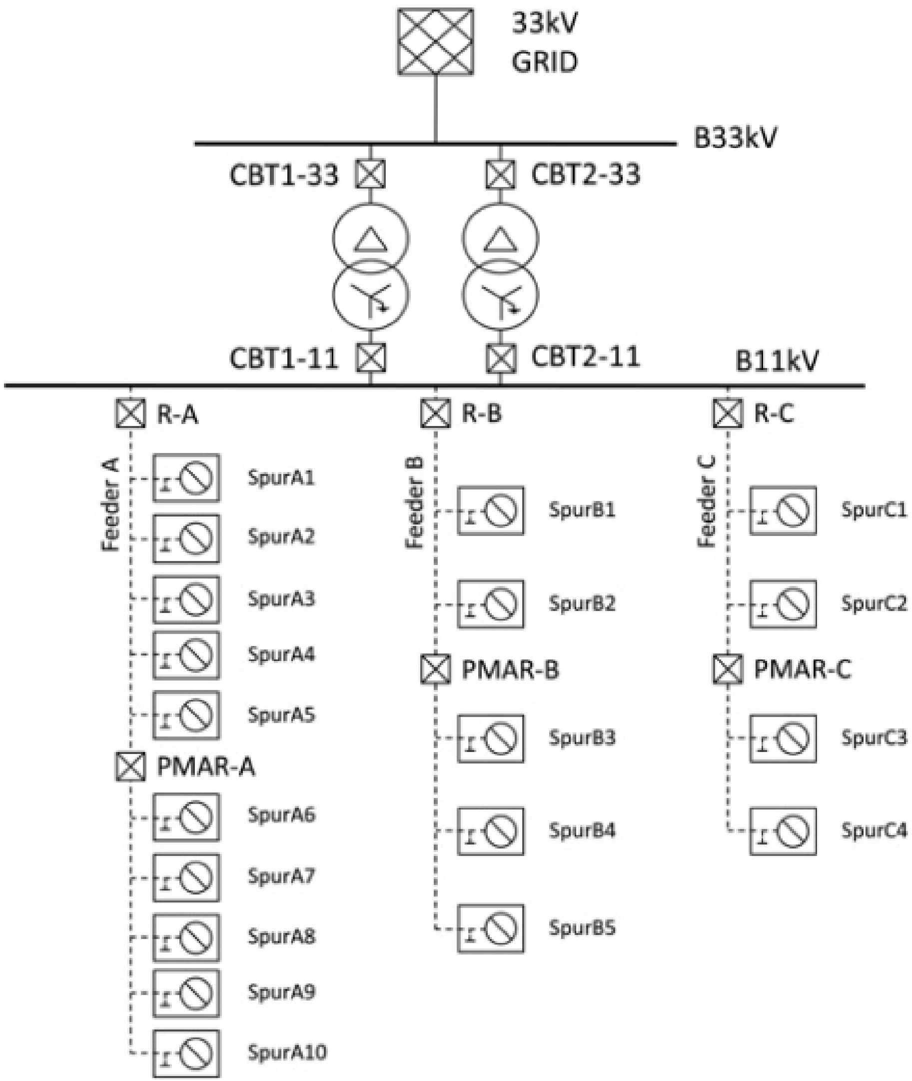
DG and “smart grids”

- **Challenges:**
  - Impact of DG on protection? Intermittency? Capacity?
  - Fault levels, current direction flows?
  - Protection coordination, discrimination, operating time
- **Solutions:**
  - Quantification and demonstration of problems
  - Adaptive/new protection
  - Network automation
  - More measurement data and applications

DG and "smart grids"

Quantification of problems

– Protection loss of coordination
– Protection blinding
– Sympathetic tripping



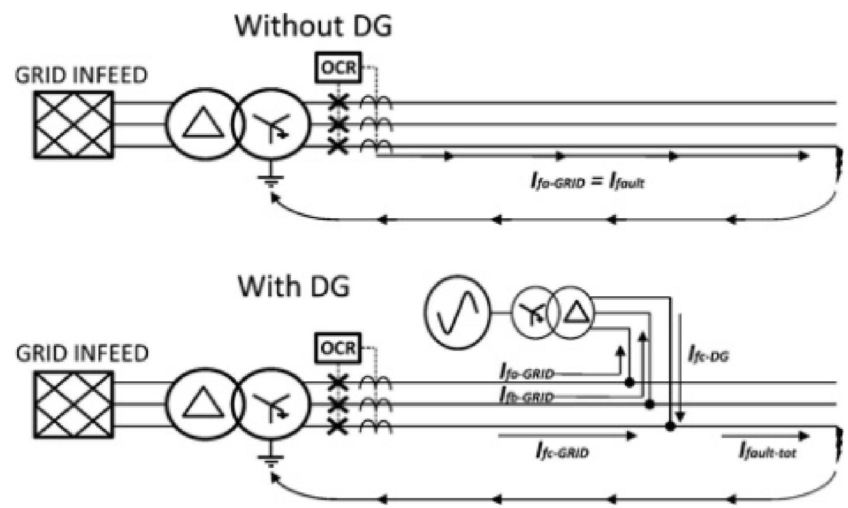


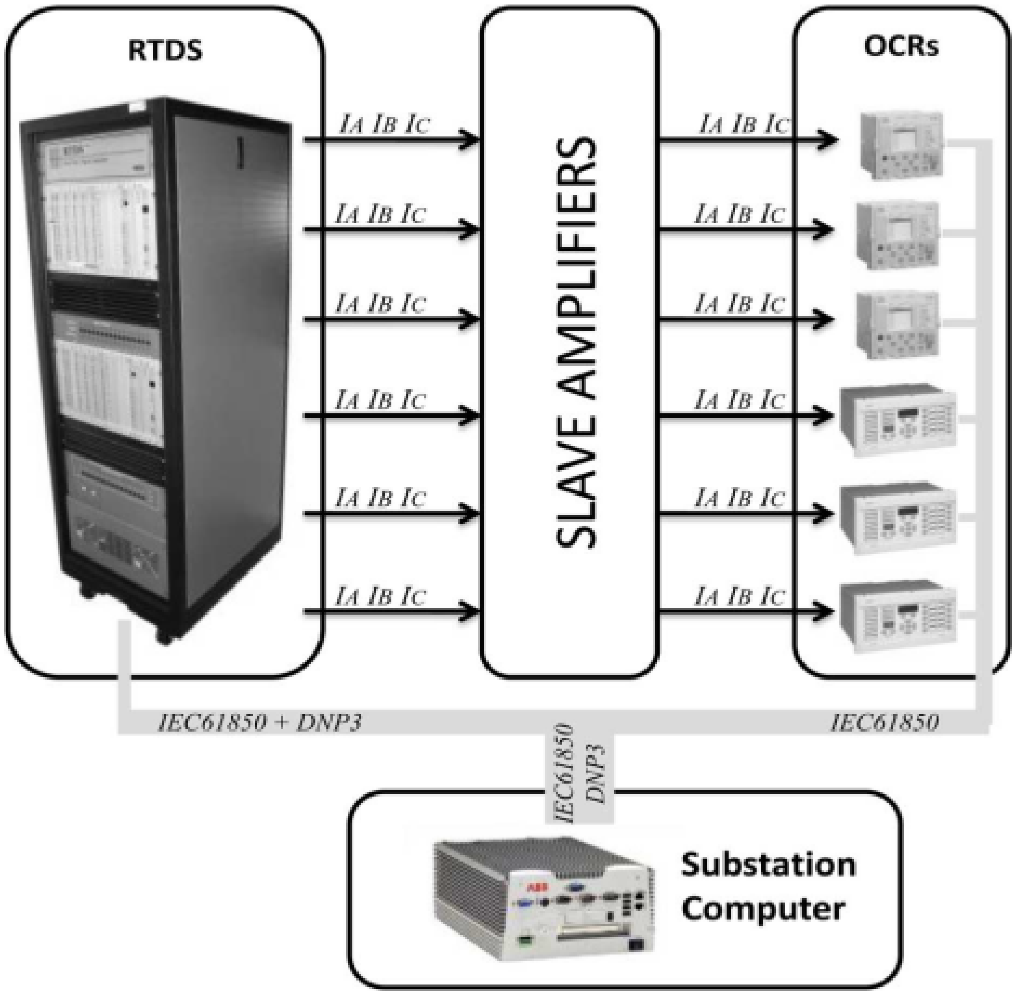
Fig. 7 *EF current with and without DG contribution*

IET Gener. Transm. Distrib., 2012, Vol. 6, Iss. 12, pp. 1218–1224
doi: 10.1049/iet-gtd.2012.0381

DG and “smart grids”

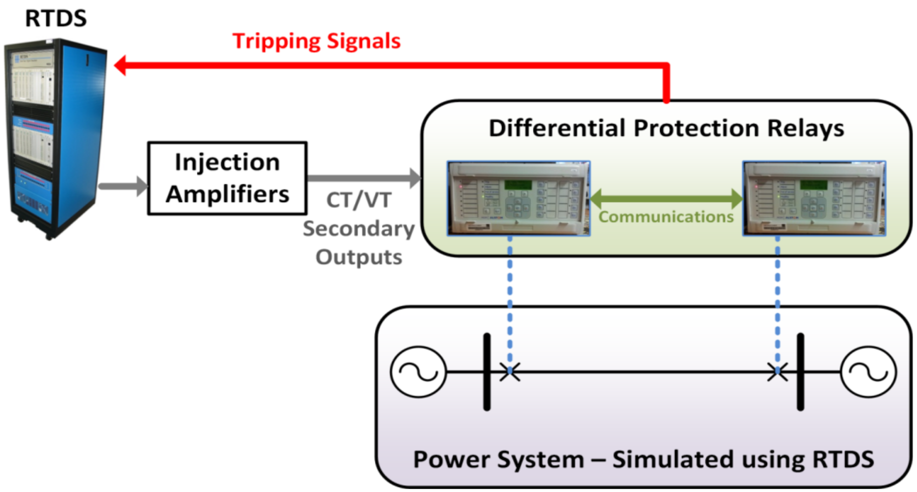
Demonstration of solutions

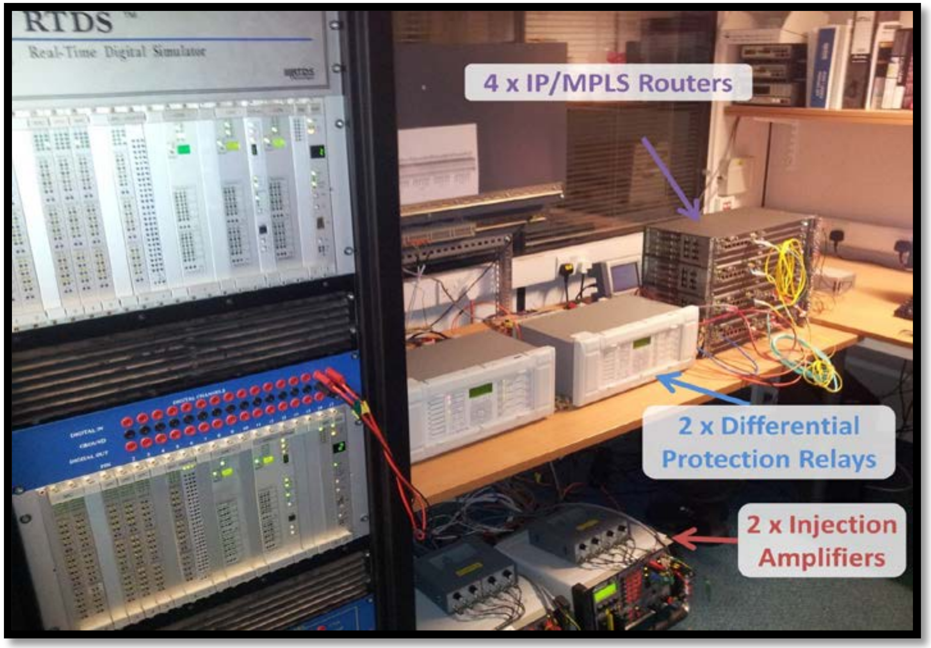
IEEE TRANSACTIONS ON POWER DELIVERY



Sensors, measurements and communications

University of Strathclyde Engineering





Hardware in the loop demonstration

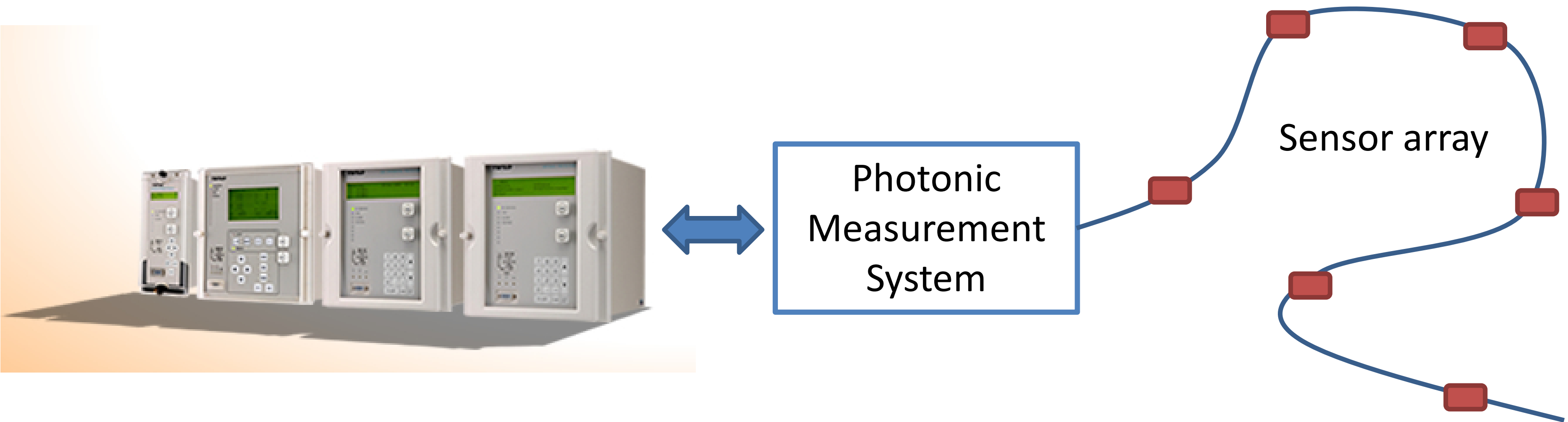
Use of IP/MPLS (internet) for power system protection

synaptec

Distributed multi-parameter sensing

Distributed sensing

- Distributed analogue sensor – current, voltage, temperature, vibration
- Uses optical fibre to interrogate multiple sensors (up to 100 sensors over 100 km)



- Interfaced to relays and/or output of IEC 61850-9-2
- Field trial projects secured
- Applications – hybrid circuits, multi-ended feeder protection, distributed monitoring and control…

Distributed sensing

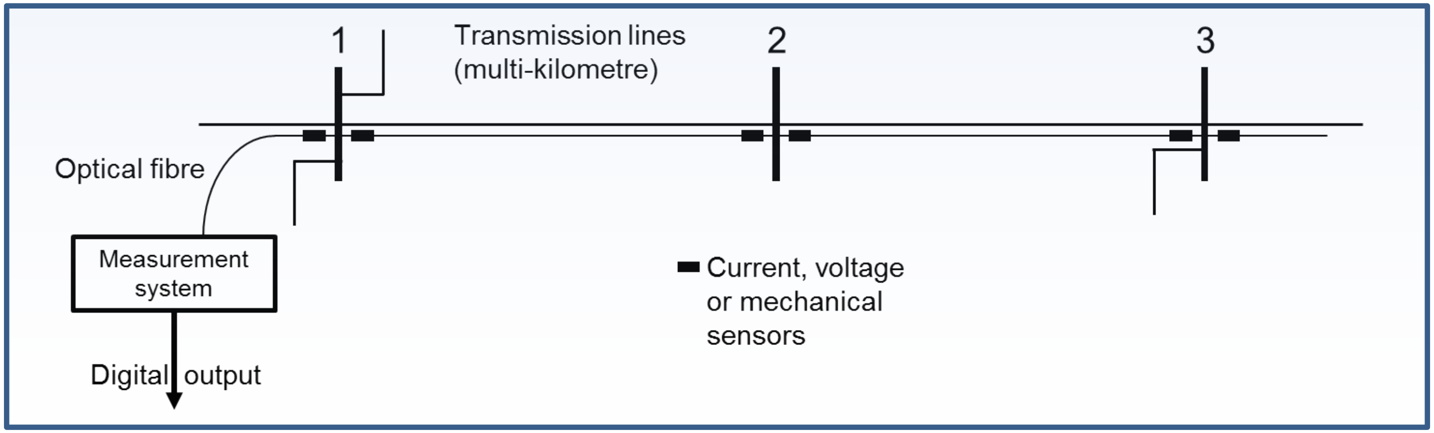
University of Strathclyde Engineering

Problem: Low-carbon grids (renewables, energy storage) – **£110bn spend**

→ **lower inertia and higher sensitivity to faults**

→ **HV** needs **faster protection** and **more discrimination**

→ **LV/MV** needs **increased coverage, without increased cost/complexity**



Our USPs:

1. **Long-distance, passive** instrui
2. **Fastest possible comparison** of measurements
3. **No data transmission** - no data rate limitations
4. **Minimal infrastructure**: multiple measurements
5. **Greater flexibility** in sensor coverage and locati

Winner of **Best University Technology** at the 2014 Energy Innovation Awards

Energy Innovation Centre

Smarter grid infrastructure without prohibitive costs

PNDC: Extending Hardware in the Loop

Main features

- Realism
- Flexibility
- Control room, industry-standard SCADA system, laboratories
- Accelerated testing (voltage, frequency, unbalance, power quality, faults…)
- Enhanced instrumentation and recording

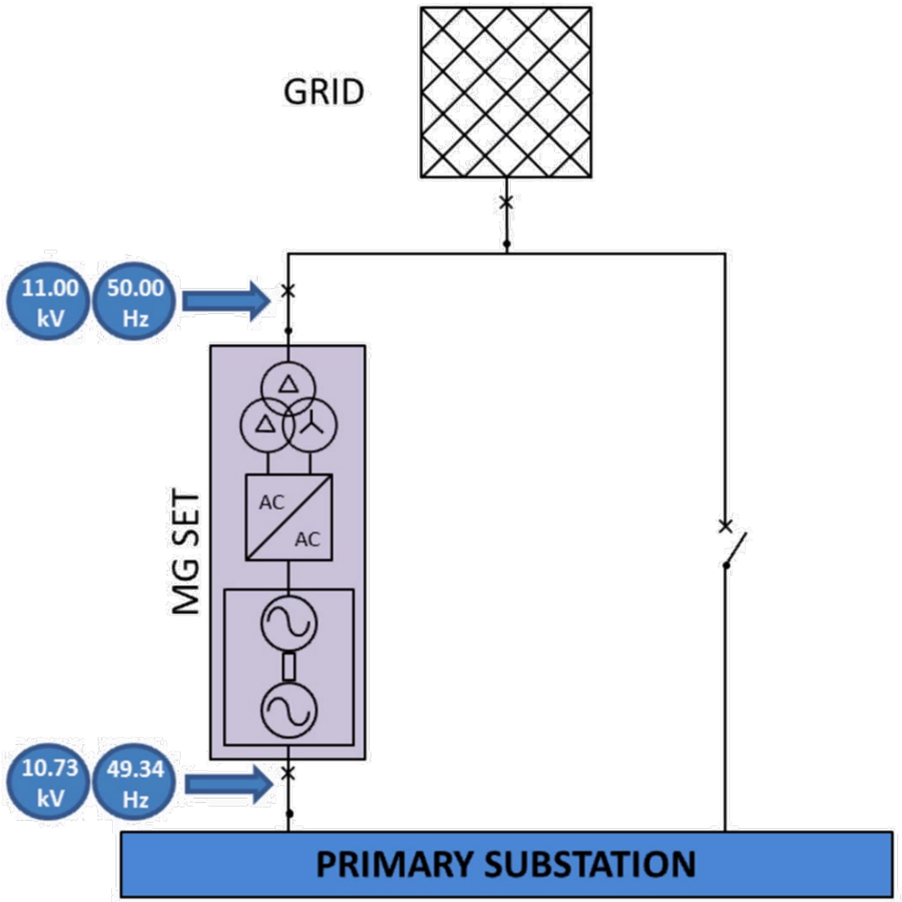
Uses and applications

- Innovation projects
- Accelerated pre-field trials and tests
- “Crash” testing
- Investigations
- Training and CPD

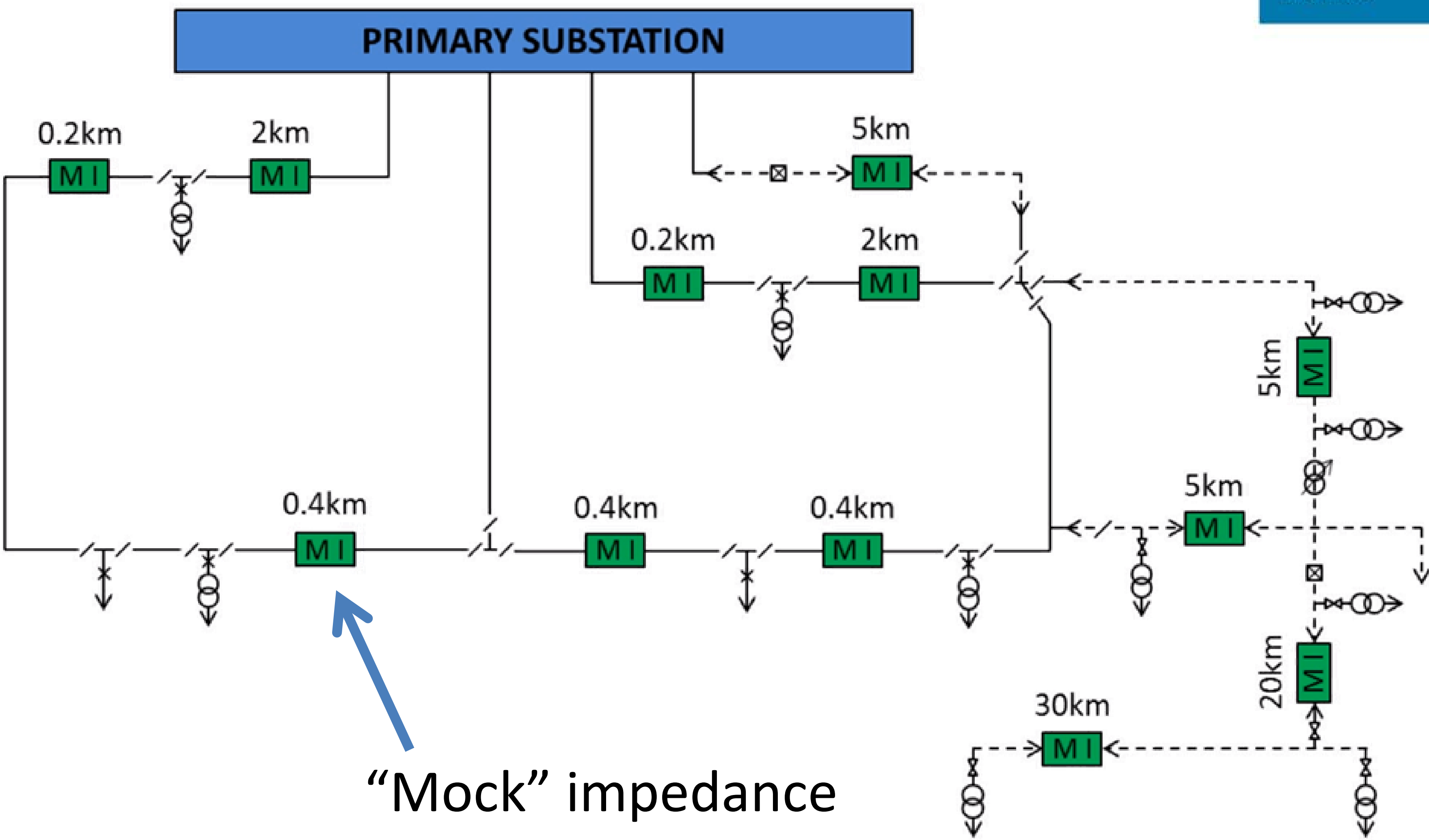
Grid/decoupled modes of operation

Power Networks Demonstration Centre

University of Strathclyde Engineering

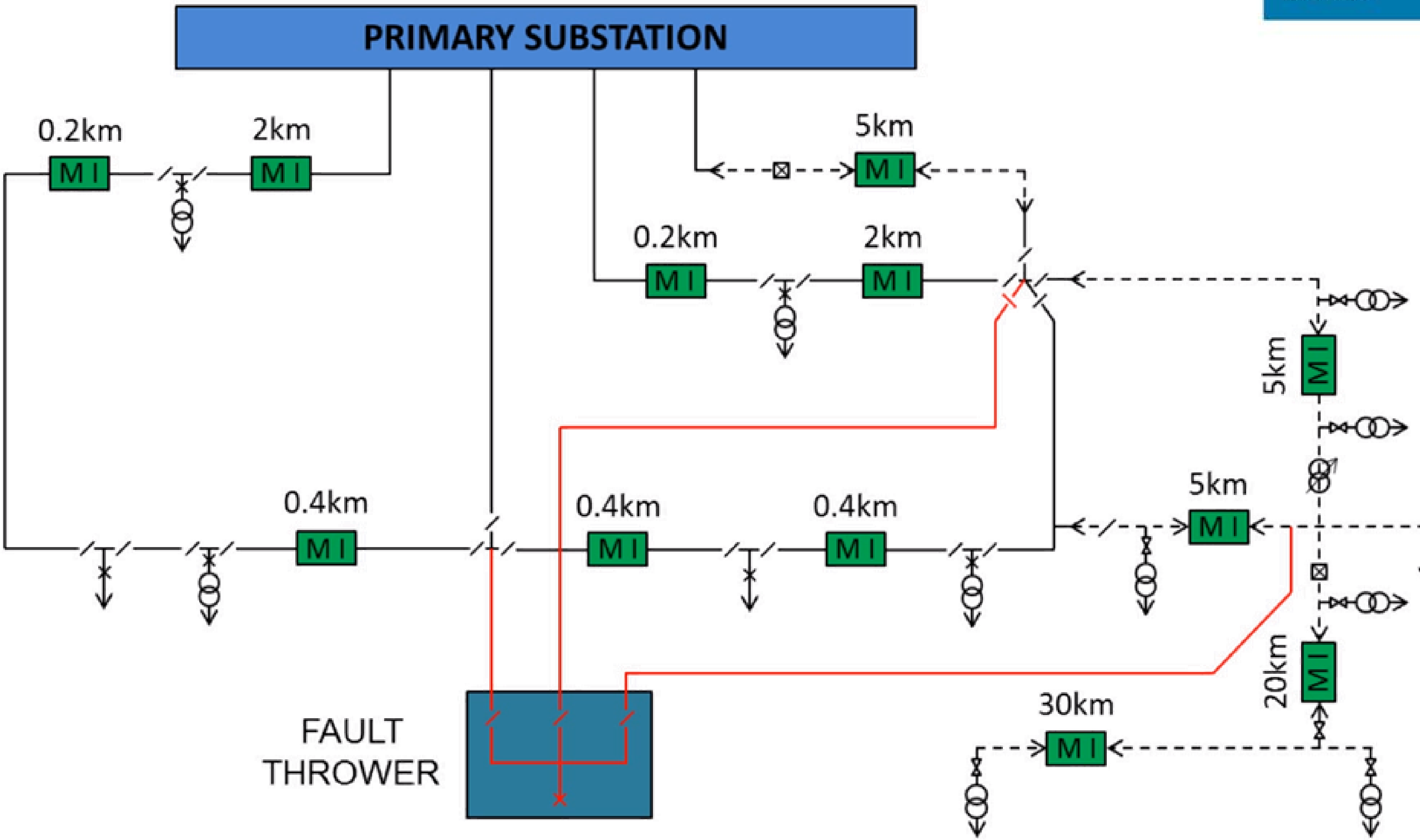


11kV system

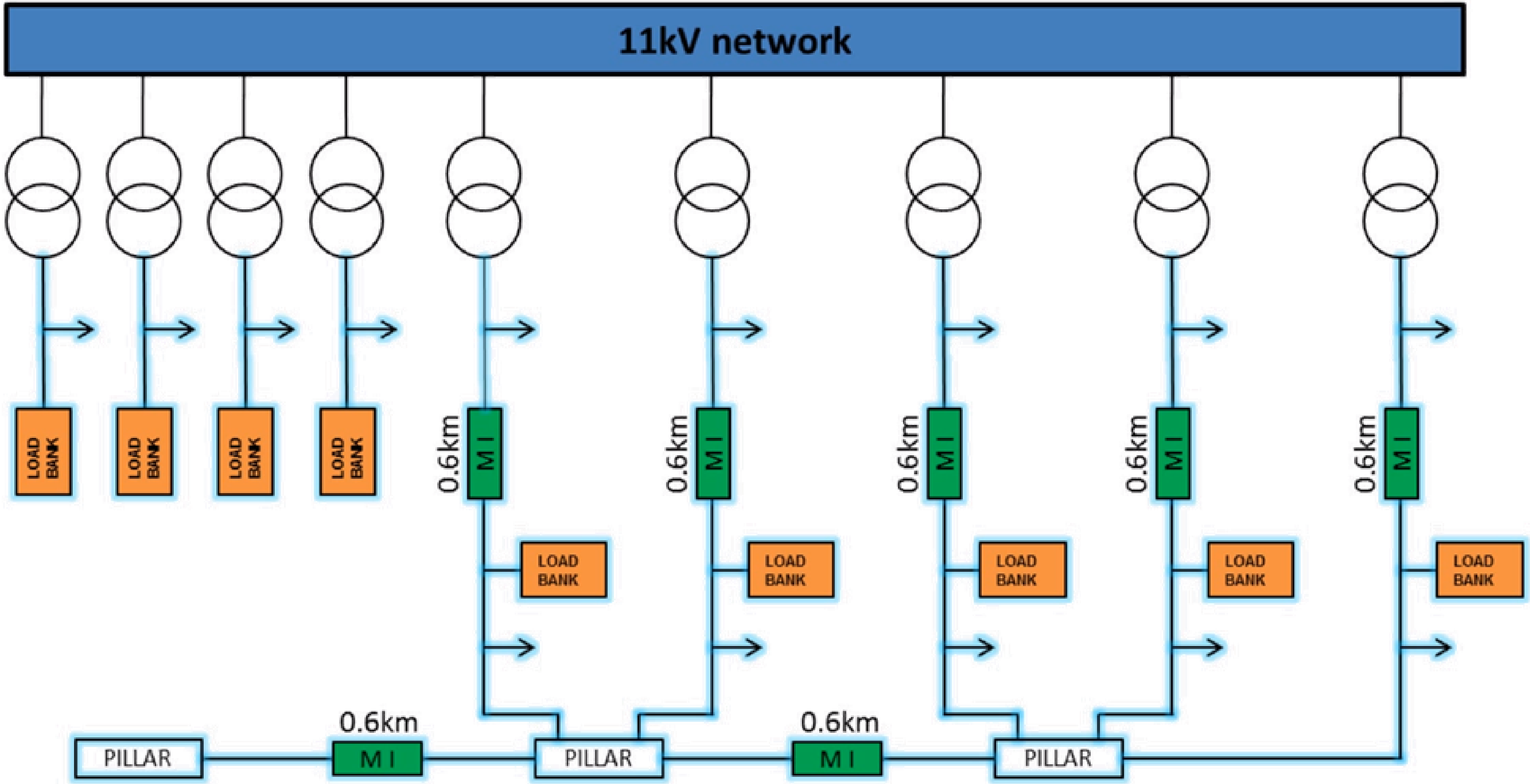


"Mock" impedance
(but it is real!)

11kV system


PRIMARY SUBSTATION
0.2km
2km
5km
0.2km
2km
5km
0.4km
0.4km
0.4km
5km
20km
30km
FAULT
THROWER
MI

LV system



11kV network
LOAD BANK
LOAD BANK
LOAD BANK
LOAD BANK
0.6km
M I
LOAD BANK
0.6km
M I
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0.6km
M I
LOAD BANK
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M I
LOAD BANK
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M I
LOAD BANK
PILLAR
0.6km
M I
PILLAR
0.6km
M I
PILLAR

Equipment

Power Networks Demonstration Centre

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Switchgear

Voltage regulator

Protection/Automation

Secondary substations

Load banks

New, v
equipm
purcha

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Beer in the loop?

Conclusions

- Several challenges lie ahead in GB
- Innovation and R&D accelerating
- But - barriers
- Need collaboration
- And engineering “dictatorship”…
- Needs engineers!

IET The Institution of Engineering and Technology

Electricity **Networks**

Handling a Shock to the System

IET position statement on the **whole system challenges** facing Britain’s electricity network

www.**theiet**.org/pnjv

Thank you

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Appendix: selected publications

University of Strathclyde Engineering

www.ietdl.org

Published in IET Renewable Power Generation
Received on 14th March 2014
Revised on 20th June 2014
Accepted on 3rd July 2014
doi: 10.1049/iet-rpg.2014.0109

Special Issue: Selected Papers from The
Renewable Power Generation Conferenc

Generic inertia emula
voltage-source-conve
systems

Jiebei Zhu[1], Josep M. Guerrero[2], W
[1]Transmission Network Service, National Grid,
United Kingdom
[2]Department of Energy Technology, Aalborg U
[3]28 Beverley Road, Leamington Spa, CV32 6PJ
[4]Department of Electronic & Electrical Engineer
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E-mail

ELSEVIER

Electric Power Systems Research

Volume 124, July 2015, Pages 55–64

Coordinated direct current matching control strategy for multi-terminal DC transmission systems with integrated wind farms

Jiebei Zhu[a], Campbell D. Booth[b], Grain P. Adam[b], Andrew J. Roscoe[b]

Open Access funded by Economic and Social Research Council

Show more

doi:10.1016/j.epsr.2015.02.015

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Open Access

IEEE TRANSACTIONS ON POWER SYSTE

Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems

Jiebei Zhu, Campbell D. Booth, Grain P. Adam, Andrew J. Roscoe, and Chris G. Bright

Appendix: selected publications

IEEE TRANSACTIONS ON POWER DELIVERY

An Adaptive Overcurrent Protection Scheme for Distribution Networks

F. Coffele, C. Booth, and A. Dyśko, *Member, IEEE*

Application of Multiple Resistive Superconducting Fault-Current Limiters for Fast Fault Detection in Highly Interc

Steven M. Blair, *Student Member, IEEE*

IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 64, NO. 1, JANUARY 2015 19

Distributed Photonic Instrumentation for Power System Protection and Control

Philip Orr, *Member, IEEE*, Grzegorz Fusiek, *Member, IEEE*, Paweł Niewczas, *Member, IEEE*, Campbell D. Booth, *Member, IEEE*, Adam Dyśko, *Member, IEEE*, Fumio Kawano, *Member, IEEE*, Tomonori Nishida, and Phil Beaumont, *Senior Member IEEE*

IEEE SENSORS JOURNAL, VOL. 13, N

An Optically-Interrogated Rogowski Coil for Passive, Multiplexable Current Measurement

Philip Orr, Pawel Niewczas, Campbell Booth, Grzegorz Fusiek, Adam Dyśko, Fumio Kawano, *Member, IEEE*, Tomonori Nishida, and Phil Beaumont, *Senior Member, IEEE*

Appendix: selected publications

www.ietdl.org

Published in IET Generation, Transmission & Dis
Received on 20th December 2011
doi: 10.1049/iet-gtd.2012.0381

Quantitative ar
for systems inc

F. Coffele C. Booth A. L
Institute for Energy and Environm
E-mail: federico.coffele@strath.ac

INNOVATION FOR SECURE AND
EFFICIENT TRANSMISSION GRIDS
CIGRÉ Belgium Conference
Crowne-Plaza – Le Palace
Brussels, Belgium | March 12 - 14, 2014

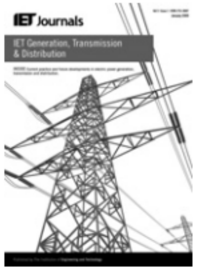
21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

Fault Discrimination in Multi-Terminal DC Supergrids

I.Dallas, C.Booth

www.ietdl.org

Published in IET Generation, Transmission & Distribution
Received on 20th February 2014
Revised on 12th September 2014
Accepted on 10th October 2014
doi: 10.1049/iet-gtd.2014.0169



ISSN 1751-8687

Investigation of the sympathetic tripping problem in power systems with large penetrations of distributed generation

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Appendix: selected publications

University of Strathclyde Engineering

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Engineering Technical Rep

139

Issue 1 – November 2009

RECOMMENDATIONS FOR SETTING OF LOSS OF MAIN

Reducing unnecessary disconnection of renewable generation from the power system

A. Dyśko, C. Booth, O. Anaya-Lara and G.M. Burt

cigré

21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

B5_111_2014

CIGRE 2014

Demonstration and analysis of IP/MPLS communications for delivering power system protection solutions using IEEE C37.94, IEC 61850 Sampled Values, and IEC 61850 GOOSE protocols

S.M. BLAIR, F. COFFELE, C.D. BOOTH
University of Strathclyde
UK

B. DE VALCK, D. VERHULST
Alcatel-Lucent
Belgium

Appendix: selected publications

IEEE TRANSACTIONS ON SMART GRID

A Practical and Open Source Implementation of IEC 61850-7-2 for IED Monitoring Applications

Steven M. Blair, *Member, IEEE*, and Campbell D. Booth

IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 28, NO. 2, APRIL 2013 1103

An Open Platform for Rapid-Prototyping Protection and Control Schemes With IEC 61850

Steven M. Blair, *Student Member, IEEE*, Federico Coffele, Campbell D. Booth, and Graeme M. Burt, *Member, IEEE*

2

Transmission and distribution (T&D) network monitoring and control

K. BELL and C. BOOTH, University of Strathclyde, UK

DOI: 10.1533/9780857097378.1.39

3

Protection of transmission and distribution (T&D) networks

C. BOOTH and K. BELL, University of Strathclyde, UK

DOI: 10.1533/9780857097378.1.75