Loss of Mains Protection

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Outline

- Background
- LOM methods and practices in different countries
- Existing research work
  - LOM relay performance assessment – ETR 139
  - Risk assessment study performed for NVD WG
  - ROCOF relay performance during 28 Sept. event
  - Dynamic modelling of the UK transmission system
- Proposed changes of settings
- Possible ROCOF alternatives
- Future research work

Background

- System inertia is lowering due to growing penetration of non-synchronous generation
- Recent experience in Ireland has demonstrated short time wind penetration of 50% of the demand.
- It is anticipated that up to 100% penetration level is achievable by 2020.
- In UK n-1 contingency will increase from 1300MW to 1800MW in April 2014.
- UK recommended ROCOF setting is 0.125Hz/s (G59/2), in Ireland the recommended setting is 0.4..0.55Hz/s (G10) but the increase to 2Hz/s is proposed.
- Continually increasing the ROCOF setting my lead to poor ROCOF dependability.

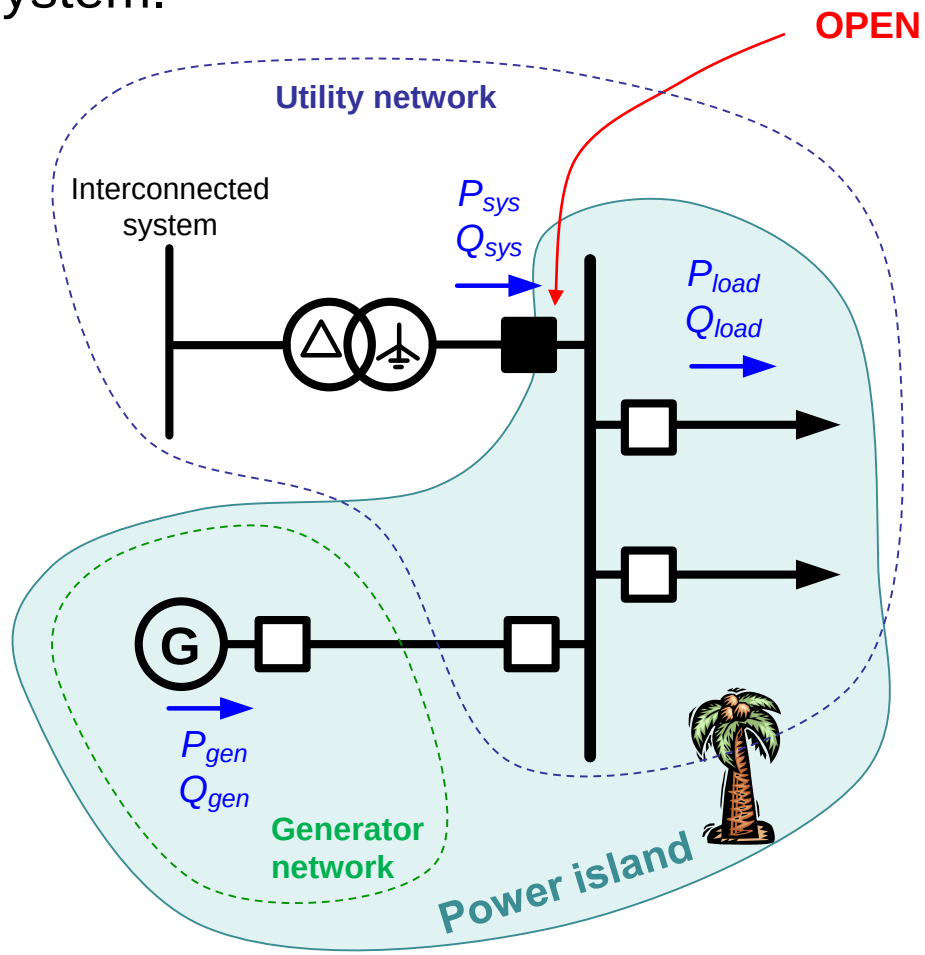
Loss-Of-Mains – LOM

- Loss of Mains (or islanding) occurs when part of the public utility network (incorporating generation) loses connection with the rest of the system.

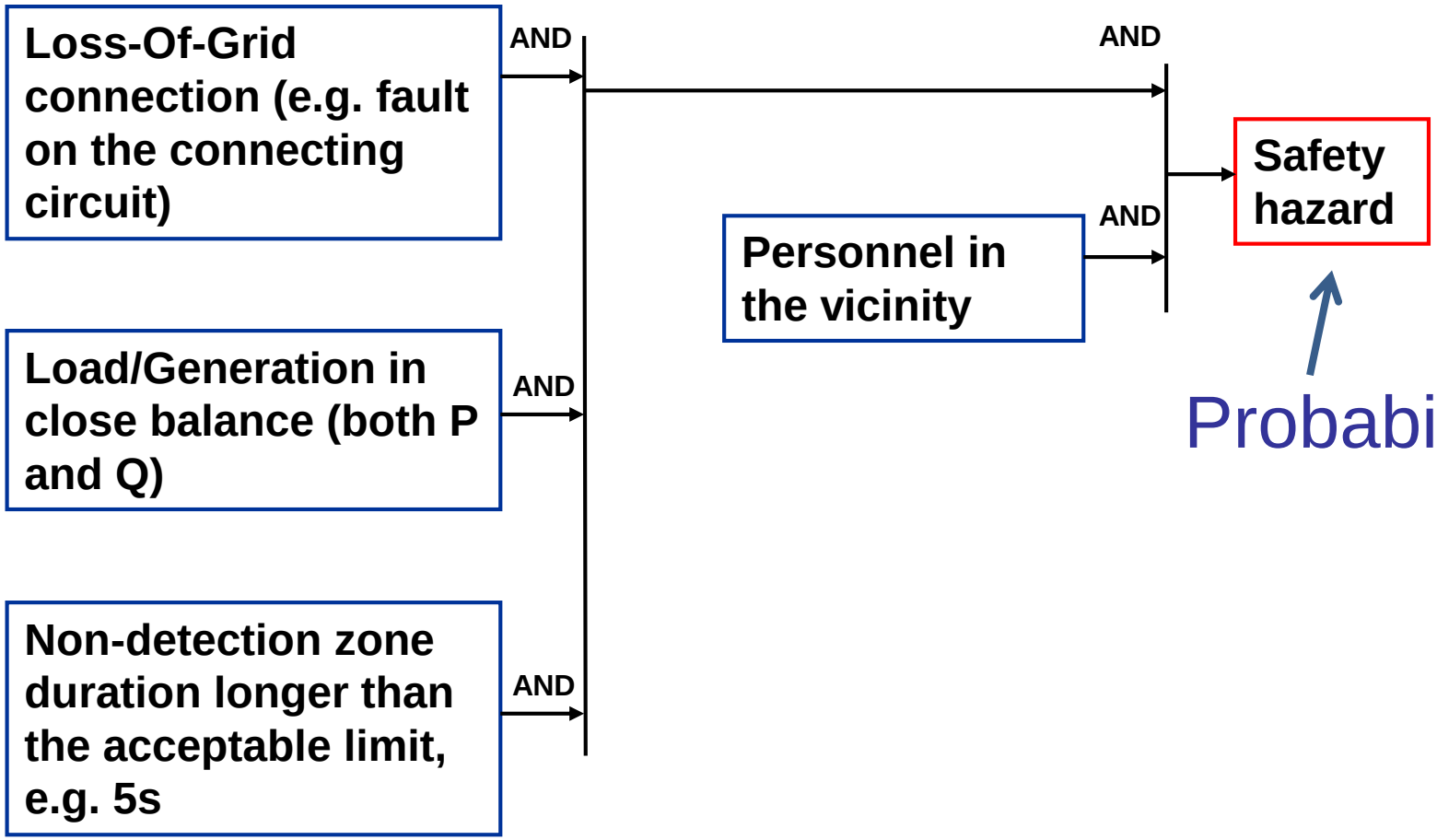
- If LOM is not detected the generator could remain connected, causing a **safety hazard** within the islanded part of the network.

- Passive LOM detection is difficult when the local load closely matches the generator output.

- Stability under remote faults and system wide events is also an issue.



Do we really need a dedicated LOM protection?



Safety hazard probability tree

Do we really need a dedicated LOM protection?

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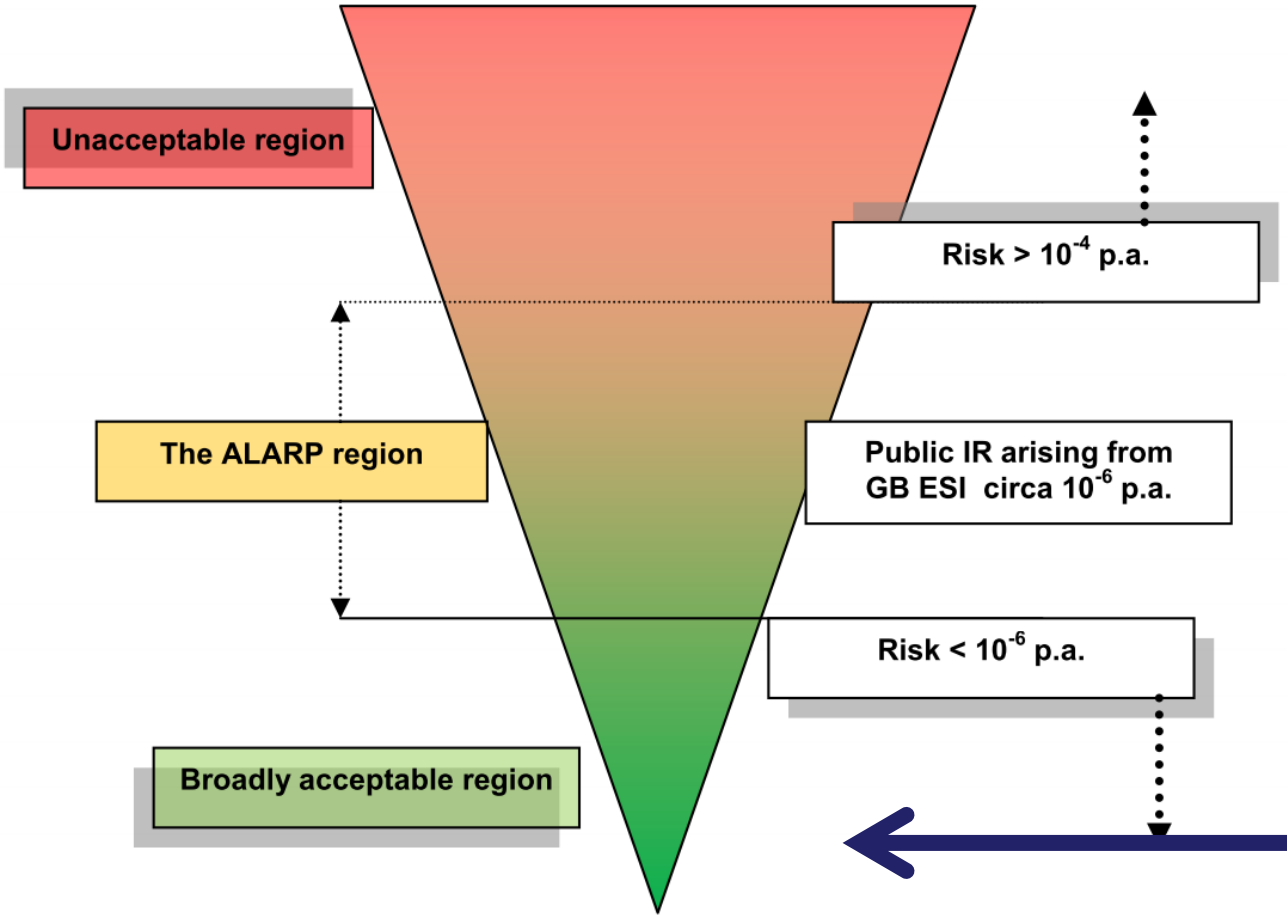
Health and Safety at Work Act 1974



Individual risk from inadvertent sustained power island

Do we really need a dedicated LOM protection?

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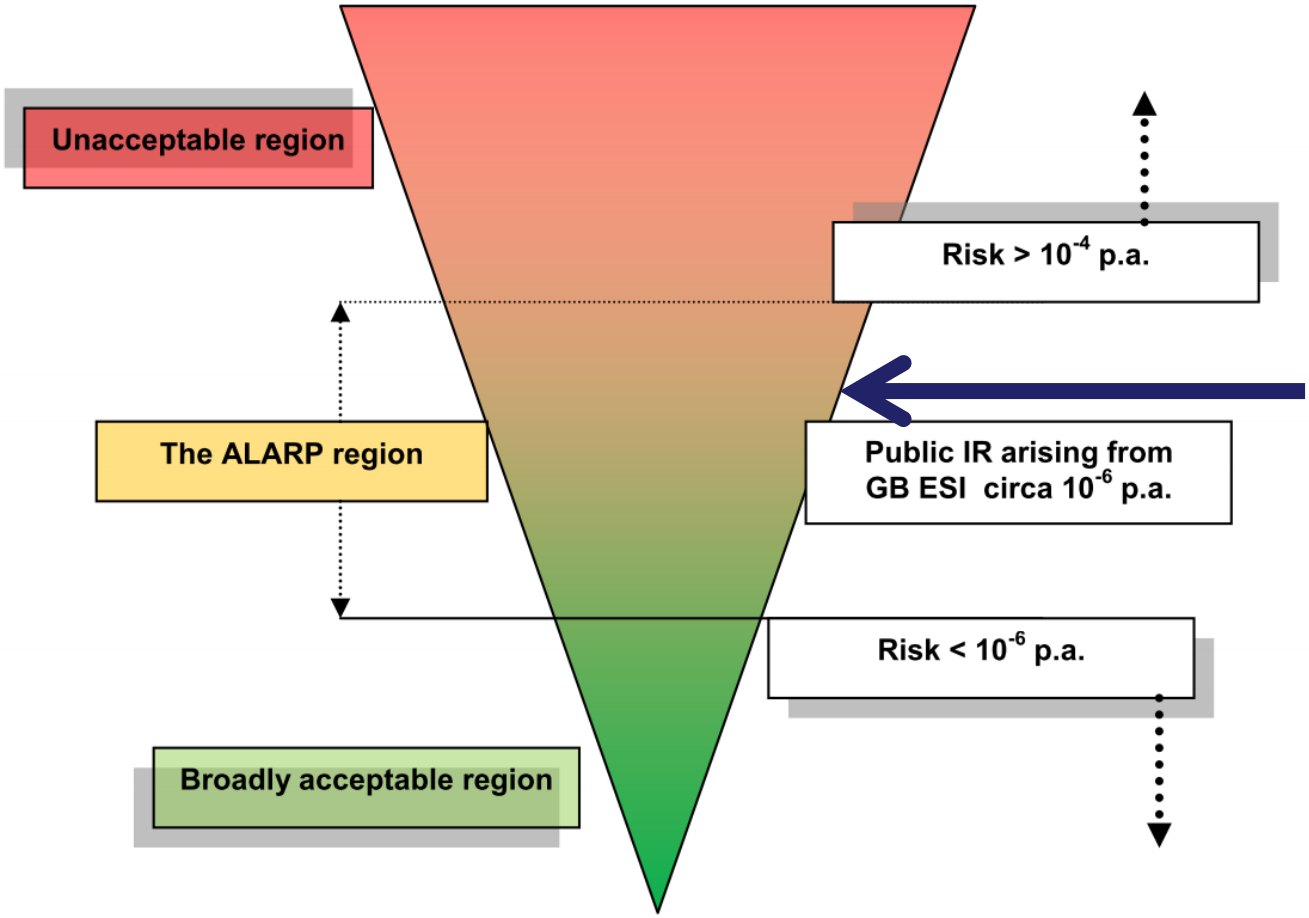


Individual risk from inadvertent sustained power island

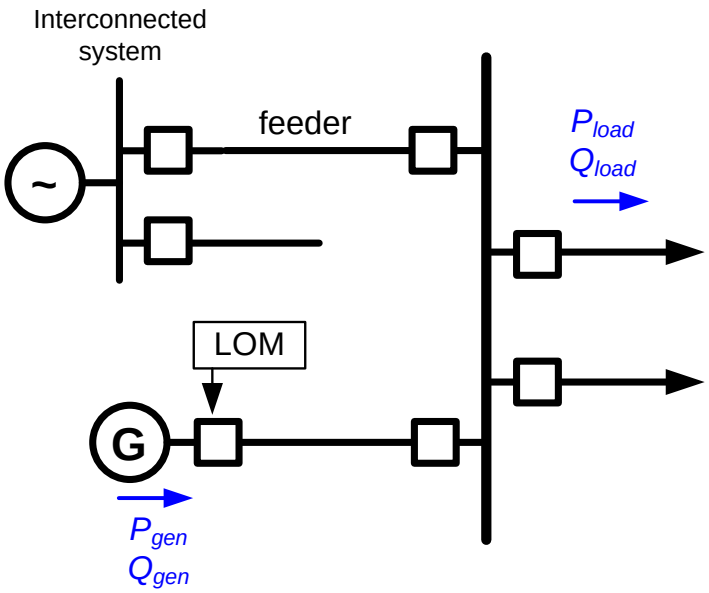
Evidence of unintentional islanding

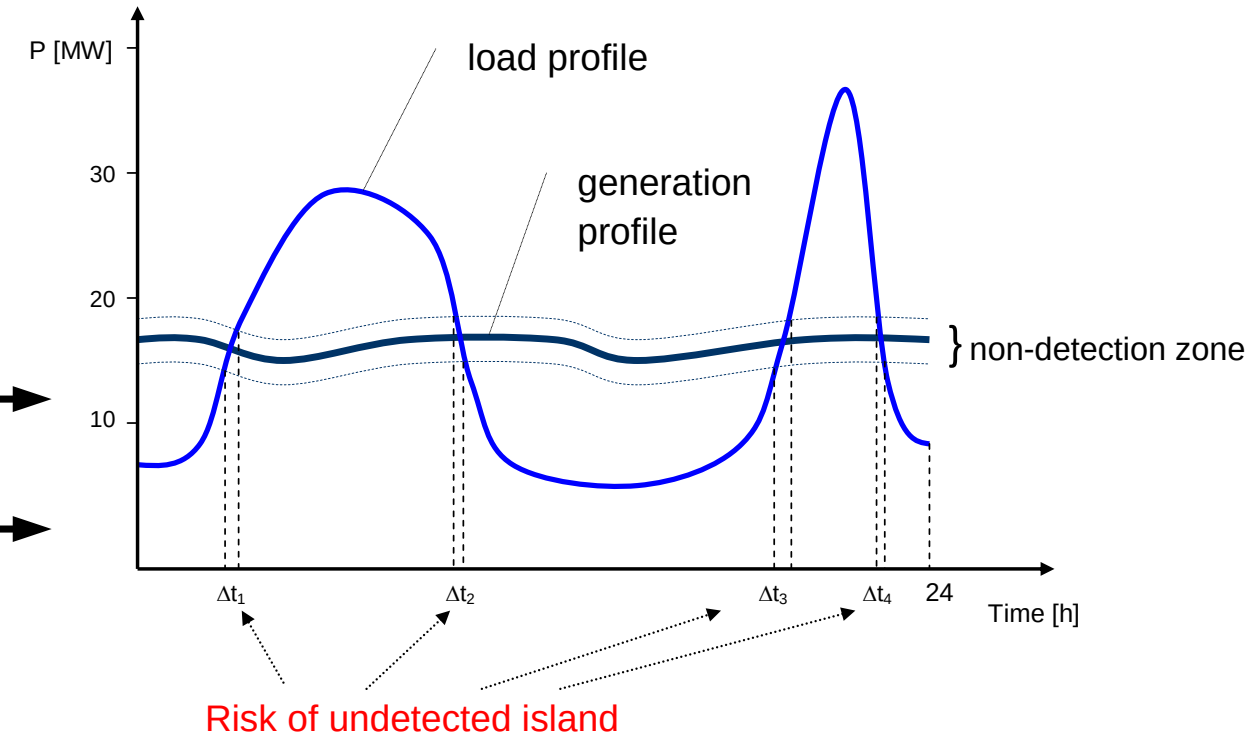
- It was reported at CIGRE 2010 session that two unintended
  islanded operations were experienced in 2009 in Brazil with small hydro generation.
  - Synchrophasor measurements for LOM applications was proposed

- Islanded operation with PV generation was experienced in Spain during maintenance disconnection (up to 40 min.)
  - Safety of maintenance staff was compromised
  - Introduce the requirement for the telecontrol systems to manually disconnect all PV generation

LOM performance requirements – sensitivity/dependability

- LOM should be sensitive under all possible load and generation scenarios.
- The most challenging scenario is when the local load closely follows the generator output both in terms of active and reactive power.

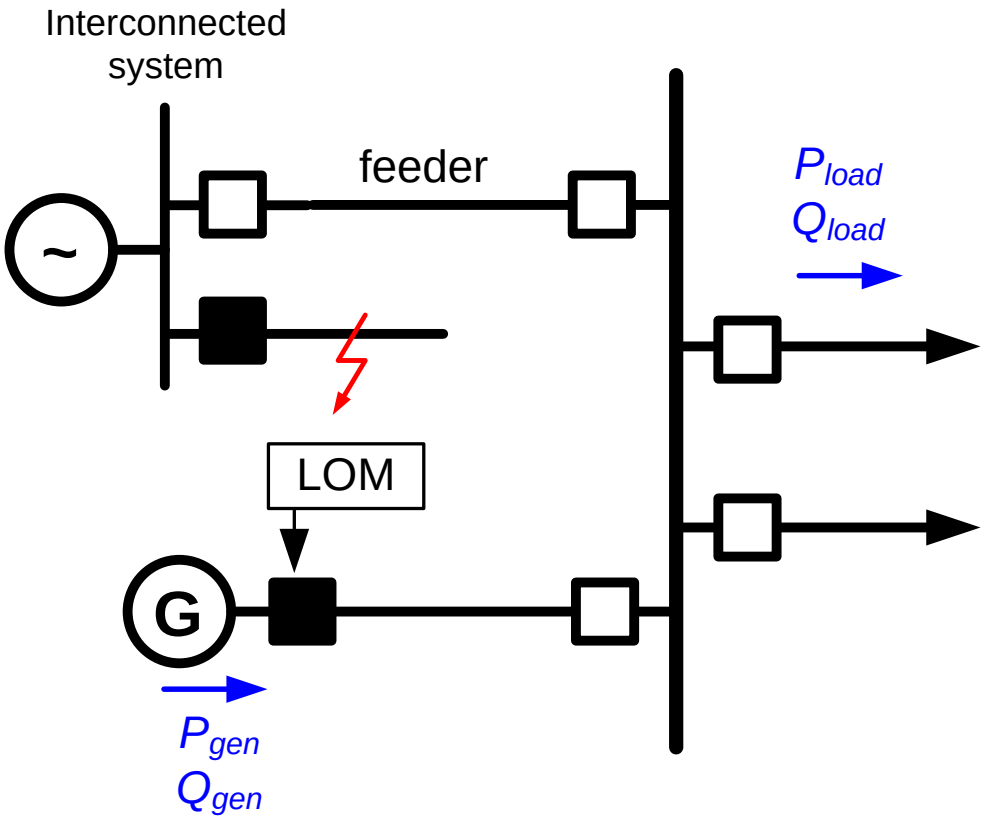




LOM performance requirements – stability/security

- LOM should be stable under remote faults cleared by the utility system as well as under system dynamic events.

- It is undesirable to issue a false trip as it leads to the unnecessary disconnection of the generator.



Current Practice in dedicated LOM protection

- Rate of Change of Frequency (ROCOF)
  - Good sensitivity but prone to spurious tripping
- Voltage Vector Shift (VS)
  - Fast but poor sensitivity to genuine LOM events and prone to spurious tripping
- Reverse VAR protection
  - Can fail if the load power factor is close to unity and/or the island contains long cables
- Intertripping
  - Best performance but cost is high and can become overcomplicated in some parts of the system.

- There is still a need for a reliable passive LOM method.

Rate-Of-Change-Of-Frequency (ROCOF) Method

- The ROCOF method is based on the local measurement of the generator voltage and estimation of the rate of change of frequency.
- The measured rate of change of frequency is compared with a preset threshold.
- Additional time delay can also be applied.
- The rate of change of frequency following an LOM event is directly proportional to the amount of active power imbalance between local load and the generator output.

$$ROCOF = \frac{\Delta P \cdot f}{2 \cdot S_n \cdot H}$$

ROCOF – estimated rate of change of frequency [Hz/s]
ΔP – change in active output power during LOM event [MW]
S_n – nominal generator rating [MVA]
f – generator rated frequency [Hz]
H – inertia constant of the generator [s]

Voltage Vector Shift (VS) LOM Method

- The relay measures voltage phase changes in consecutive cycles (or half cycles) and compares the value with the preset threshold.

- Zero crossing technique is often used as method of angle measurement

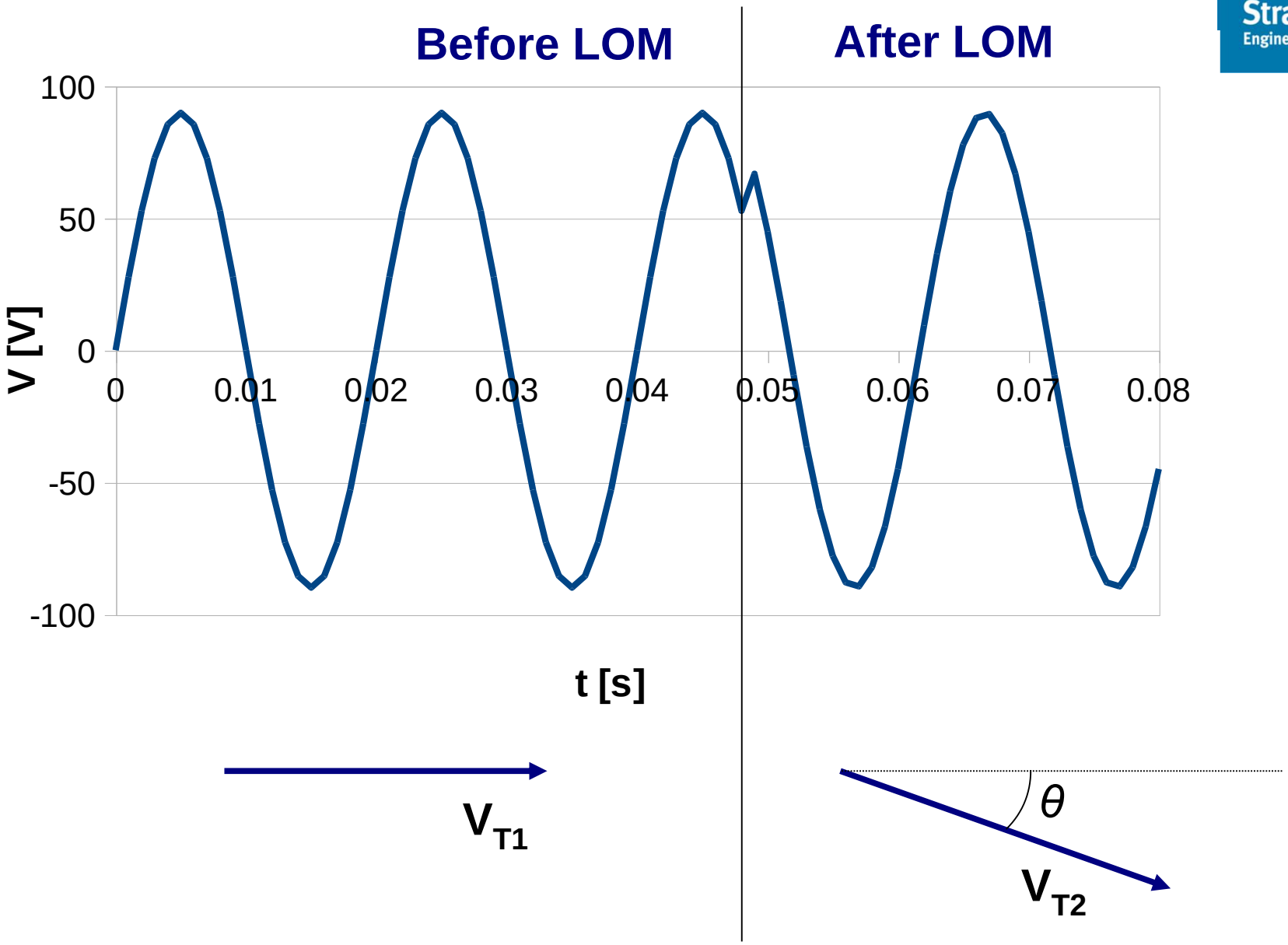
✓ - VS is very fast in comparison to other methods such as ROCOF

✗ - VS is sensitive to network faults (both resulting in islanding situation and remote faults cleared by the utility)

✓ - VS is not sensitive to rate of change of frequency

✗ - Low sensitivity to genuine LOM events. The setting of 6° requires imbalance of more than 30%S_n to cause operation.

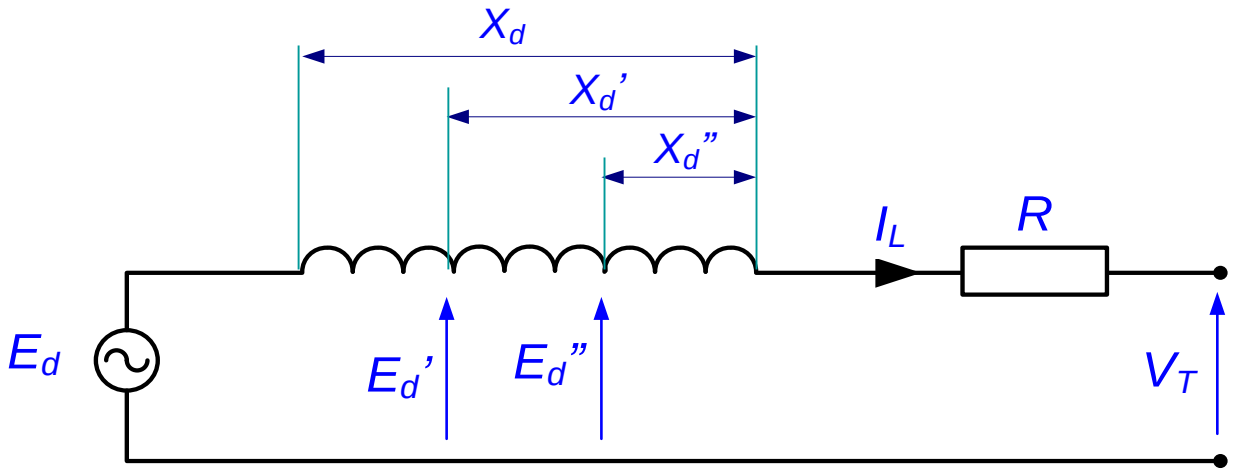
Voltage Vector Shift (VS) LOM Method



Example – Vector Shift Relay Operation

Vector Shift is used to protect an Embedded Generator. Calculate the voltage angle change if the generator output increased from 15MW to 25MW as a result of an LOM event. Before and islanding the generator operated at unity power factor pf_1=1. Assume that at the time of islanding the generator terminal voltage was V_{T1} = 1/0°pu.

Generator: S_n = 30 MVA V_n = 33 kV
X_d" = 0.23 pu R_a = 0.05 pu



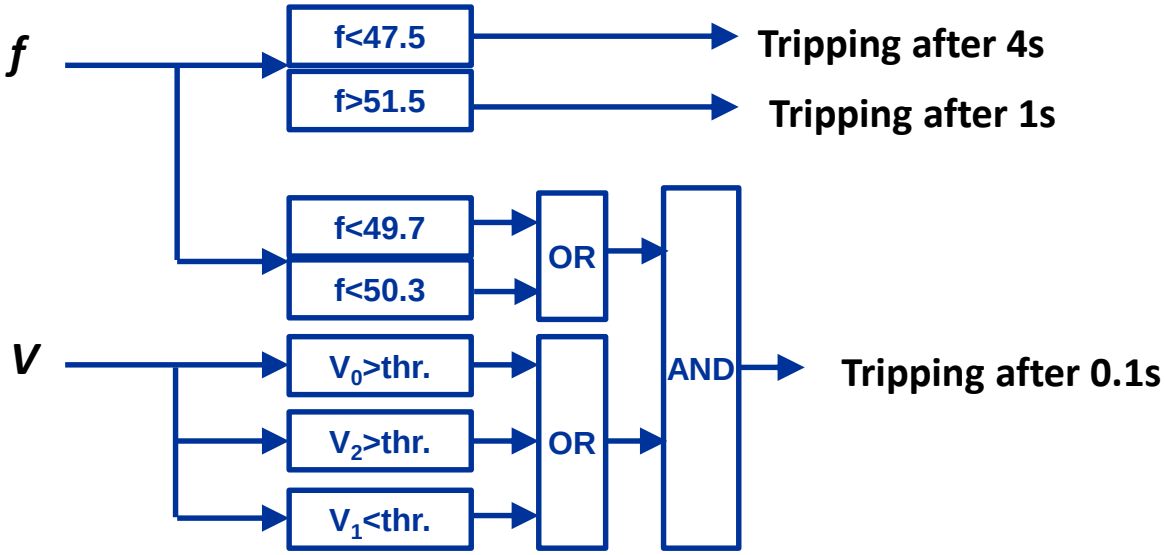
The resulting angle shift would be $\theta = 6.23°$

This is way below the recommended setting of 12°.

DG protection in different countries

- Italy

New directive 84/2012/R/EEL (8 March 2012) was issued by the Italian Regulatory Authority for Electricity and Gas (Aeeg), with the aim of integrate the CEI 0-16 (Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution) with a technical document from TERNA (the Italian TSO) defining the system requirements of the DG.



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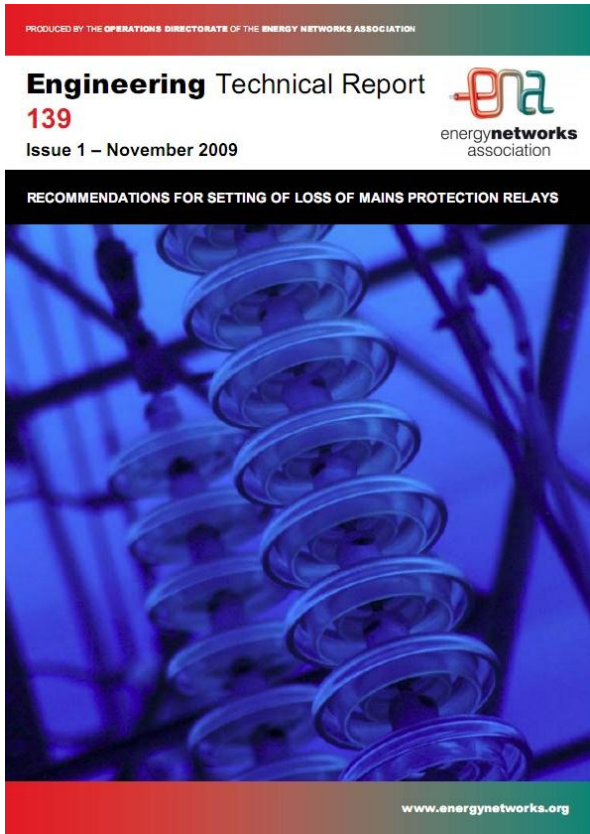
Systematic LOM relay testing
ETR 139

Systematic LOM relay testing – ETR 139

- Main objectives
  - To establish the behaviour, under various scenarios, of different Loss of Mains (LOM) protection relays that are typically applied to the protection of distributed generation installations
  - Produce a matrix of recommended settings for LOM
  - Propose standard test scenarios for LOM relays



- Case studies
  - Scenario 1: Generator of 30MVA connected to 33kV network
  - Scenario 2: Generator of less than 5MVA connected to a section of 11kV network

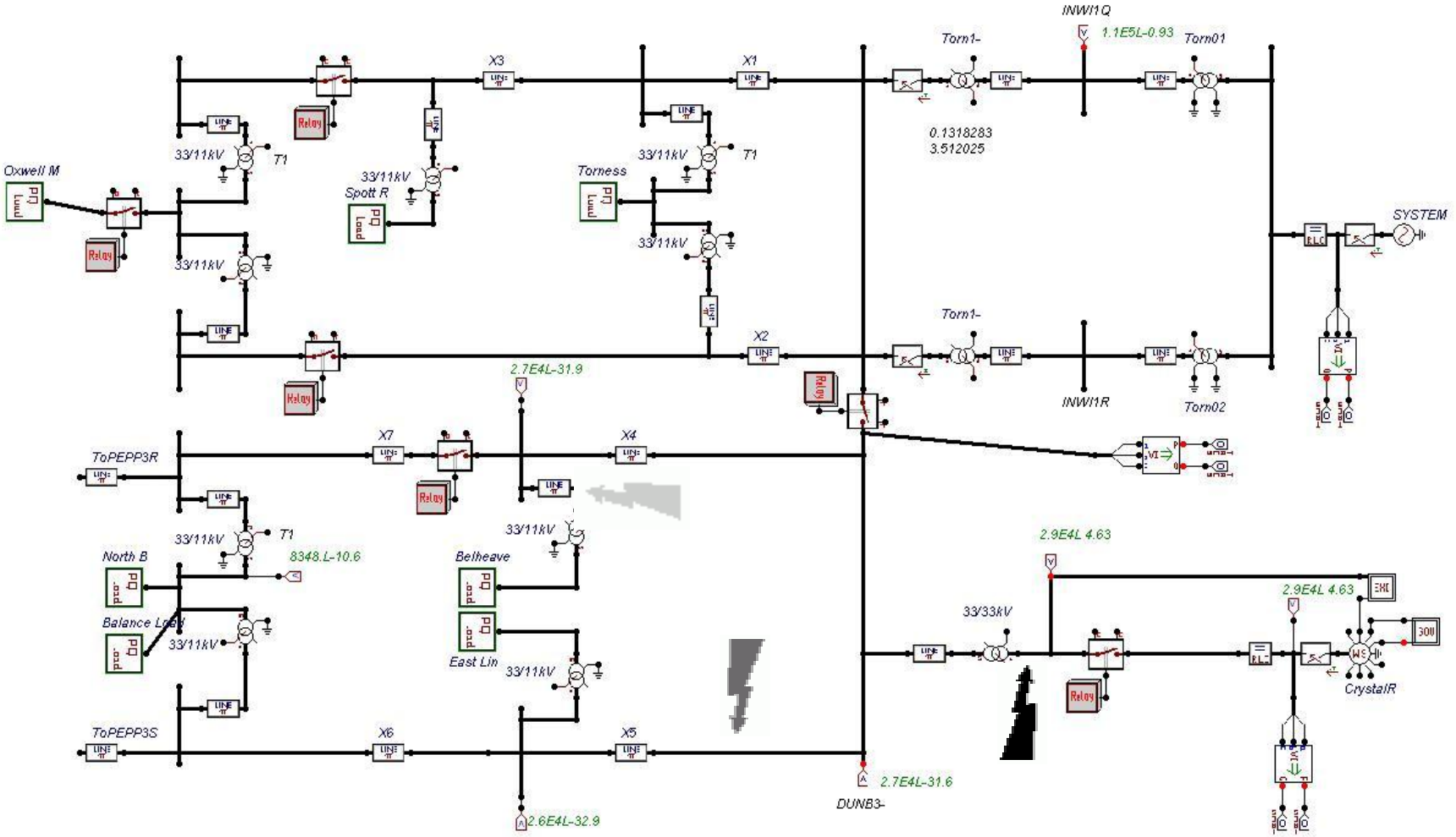
- It was assumed that maximum system $\frac{df}{dt} < 0.16\text{Hz/s}$

Systematic LOM relay testing – ETR 139

- Type of studies
  - Genuine loss of mains events – sensitivity
  - Cleared system faults (where there is no actual loss of mains) on adjacent circuits – stability
- Generator types
  - Gas turbine with synchronous machine
  - Wind turbine driven DFIG generator
  - Induction machine driven generator (11kV scenario only)
  - DC/AC inverter connected source (11kV scenario only)

Systematic LOM relay testing – ETR 139

- Network model



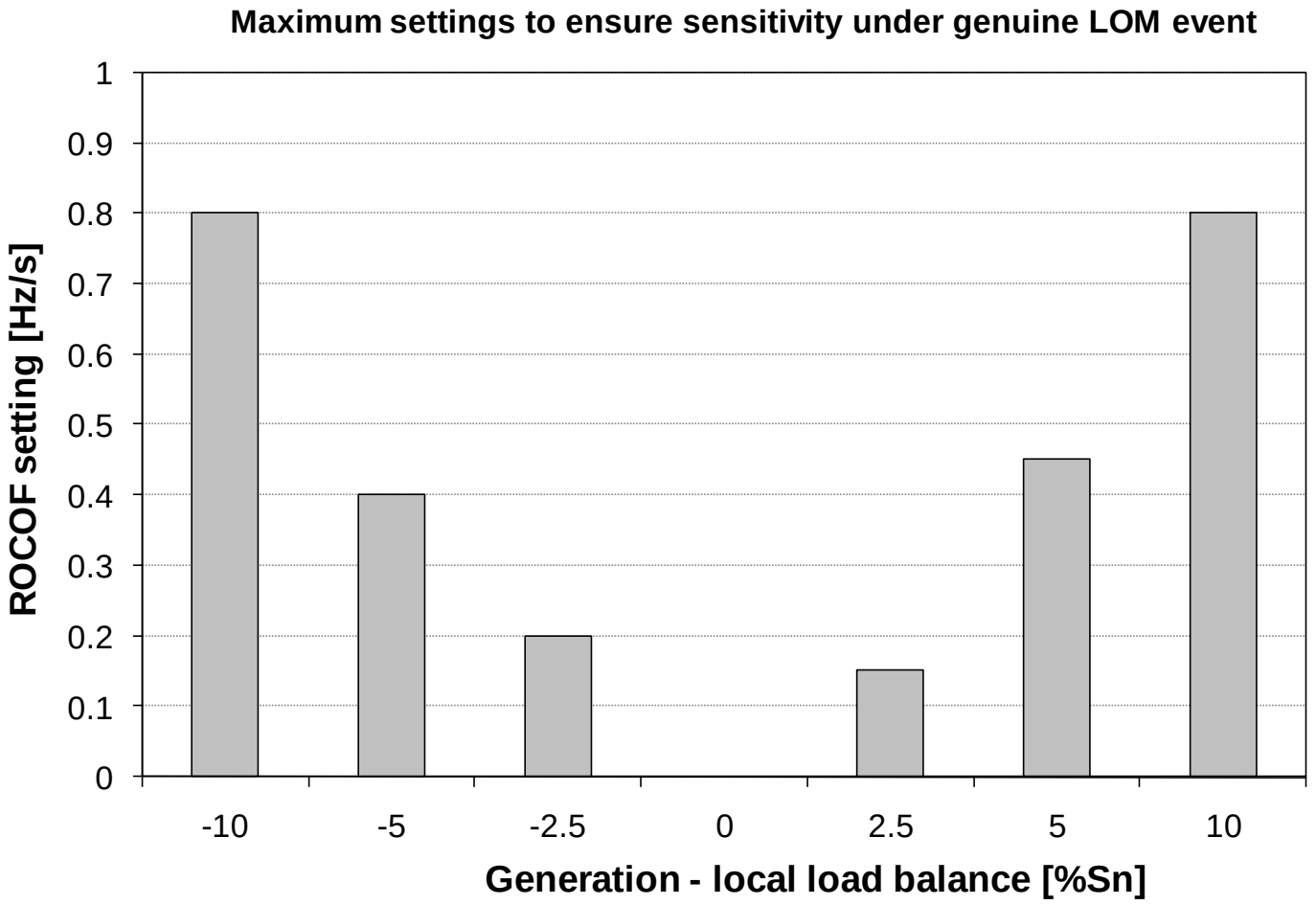
Fault Position A (20% Retained Gen Voltage)

Fault Position B (50% Retained Gen Voltage)

Fault Position C (80% Retained Gen Voltage)

Systematic LOM relay testing – ETR 139

- Typical results – sensitivity (SM based generator)



Systematic LOM relay testing – ETR 139

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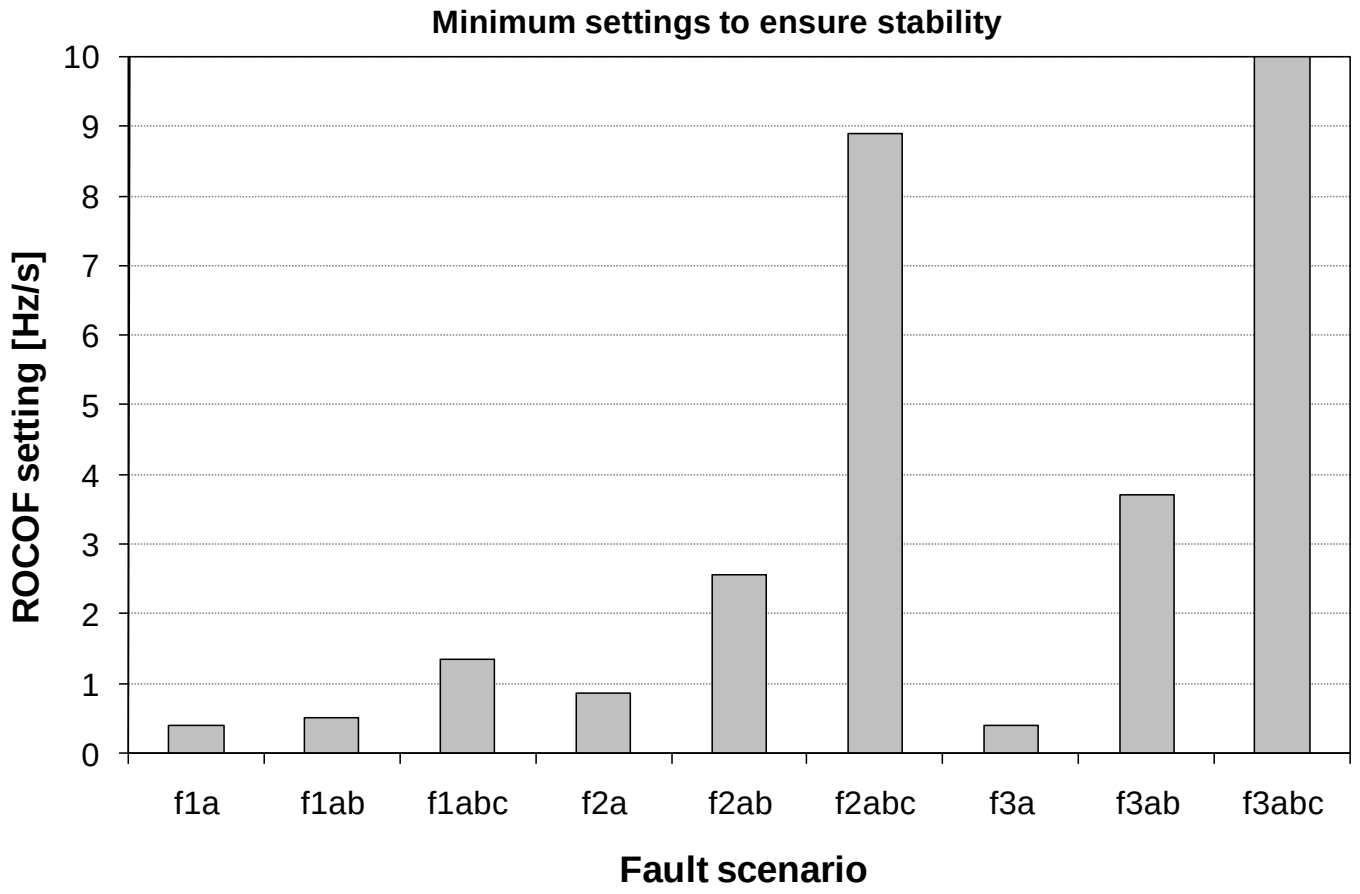
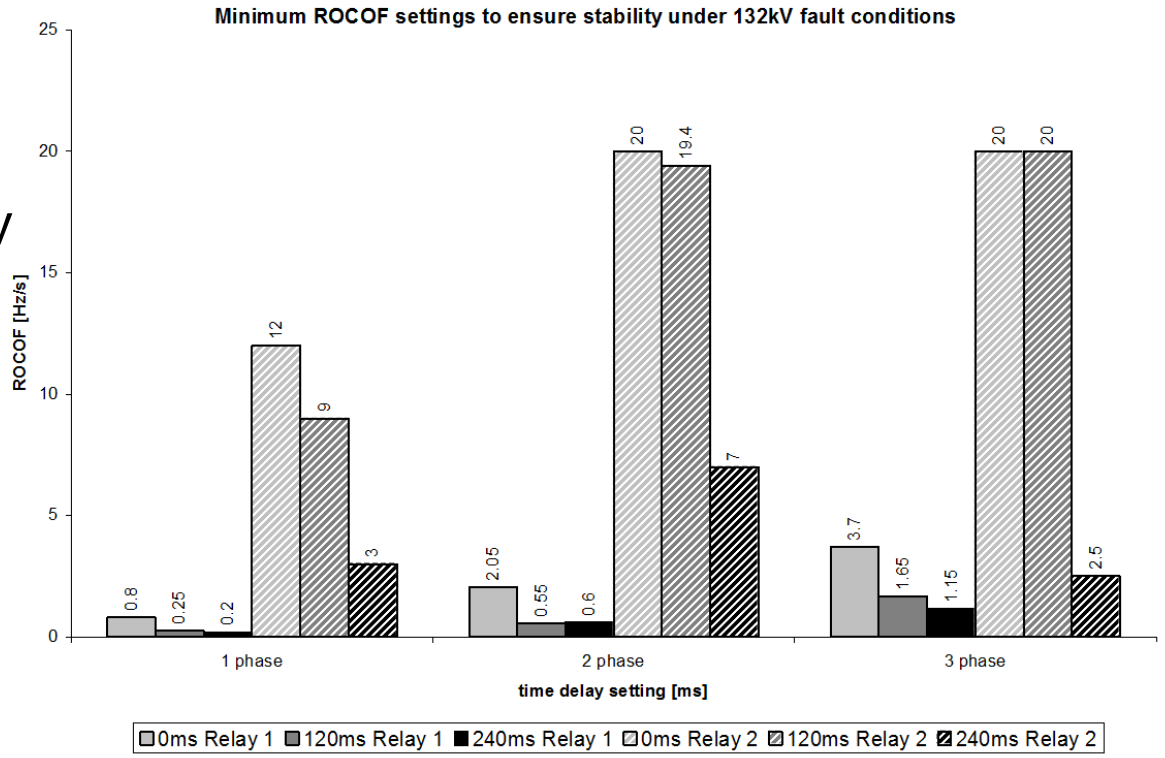


Systematic LOM relay testing – ETR 139

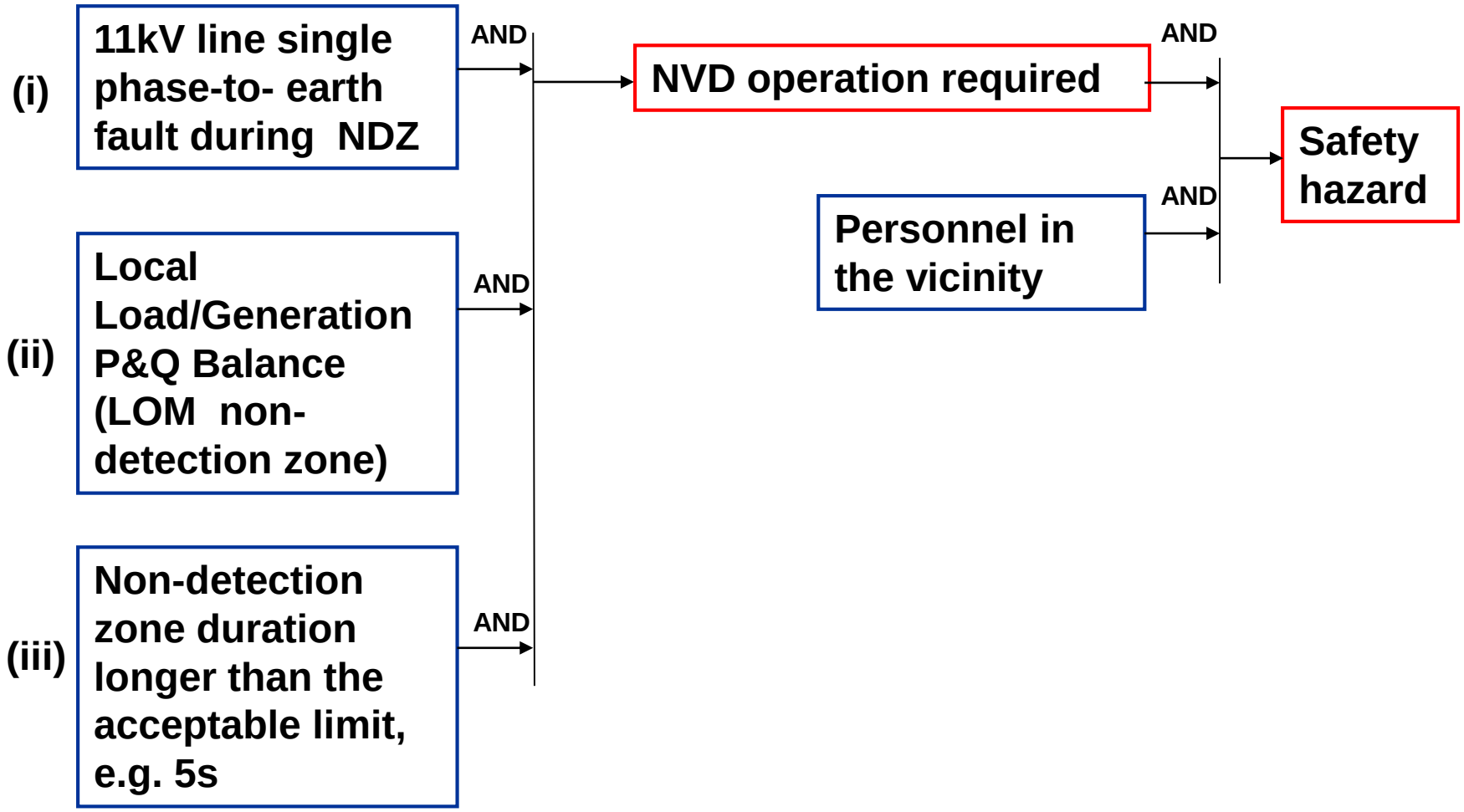
- Main findings
  - The LOM performance is affected primarily by the generation technology – the most challenging is a synchronous generator
  - Stability causes more problems than sensitivity
  - Improvement in stability can be achieved by providing additional time delay which does not significantly compromise the sensitivity
  - Significant difference in performance between different relay manufac-turers was noted, mainly in terms of stability



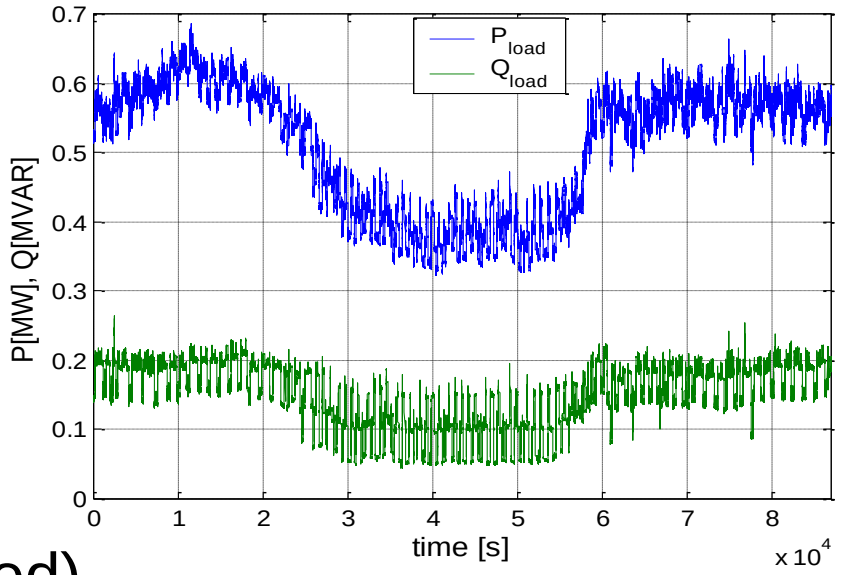
Example ROCOF Stability results for as synchronous generator

Risk assessment of NVD protection requirement

Safety hazard probability tree



Example NVD Requirement probability calculation (ENW 11kV data – Circuit 1)



- Assumptions
  - ENW 11kV data – Circuit 1
  - 5km of 95mm^2 (5MVA) cable is present
  - Non-detection zone 8% (due to presence of phase-to-earth fault a value less than 10% is assumed)
  - Generator at 0.98pf (lead)
  - Generator sizes are spread evenly between $P_{DG,min}$=100kW and $P_{DG,max}$=5MW
  - Maximum acceptable non-detection zone duration $T_{NDZ,max}$ = 5s
  - Number of affected generators in 2020 is n_{DG}=18,000x0.75 (75% LV connected).

Example NVD Requirement probability calculation (ENW 11kV data – Circuit 1)

- Average time of non-detection zone:

$$T_{NDZ,avr} = 54.972\,\text{s}$$

- Number of expected incidents in a single scheme:

$$N_{NVD,1DG} = P_{23}\frac{n_{OHE}}{100}l = 0.000220\frac{6.76}{100}5 = 0.000074 \text{ incidents p/a}$$

- National number of expected incidents:

$$N_{NVD} = N_{NVD,1DG}\,n_{DG} = 0.000074 \times 18000 \times 0.75 = 1.003 \text{ incidents p/a}$$

- Total annual time of expected incidents:

$$T_{NVD} = N_{NVD}\left(T_{NDZ,avr} - T_{NDZ,max}\right) = 1.03 \times \left(54.972 - 5\right) = 50.10 \text{ s}$$

- Annual probability of existence of hazardous islanded system condition resulting from the relaxation of the NVD protection requirement is:

$$P_{NVD} = \frac{T_{NVD}}{T_a} = \frac{50.10}{8760 \times 60 \times 60} = 1.59 \cdot 10^{-6}$$

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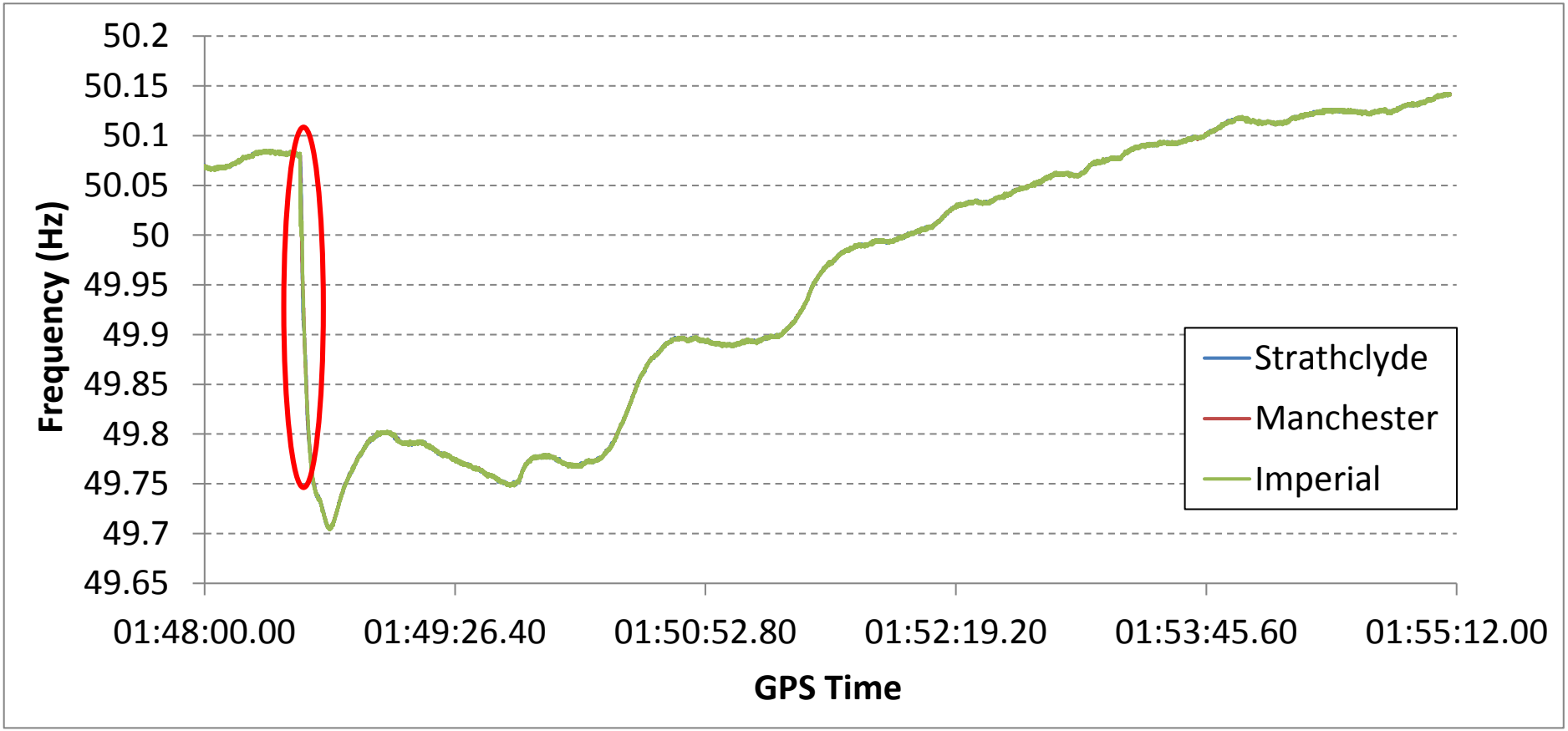
System event
28 September 2012

PMU Frequency Record



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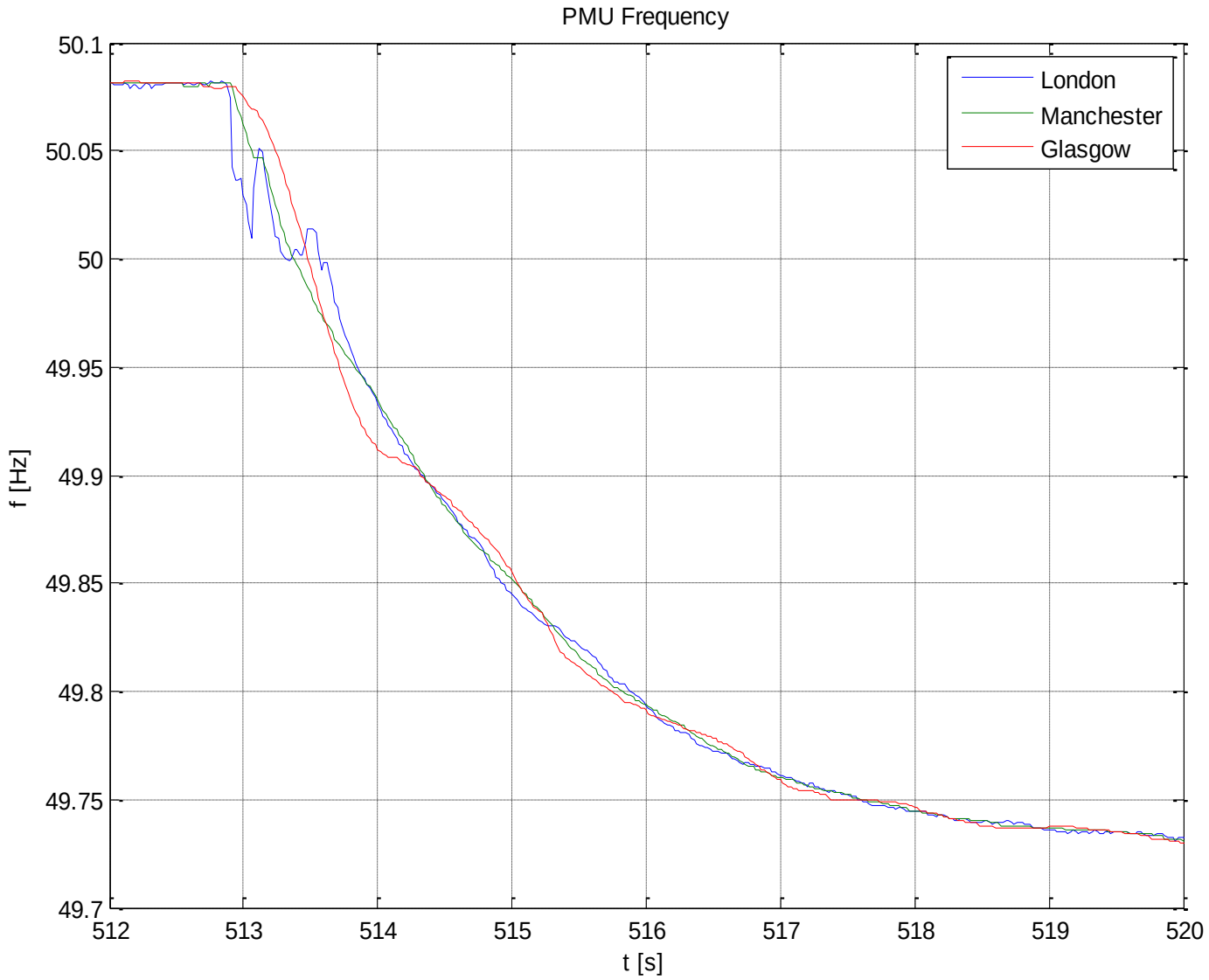
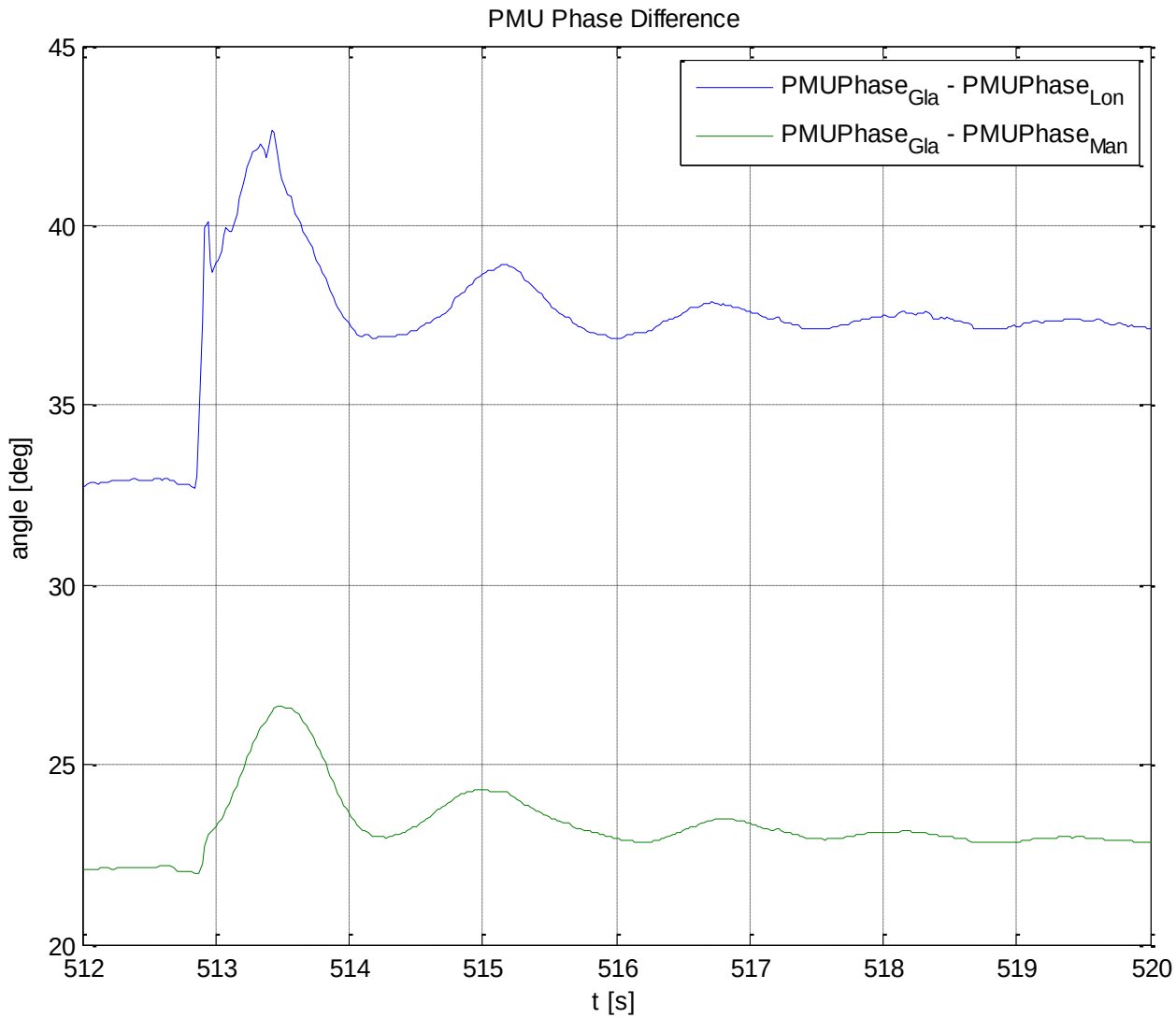
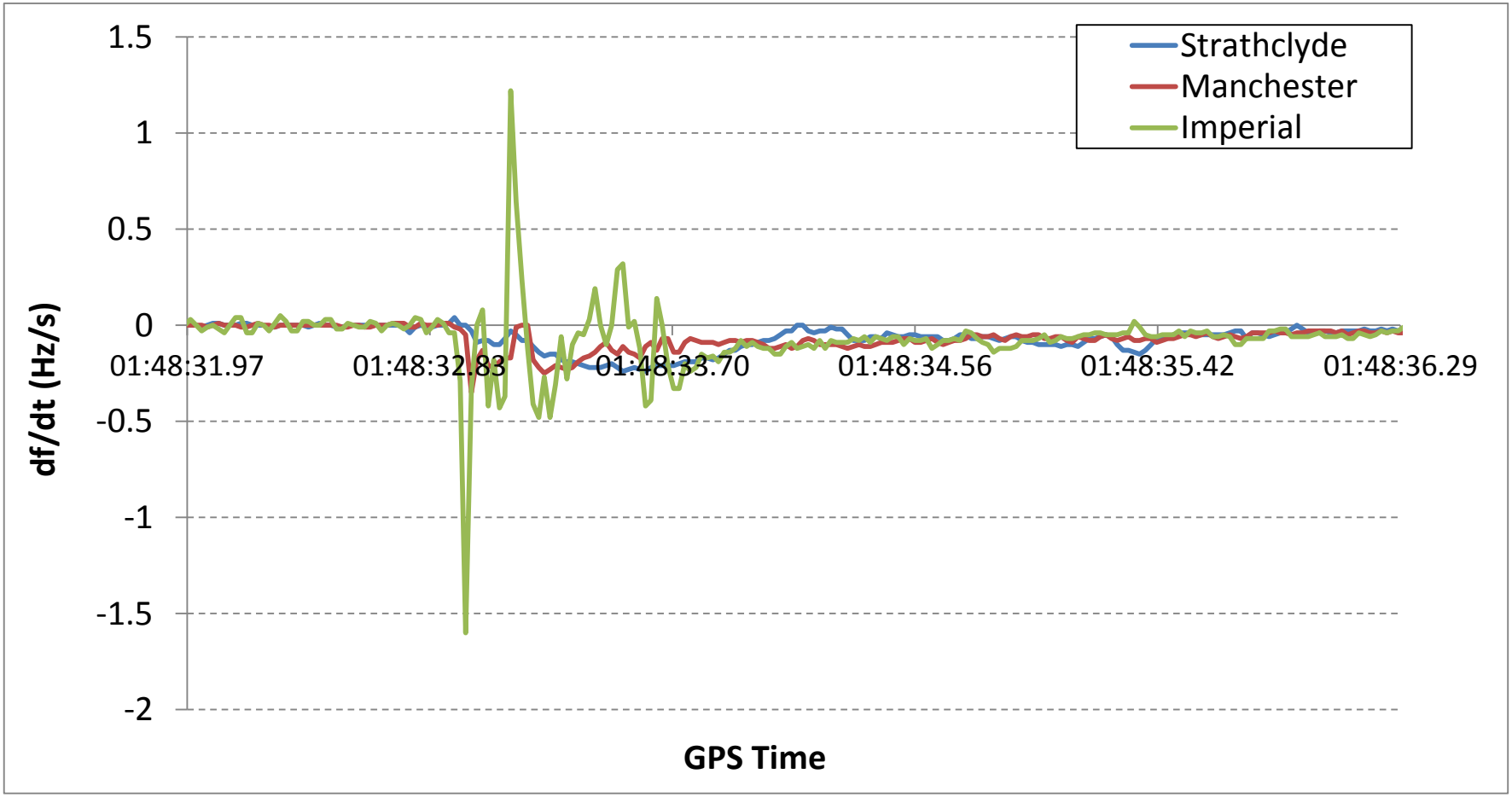


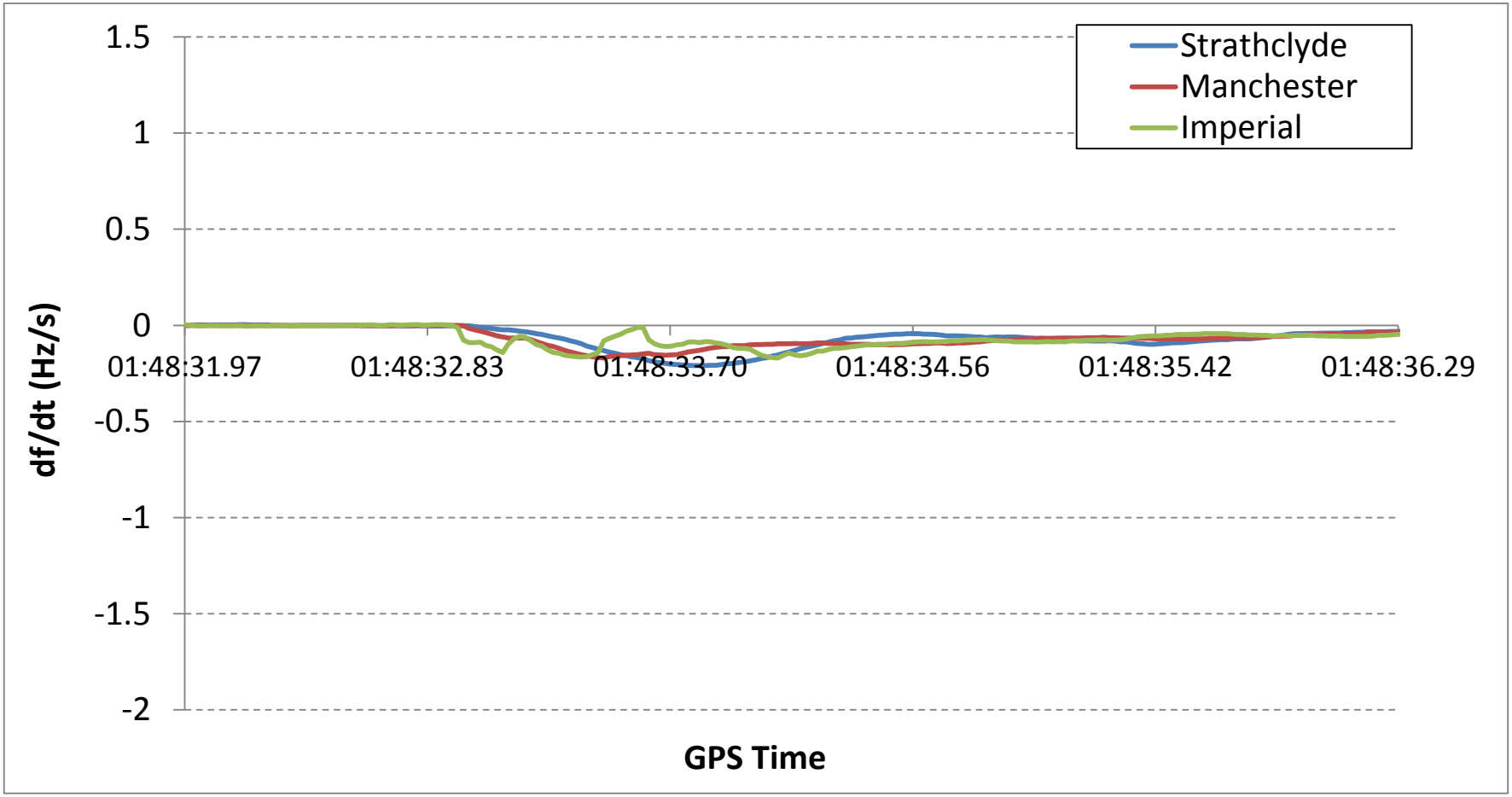
PMU Phase Angle Difference



PMU df/dt Record



df/dt calculated from PMU frequency as 0.5s average



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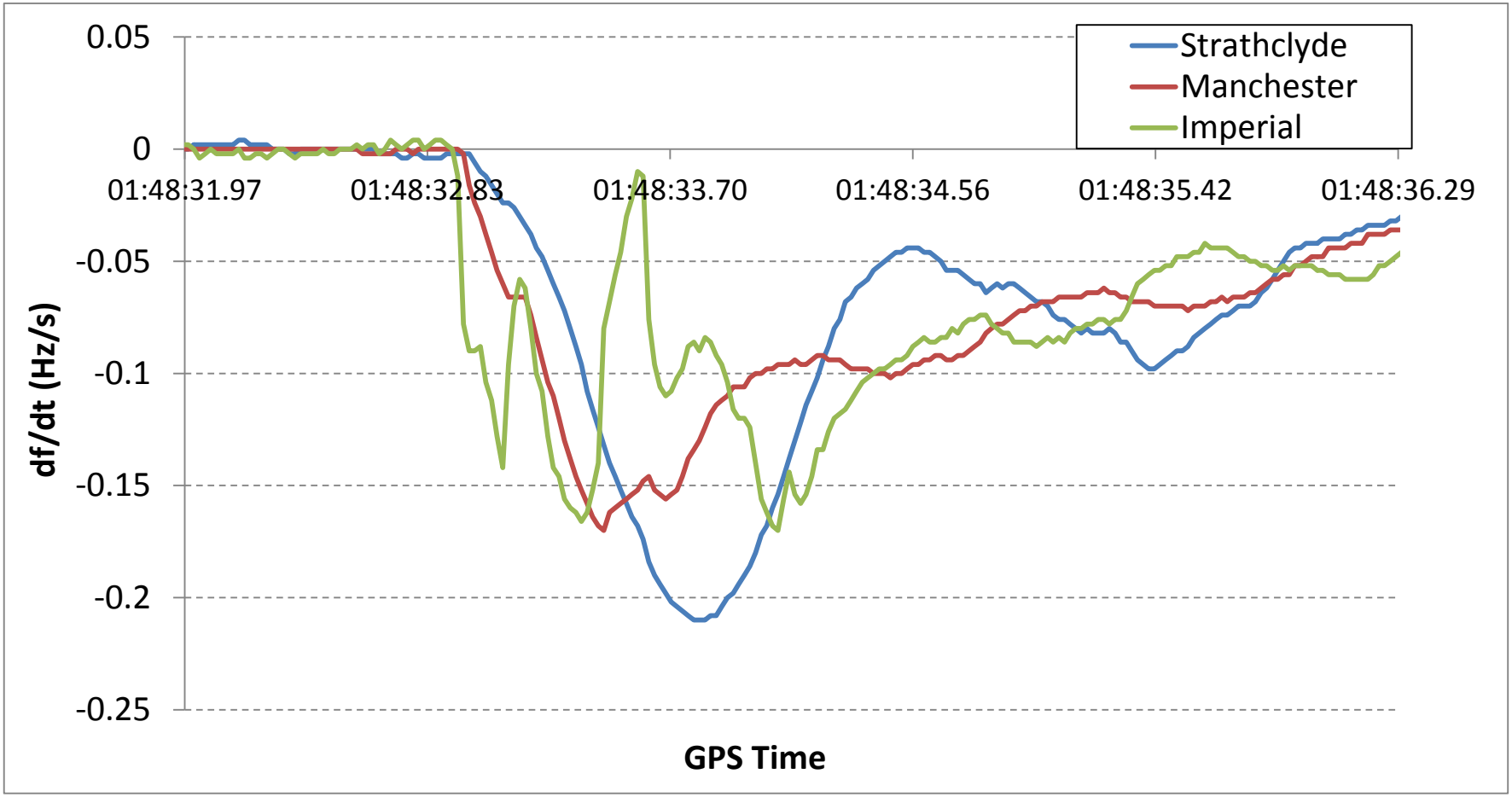

ROCOF relay testing

Three COMTRADE waveform records have been synthesised on a cycle by cycle basis from the available PMU frequency profiles and subsequently injected into the MiCOM P341 relay.

Record	Delay (s)	Trip setting (Hz/s)*	Tripping time (s)**	No trip setting (Hz/s)***
Glasgow	0	0.16	0.96	0.18
	0.25	0.15	1.15	0.17
	0.50	0.12	1.32	**0.14**
Manchester	0	0.11	0.80	0.12
	0.25	0.10	1.14	0.12
	0.50	0.10 (2/5 times)	1.27	**0.11**
London	0	0.16	0.31	0.18
	0.25	0.10	0.50	0.13
	0.50	0.10 (2/5 times)	1.72	**0.11**

* 5/5 injections result in a trip unless otherwise stated

** This is the average of 5 (or less) injections' tripping times recorded at the trip setting

*** 0/5 injections result in a trip

Observations

- df/dt seen by the DG depends on the position in the network and position in relation to the initiating event
- df/df seen by the relay depends on the frequency and ROCOF calculation method (i.e. mainly the averaging period)
- Applying additional time delay increases relay stability
- Applying additional frequency dead band (e.g. 49.5Hz to 50.5Hz) will block ROCOF operation during the majority of system wide events.

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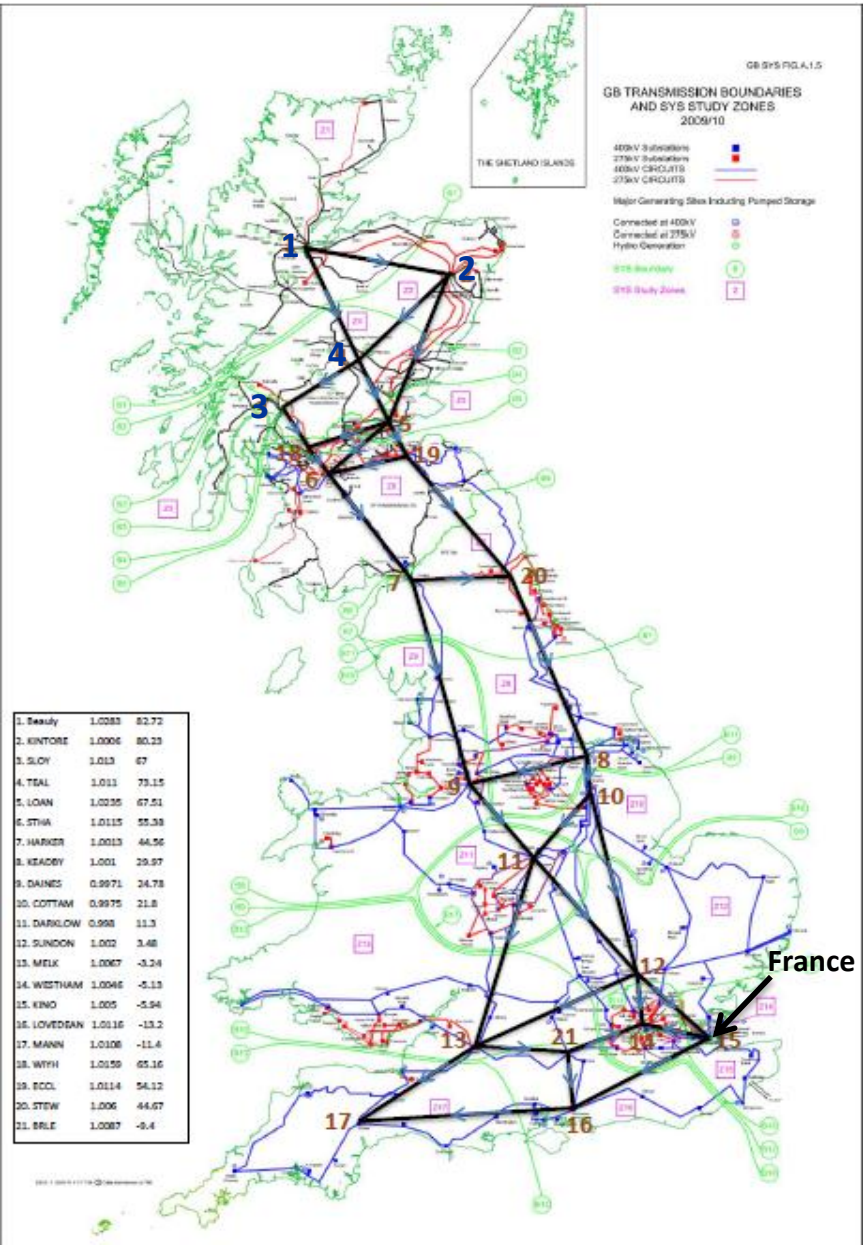
Equivalent dynamic model of the UK transmission system

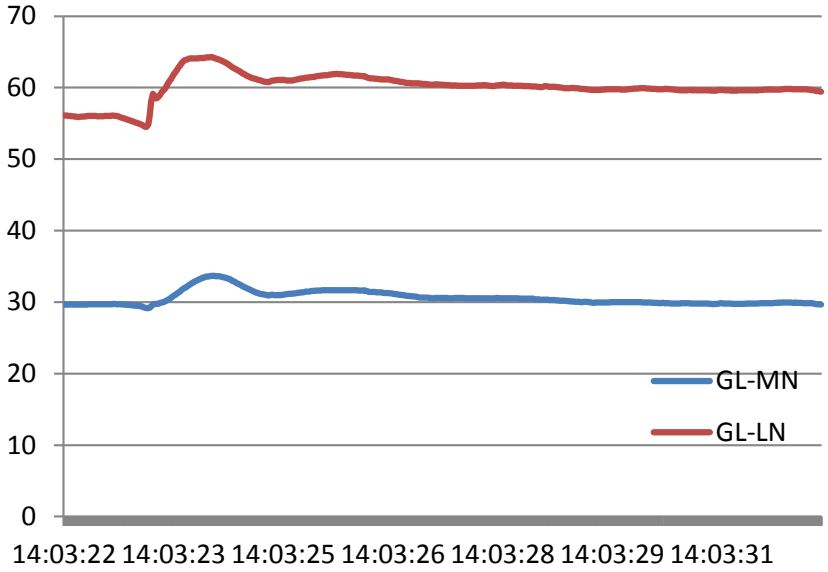
UK Transmission System model



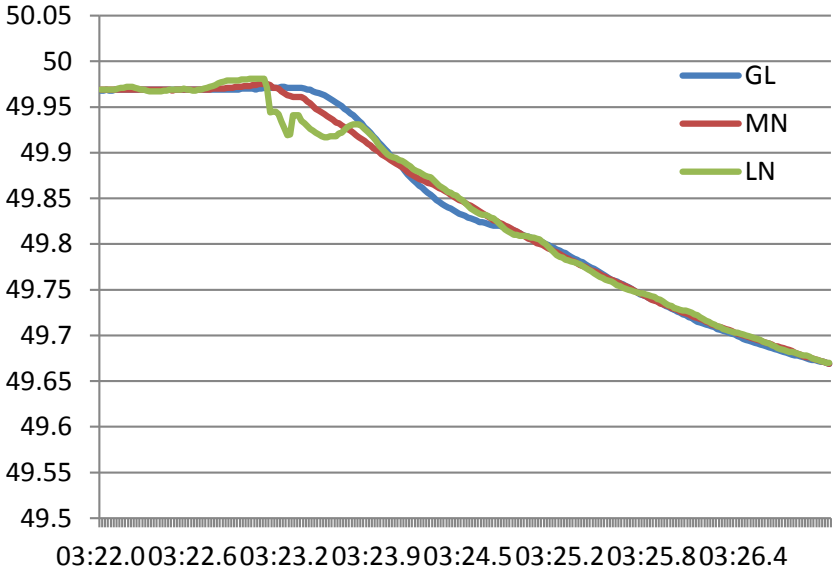
- 21 bus equivalent transmission network model is proposed
- 7YS was used to obtain the load and generation data in each zone.
- Available PSS/E full load flow model was used to obtain the circuit equivalent impedances.
- PMU data was used to verify the dynamic performance.

Dynamic Validation: PMU Data

- PMU data captured during a major event in the UK transmission system – 28 September 2012



Phase difference

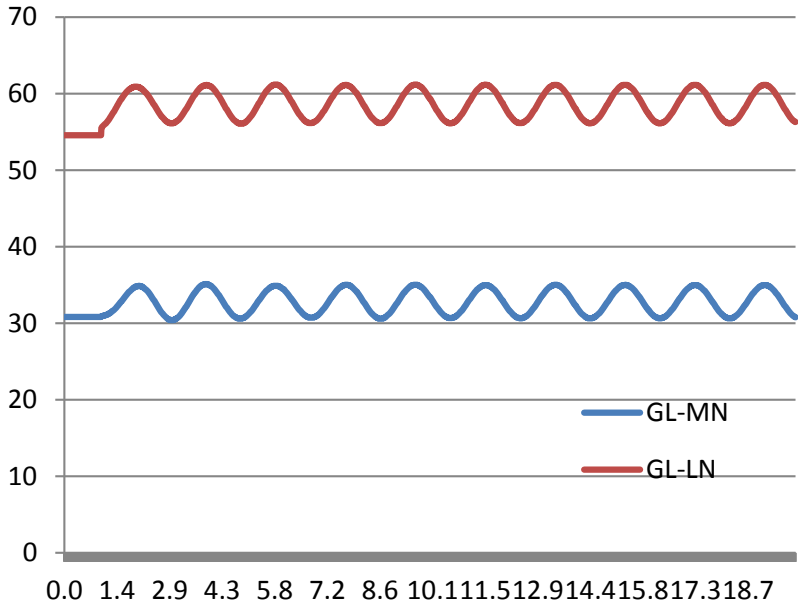


Frequency

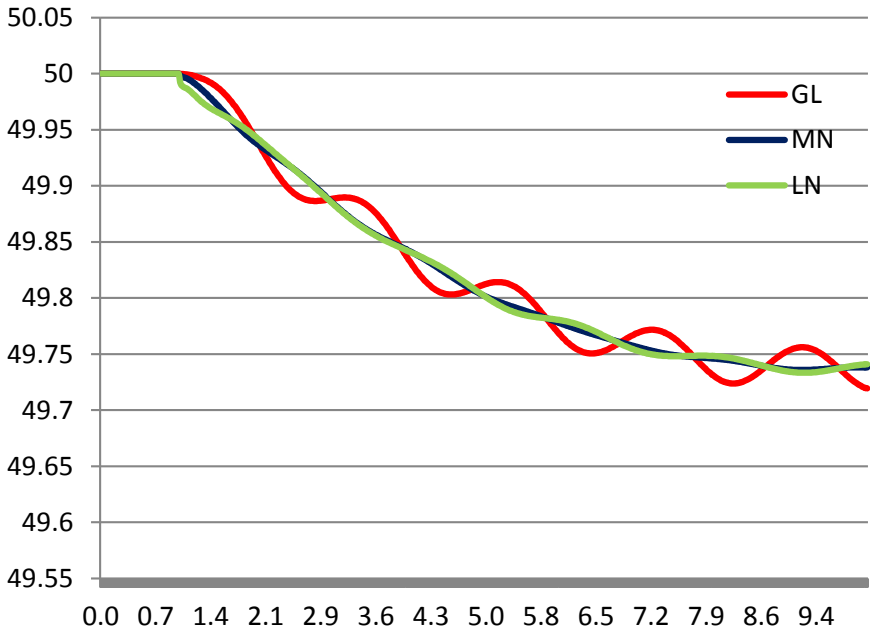
- The analysis of the voltage angle shift from different parts of the system, prior to, and after the event can assist the load flow solution validation.
- The frequency response can be used to validate the inertia and system dynamics, potentially revealing power flow oscillations.

Simulation of the 28 September event

- No PSSs included



Phase difference

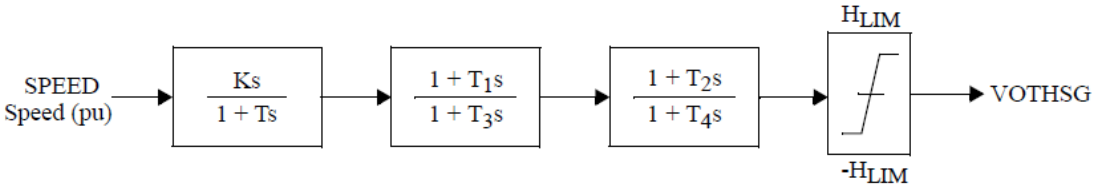


Frequency

Adding stabilisers

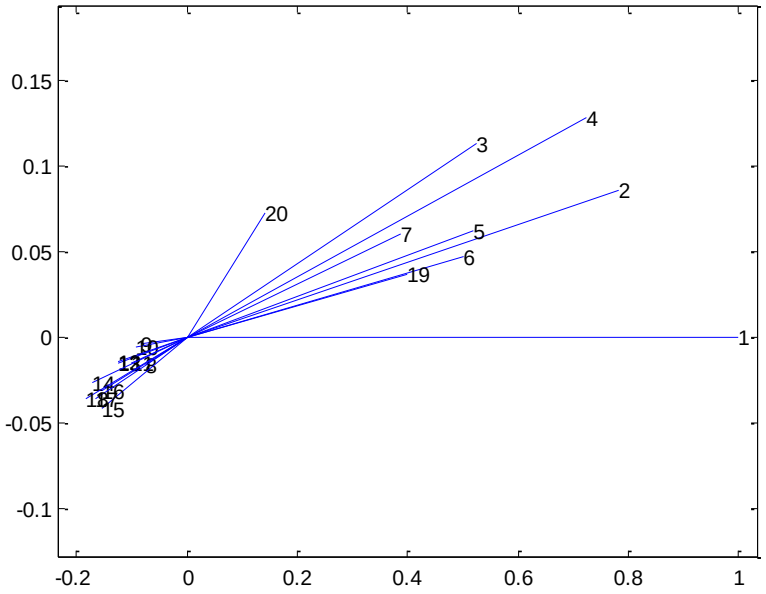
STAB1 provided by PSS/E is used in following buses:

1,2,3,8,9,10,13,19,20



STAB1 transfer function

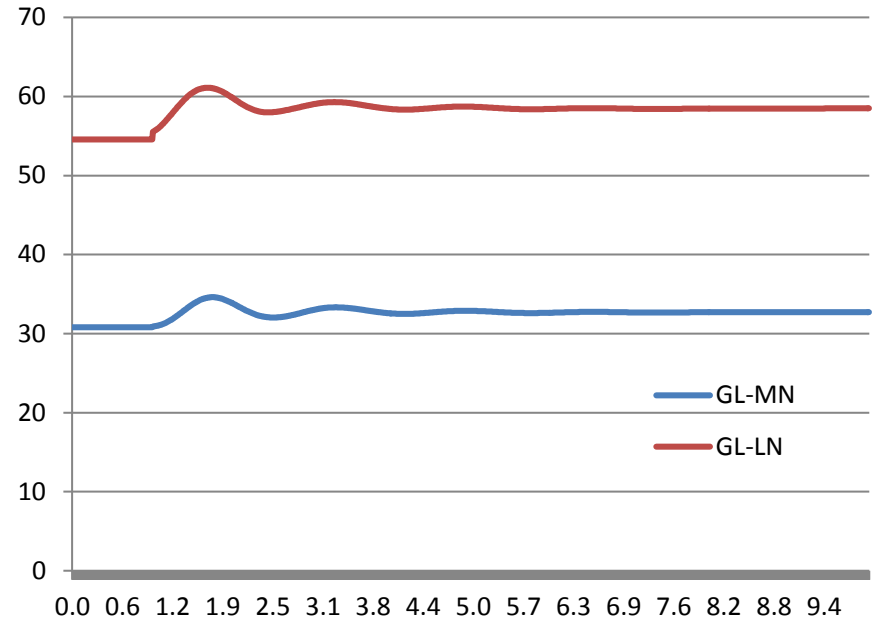
Eigenvectors and participation factors of each lightly damped oscillation mode indicate the need for a stabiliser.



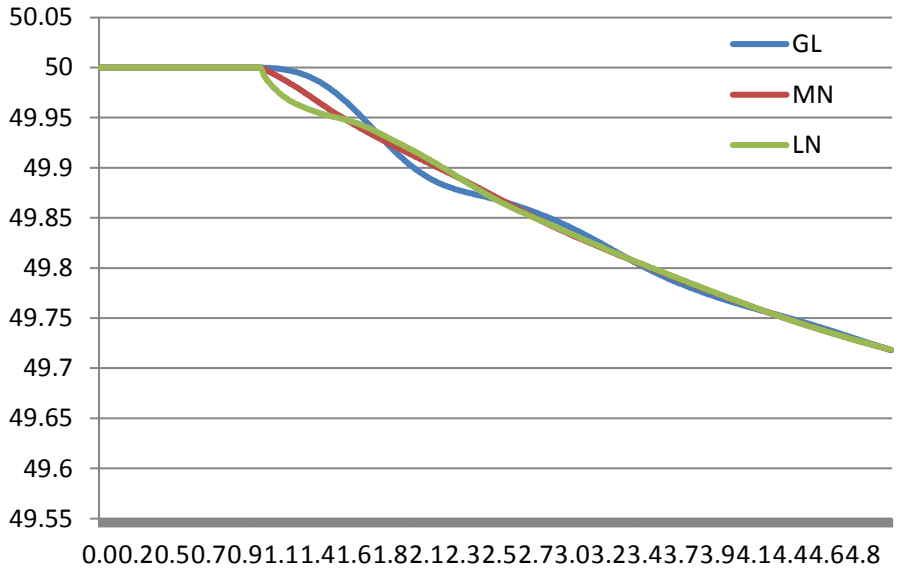
Eigenvectors of one lightly damped oscillation mode

Simulation of the 28 September event

- Dynamic performance after adding PSSs into the system



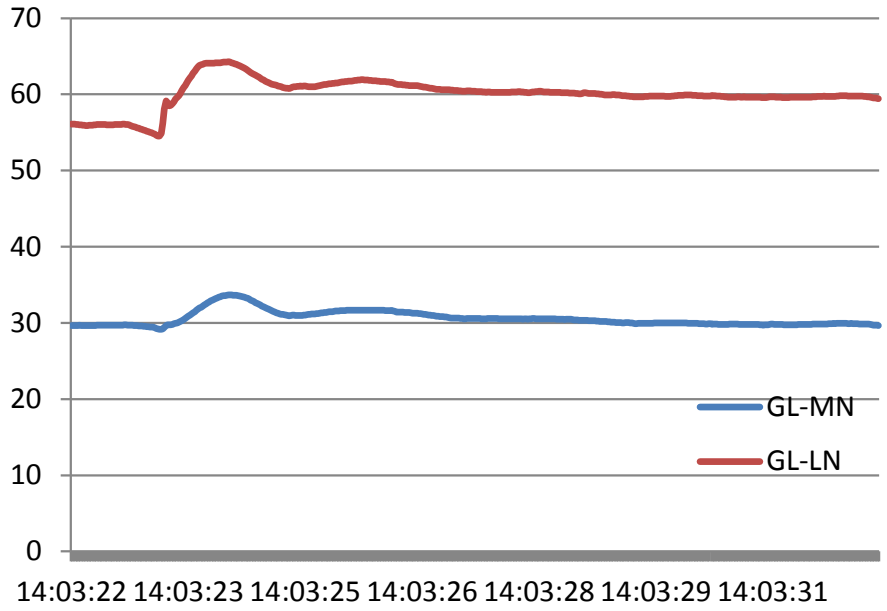
Phase difference



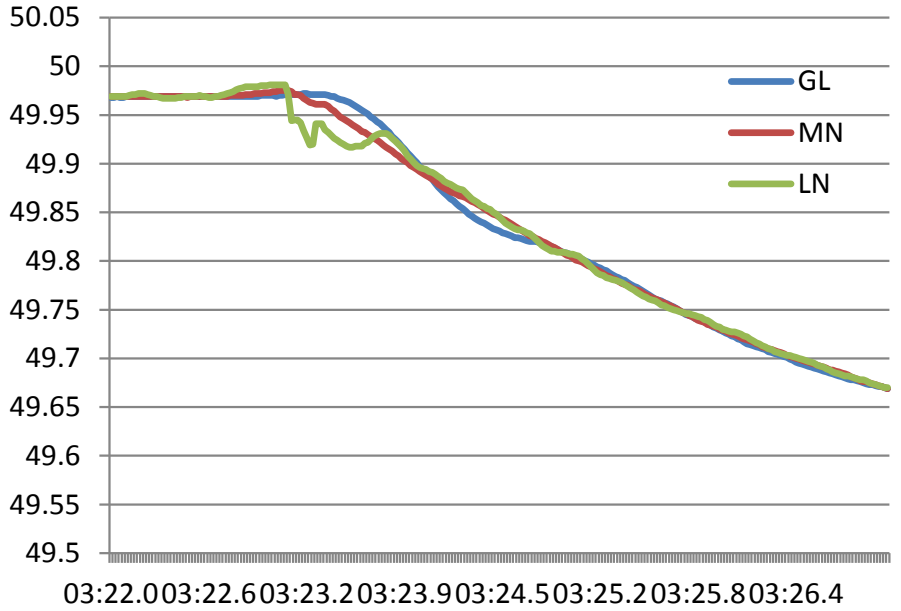
Frequency

PMU Data - 28 September

- Original PMU record



Phase difference



Frequency

ROCOF settings adjustment

nationalgrid
THE POWER OF ACTION

Initial Thoughts on Minimising System Risks

- New plant connecting in and beyond Apr 2014
  - must not have LoM protection sensitive to RoCoF; or
  - the RoCoF setting must be at or above 1Hz/s and with a minimum timer setting of 0.5 s
- New plant connecting after Apr 2013 but before Apr 2014
  - must not have LoM protection sensitive to RoCoF; or
  - the RoCoF setting must be at or above 0.5Hz/s with a minimum timer setting of 0.5 s with a provision of changing to 1 Hz by Apr 2014
- Existing plant
  - If LoM protection is sensitive to RoCoF, its setting is required to be changed to 0.5Hz/s or above and with a minimum timer setting of 0.5s as soon as practically possible
  - Provision should be made to change to 1 Hz by Apr 2014

… this may be an ideal solution from system security perspective, but…

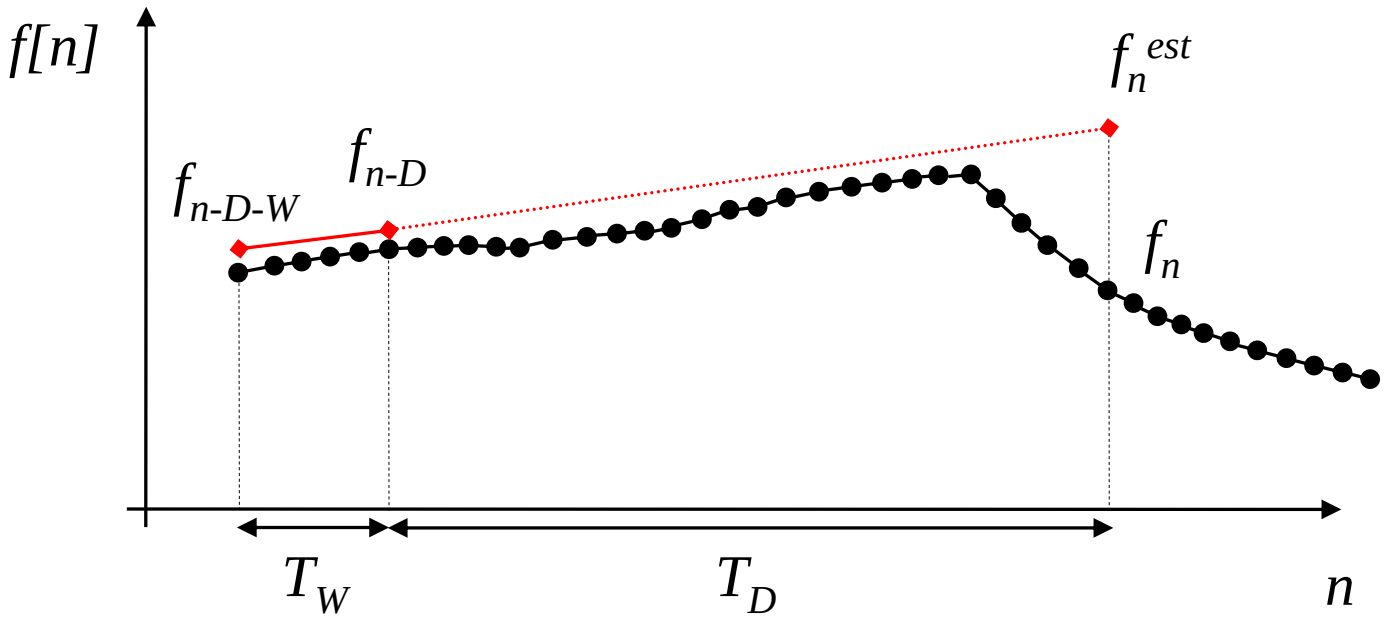
Issues to consider

- Can the setting of 1Hz/s and 0.5s delay provide acceptable LOM sensitivity?
- Are there any time coordination issues with the delayed LOM operation (in excess of 500ms)?
- Can the ROCOF setting recommendation be made dependent on the generating technology?
- Should ROCOF be removed from the acceptable LOM methods?
- What LOM methods (if any) should be adopted in the future?

University of Strathclyde Engineering

Other LOM methods

Phase Angle Drift (PAD) LOM Protection



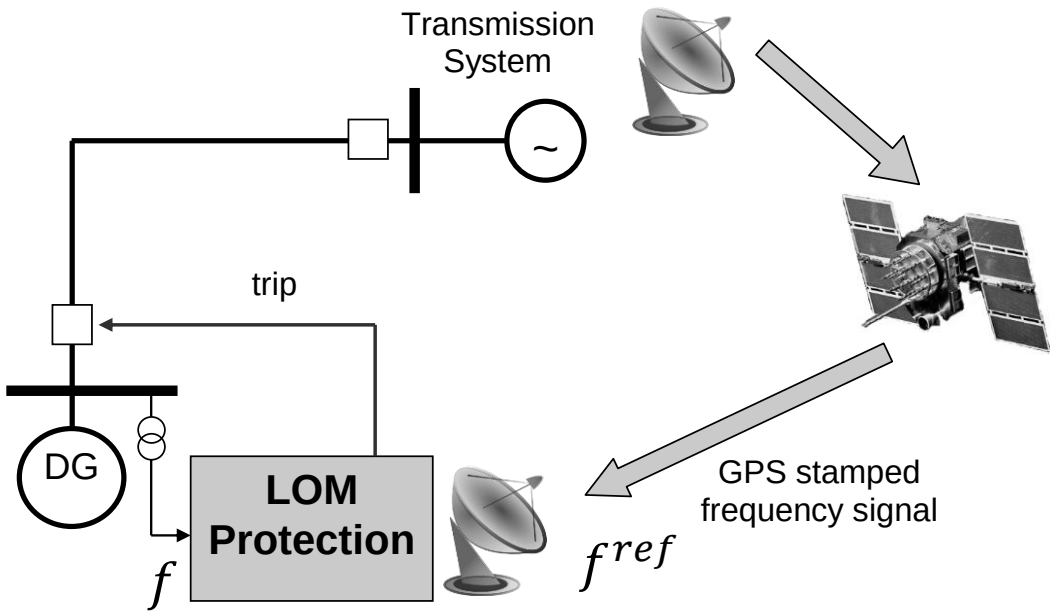
- Local frequency is measured by the relay
- Grid frequency is estimated using linear extrapolation of recorded historical data
- The PAD algorithm is based on a threshold comparison of an accumulated voltage phase angle derived from the difference between the current measured frequency and estimated frequency

H.T. Yip, G. Lloyd, A. Dysko, G.M. Burt, R.M. Tumilty, "Islanding Detection Using an Accumulated Phase Angle Drift Measurement", 10*th International Conference on Developments in Power System Protection, Manchester – UK, 2010.*

Satellite based LOM protection

- The LOM protection algorithm uses the difference between the received signal and the locally measured frequency to estimate the voltage angle shift according to the following formula:

$$\alpha_n = \alpha_{n-1} + 2\pi(f_n - f_n^{ref})\Delta t$$



α_n – calculated angle

f_n – frequency measured locally

f_n^{ref} – reference frequency received from the satellite

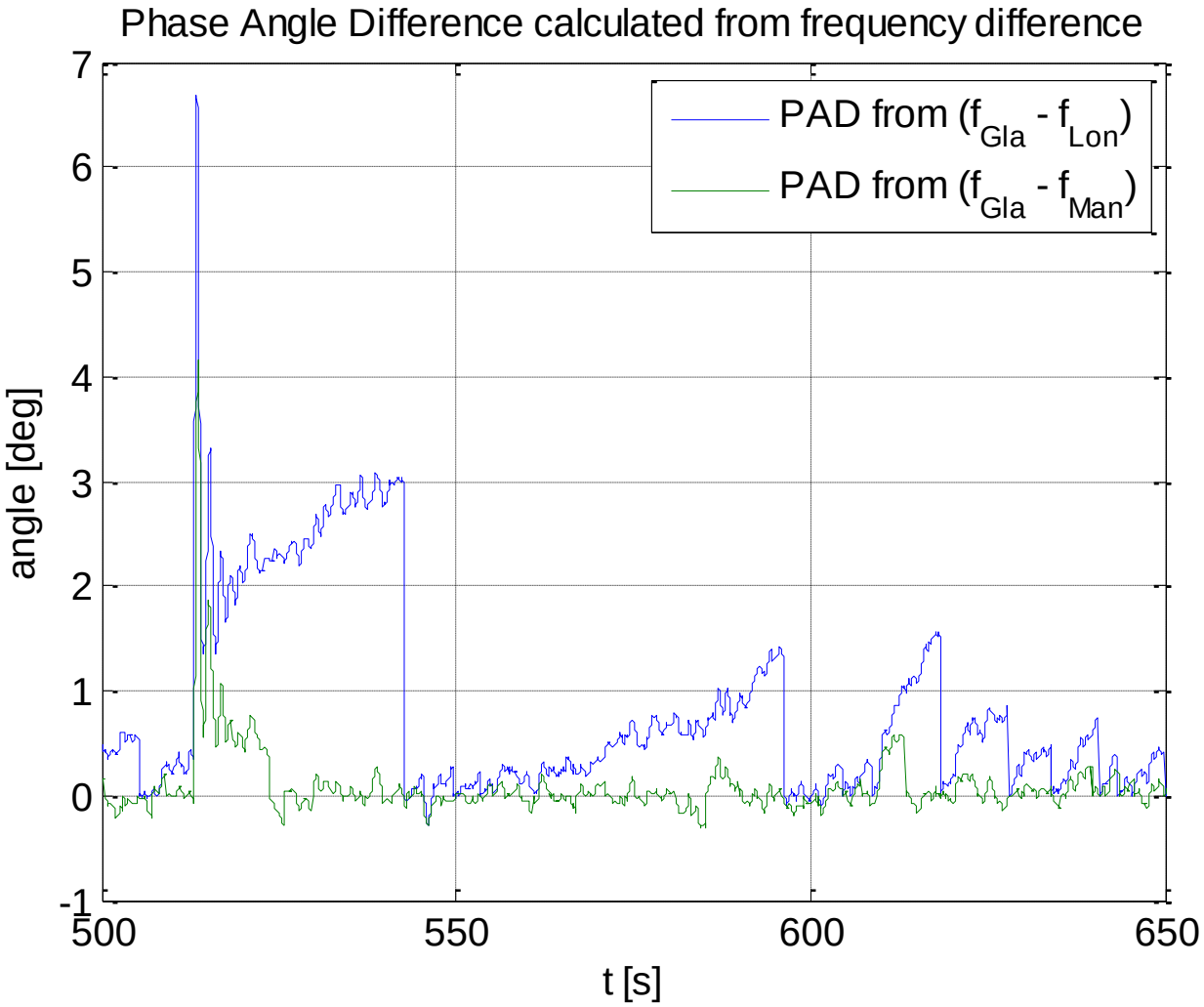
Δt – angle calculation time step

- A tripping signal is sent when α_n exceeds the preset threshold.
- Satellite channel latency can be easily compensated using GPS

A. Dyśko, G.M. Burt, P.J. Moore, I.A. Glover, J.R. McDonald, "Satellite Communication Based Loss-of-Mains Protection", *9th International Conference on Developments in Power System Protection, Glasgow – UK, vol. 1, pp. 687-692, March 2008.*

Satellite based LOM protection

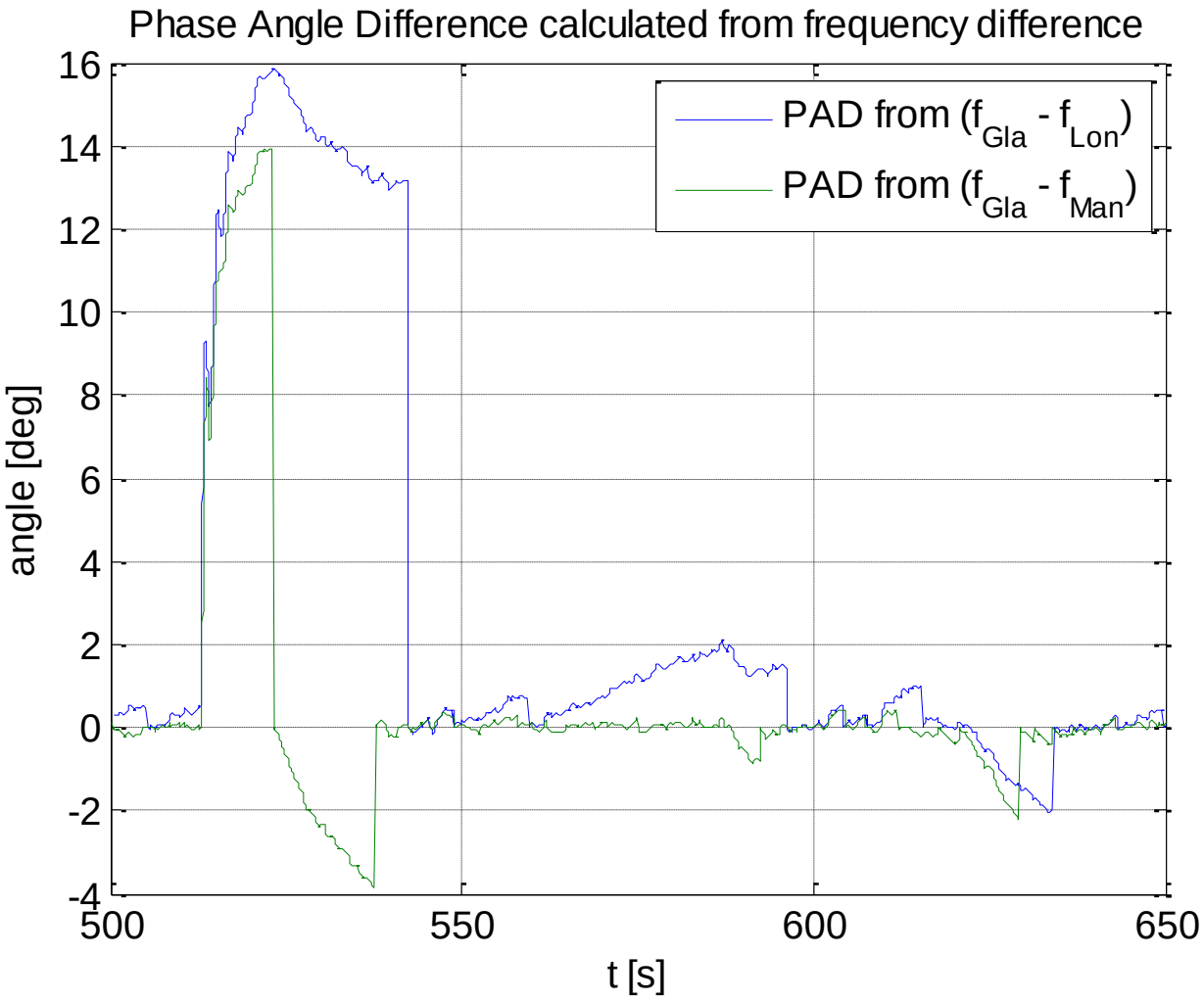
- Relay response to 28 September event



- Manchester and London PMU record as a reference frequency
- Glasgow PMU record as a DG local frequency
- Accumulated phase angle difference contained within 7deg.
- Accumulated angle resets if df<0.002Hz for more than 2s.

Satellite based LOM protection

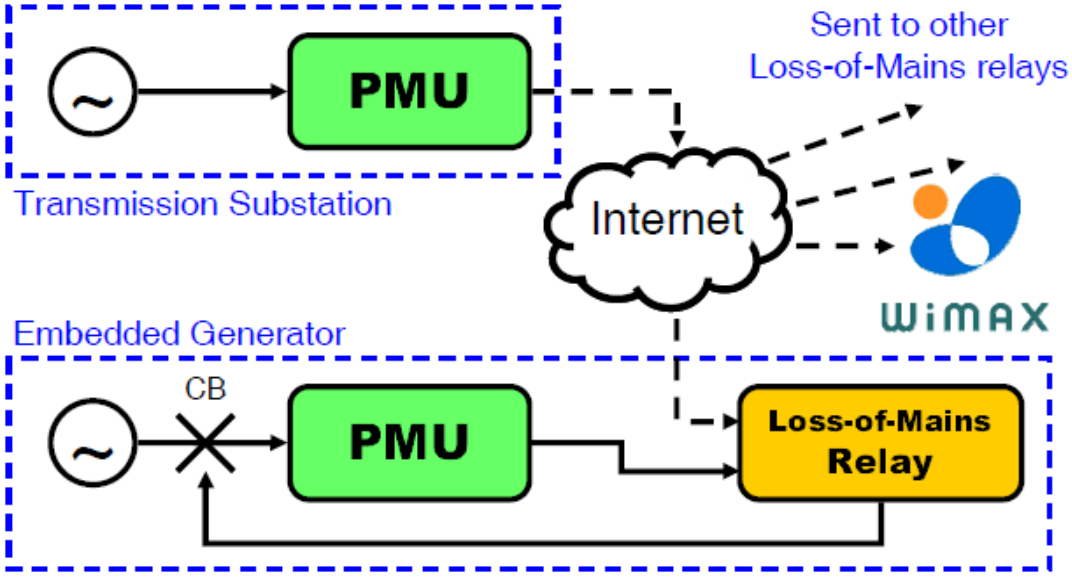
- Relay response to 28 September event



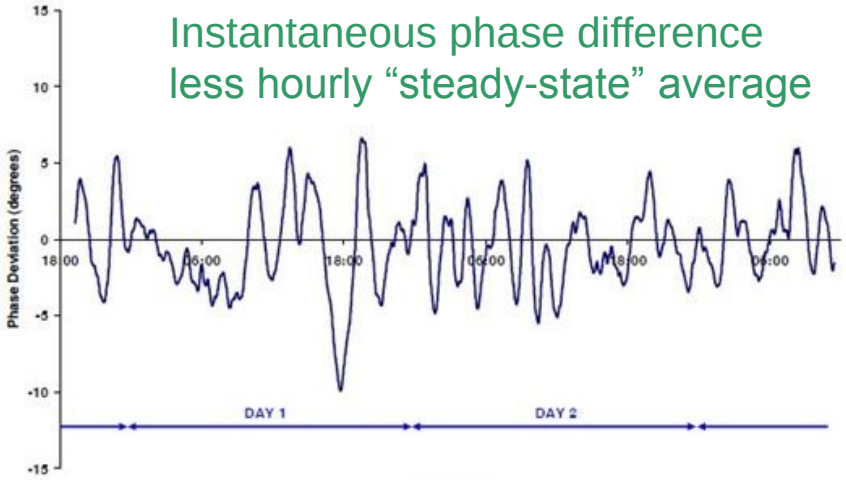
- Artificial time delay of 100ms has been introduced.
- Angle difference still contained within reasonable margin (16deg), i.e. GPS accuracy in time synchronisation is not essential.

Internet based LOM protection

General WAM system for LOM



Instantaneous phase difference
less hourly “steady-state” average



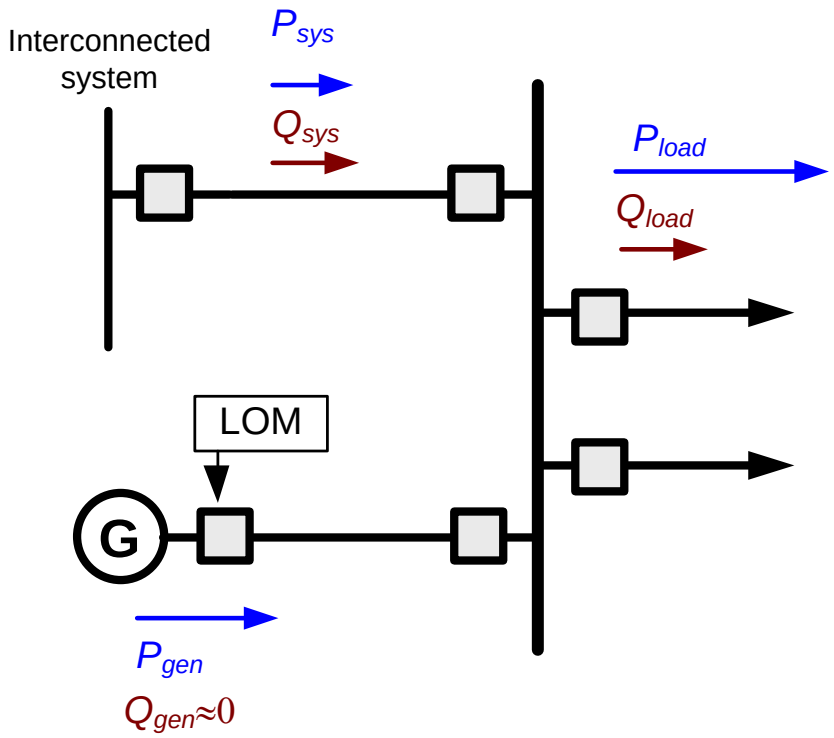
oscillation of phase angle difference rarely exceeded ±5°

Laverty, D.M.; Morrow, D.J.; Best, R.J.; Crossley, P.A.; , "Differential ROCOF relay for Loss-of-Mains protection of Renewable Generation using phasor measurement over Internet Protocol," *Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009*

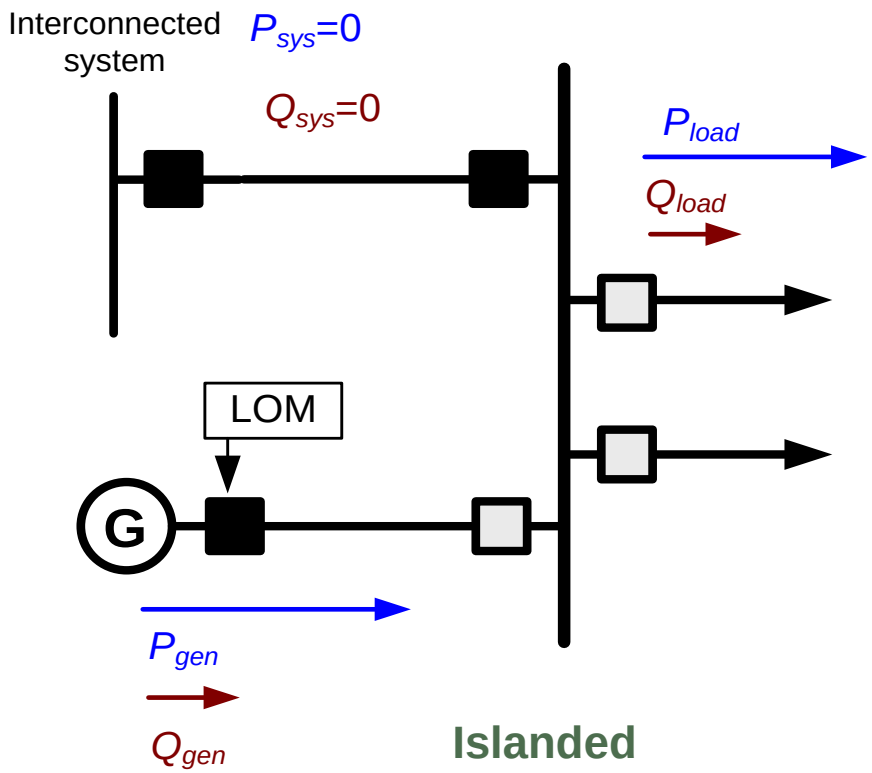
Reverse VAR Method

- Reverse VAR relay measures the generator reactive power flow Q_{gen} and operates when it exceeds a fixed threshold.

Trip if $Q_{gen} > Q_s$



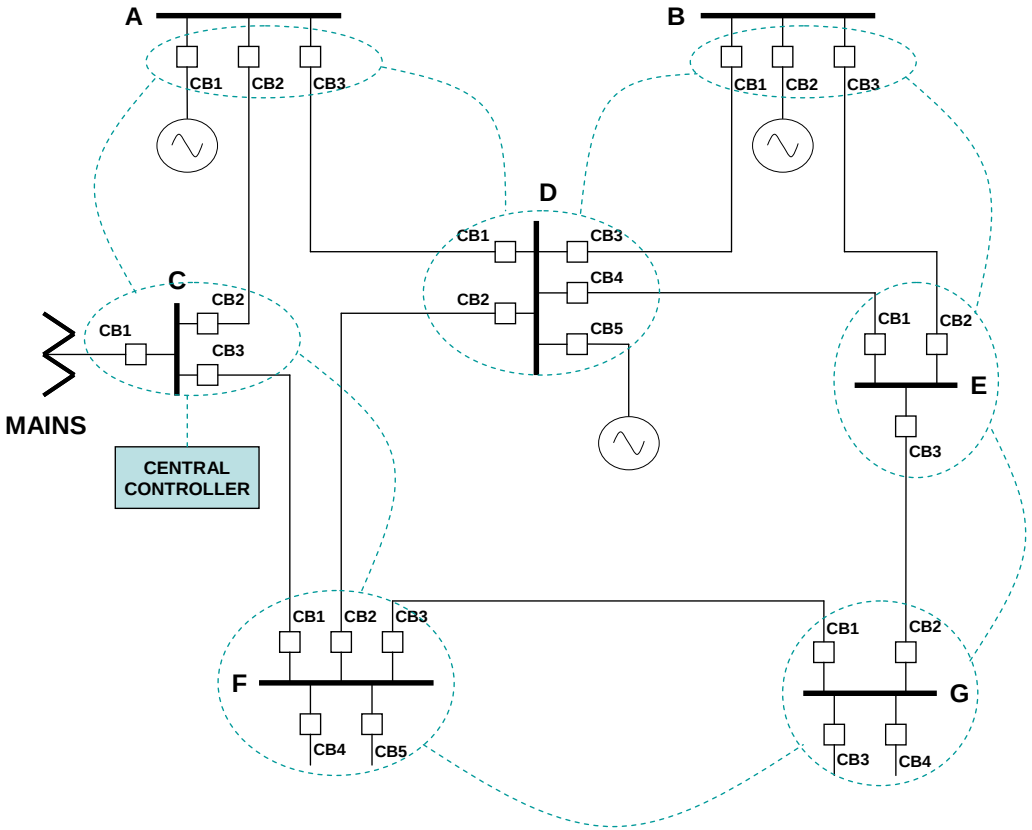
Connected



Islanded

Centralised LOM protection using IEC-61850

- The technique is based on communication of CB status to the central controller.
- Can be combined with conventional passive LOM method with adaptive settings as a backup.

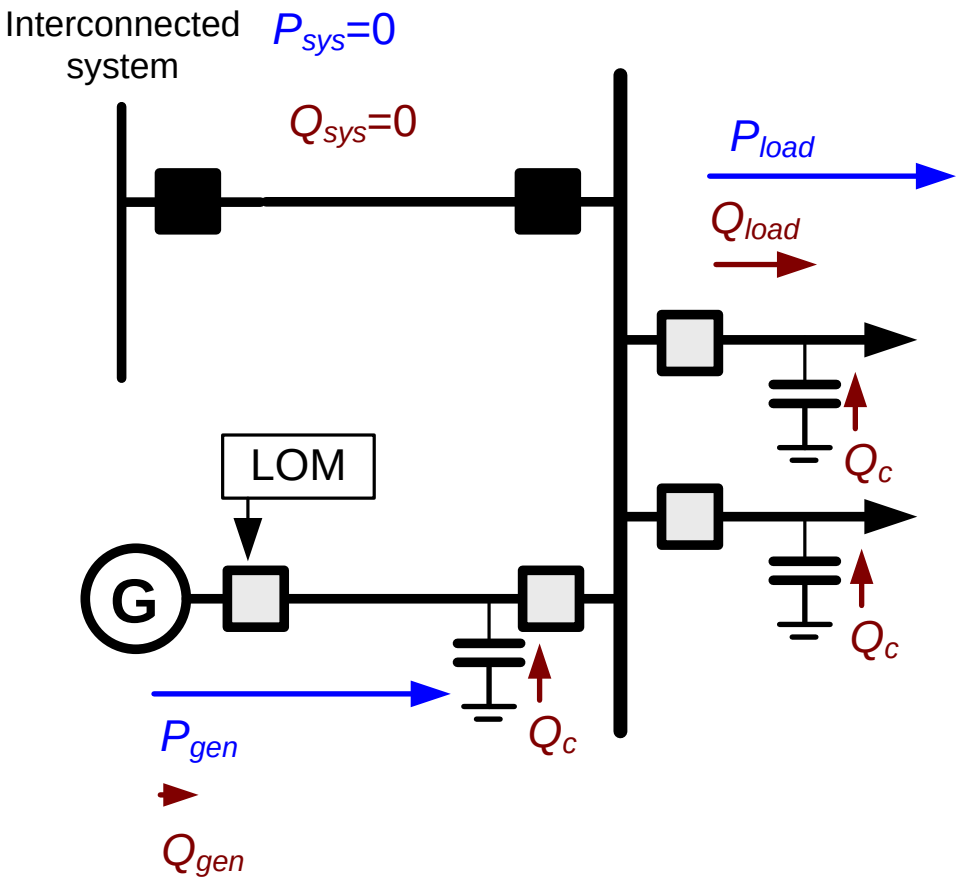


Coffele, F.; Moore, P.; Booth, C.; Dysko, A.; Burt, G.; Spearing, T.; Dolan, P., “Centralised Loss of Mains protection using IEC-61850”, *Developments in Power System Protection (DPSP 2010).*

Reverse VAR Method

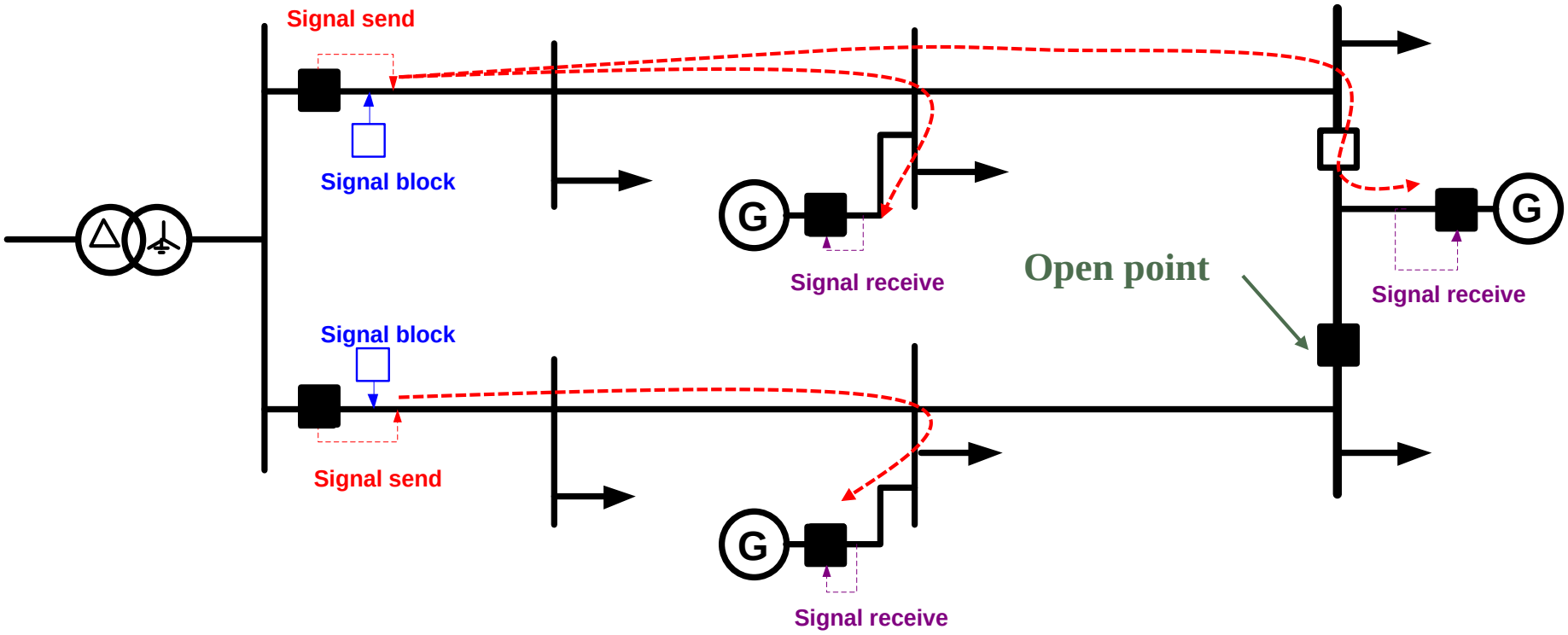
- The amount of reactive power from the generator Q_{gen} may become insufficient to activate the relay if the total capacitance of the connecting cables is high delivering reactive power to the loads.

Islanded



Intertripping of Open Ring Feeders

- Intertripping for open ring feeders can be facilitated using Power Line Carrier (PLC) technique.
- Intertripping signal is always delivered to the correct generators regardless of the position of the open point.



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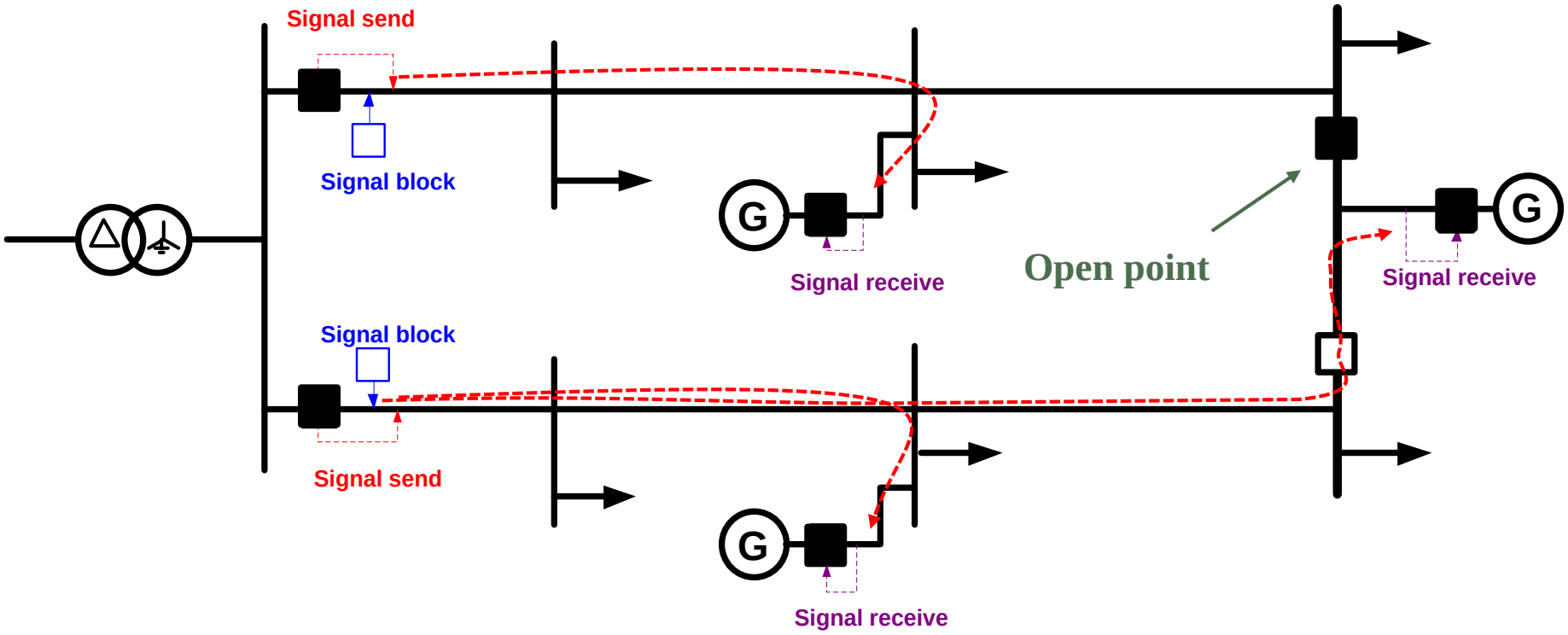

Active methods

- Active methods are more reliable but may be slower and loose performance in larger groups of generators
- The use of active frequency shift method was suggested such as Sandia Frequency Shift.
- This could also be combined with ROCOF to achieve the best performance (combined use of active and passive methods).
- The Grid Connection Code in Japan mandates the combined use of the passive and the active methods.

Future research

- One Year Satellite Applications Catapult funded LOM demonstrator project has been awarded and will commence in March 2013.
- A research team has been set up at Strathclyde to look into equivalent modelling of the UK transmission system.
- Hardware LOM relay testing under recorded and simulated system wide disturbances (?).
- Risk assessment of the LOM protection under new proposed setting guidelines (?).