Date:- 8 – 10 March 2011
Venue: University of Manchester

EES-UETP Course title

Advanced Protection of Distribution Networks with Distributed Generators

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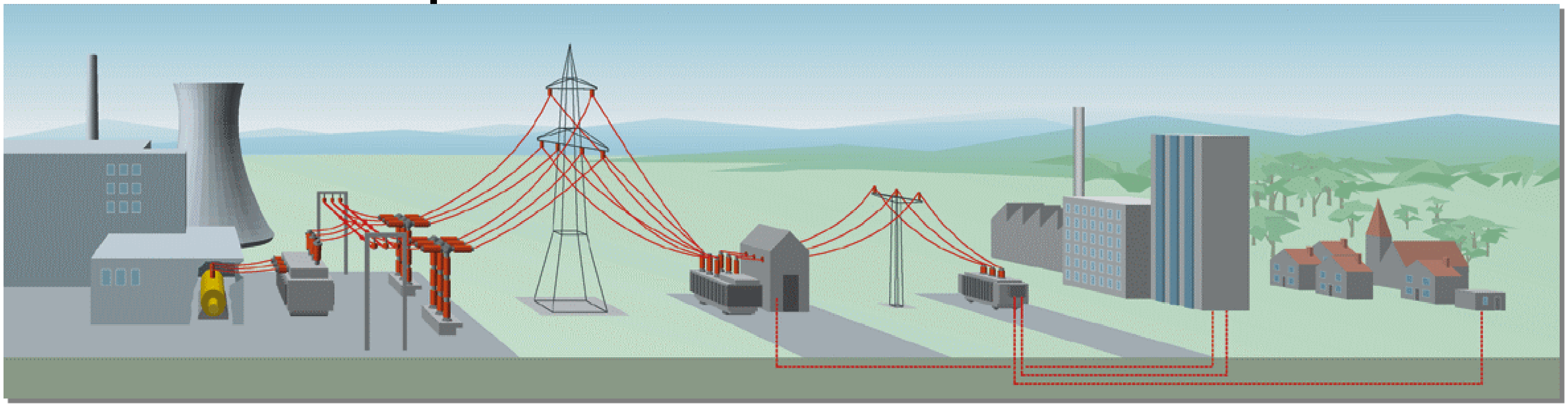
Can we prevent Distributed Generation ?



Options:

- large numbers of bulk generators (coal, gas, nuclear, hydro)
- DC and UHV AC transmission links between regions
- limited role for renewables (mainly wind)
- conventional distributed generation & combined heat and power

Is this option politically/socially/economically viable?

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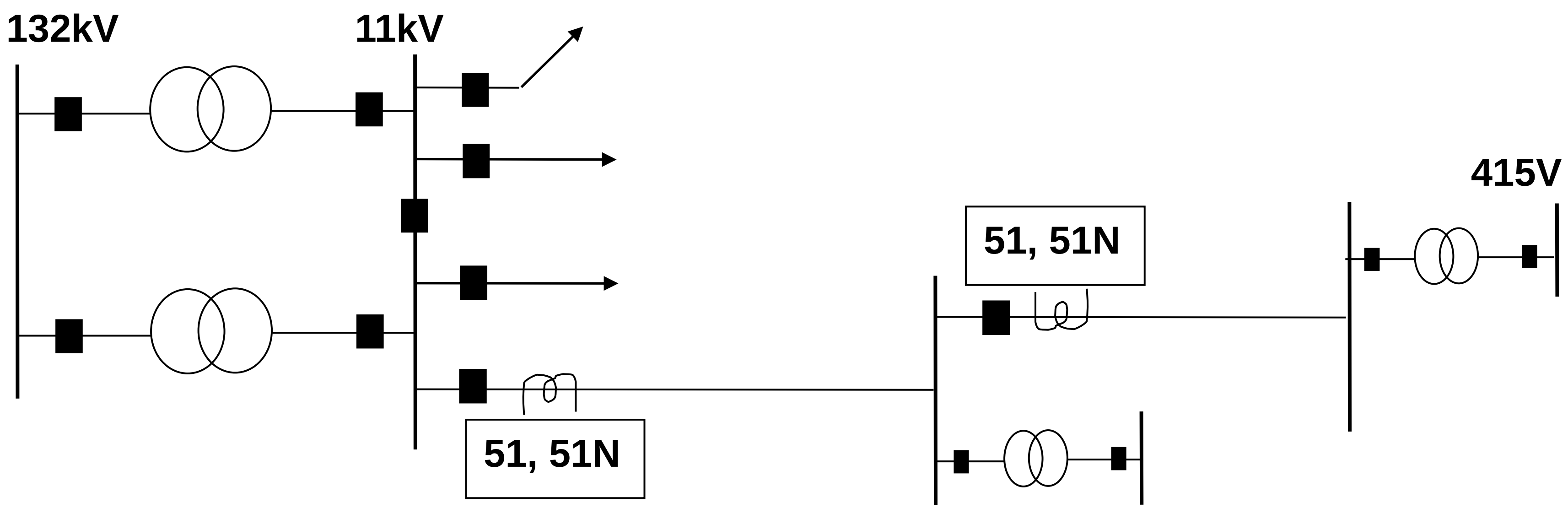
Existing distribution networks

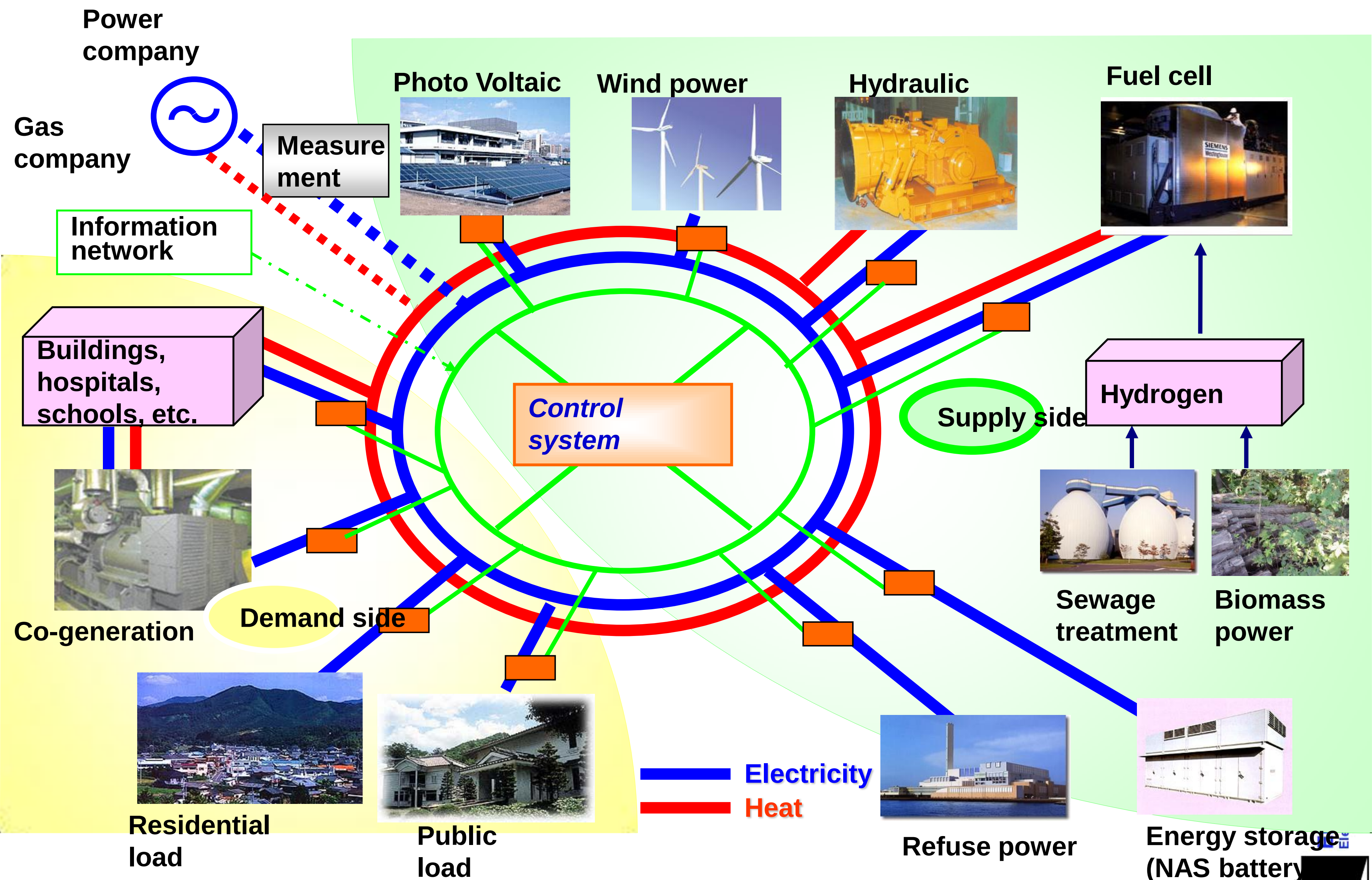


- power flows from grid supply to LV network
- protection based on phase & earth inverse overcurrent relays

Effect of distributed generation on existing overcurrent protection

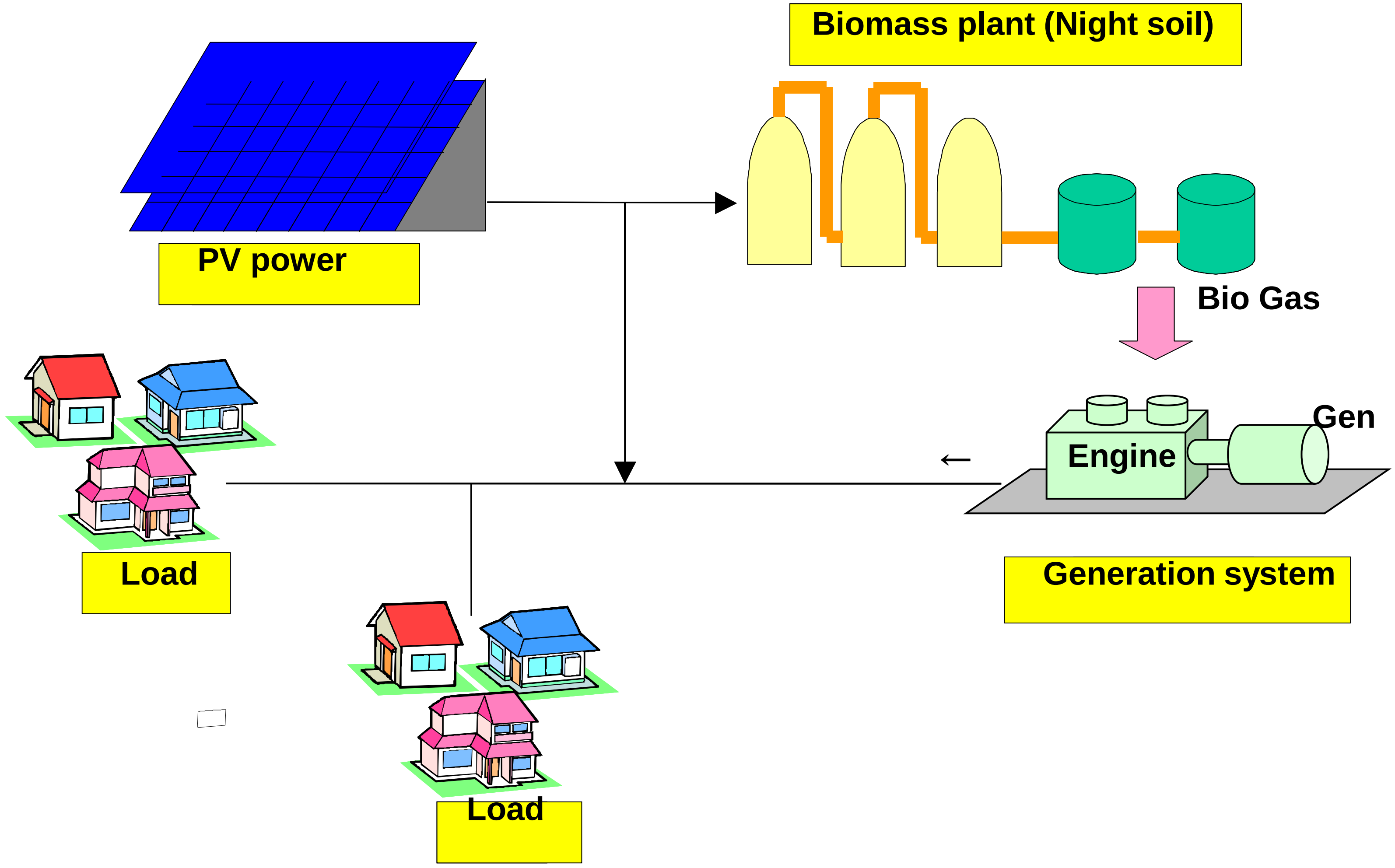
- Fault current seen by relay may increase or decrease:
  - depends on relay and fault location, network fault levels, strength and location of distributed generators
- Grading studies must consider:
  - max & min infeed from all possible distributed generators
  - problems:- intermittent nature of distributed generators
- Main problem:
  - how to protect intertie between generator and utility network
  - must correctly co-ordinate with network protection for all operating conditions

Is this the future of our urban distribution networks?

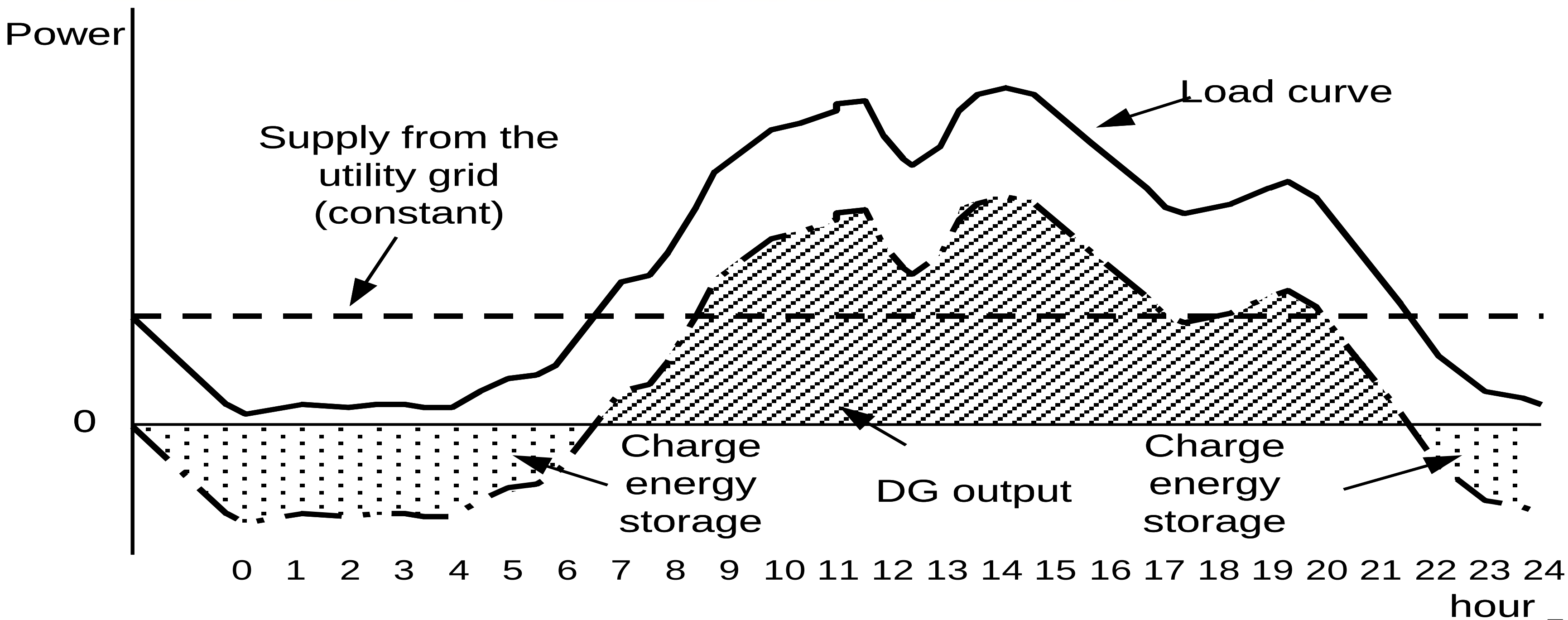


what about our rural communities?

Are small self-sufficient rural islands viable?



new-build estates with micro-generators, PV & storage:



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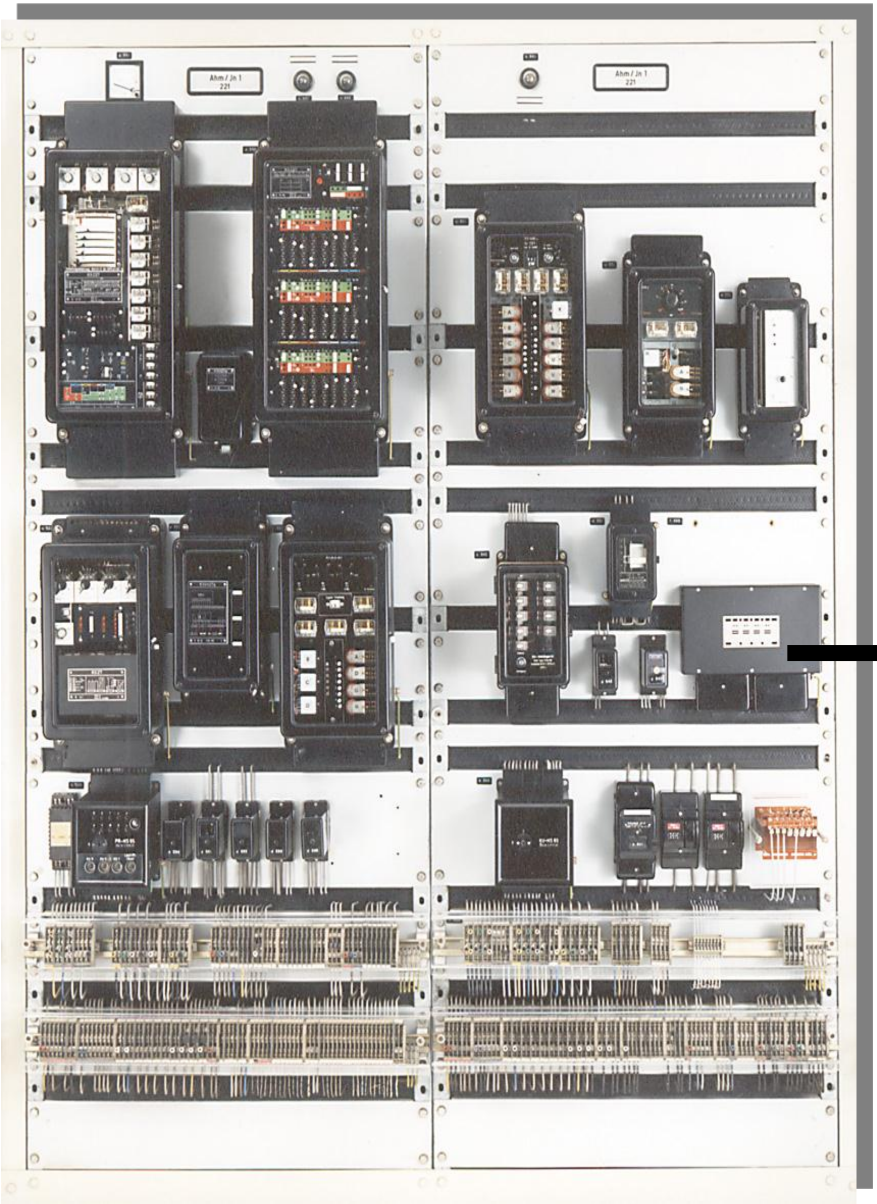
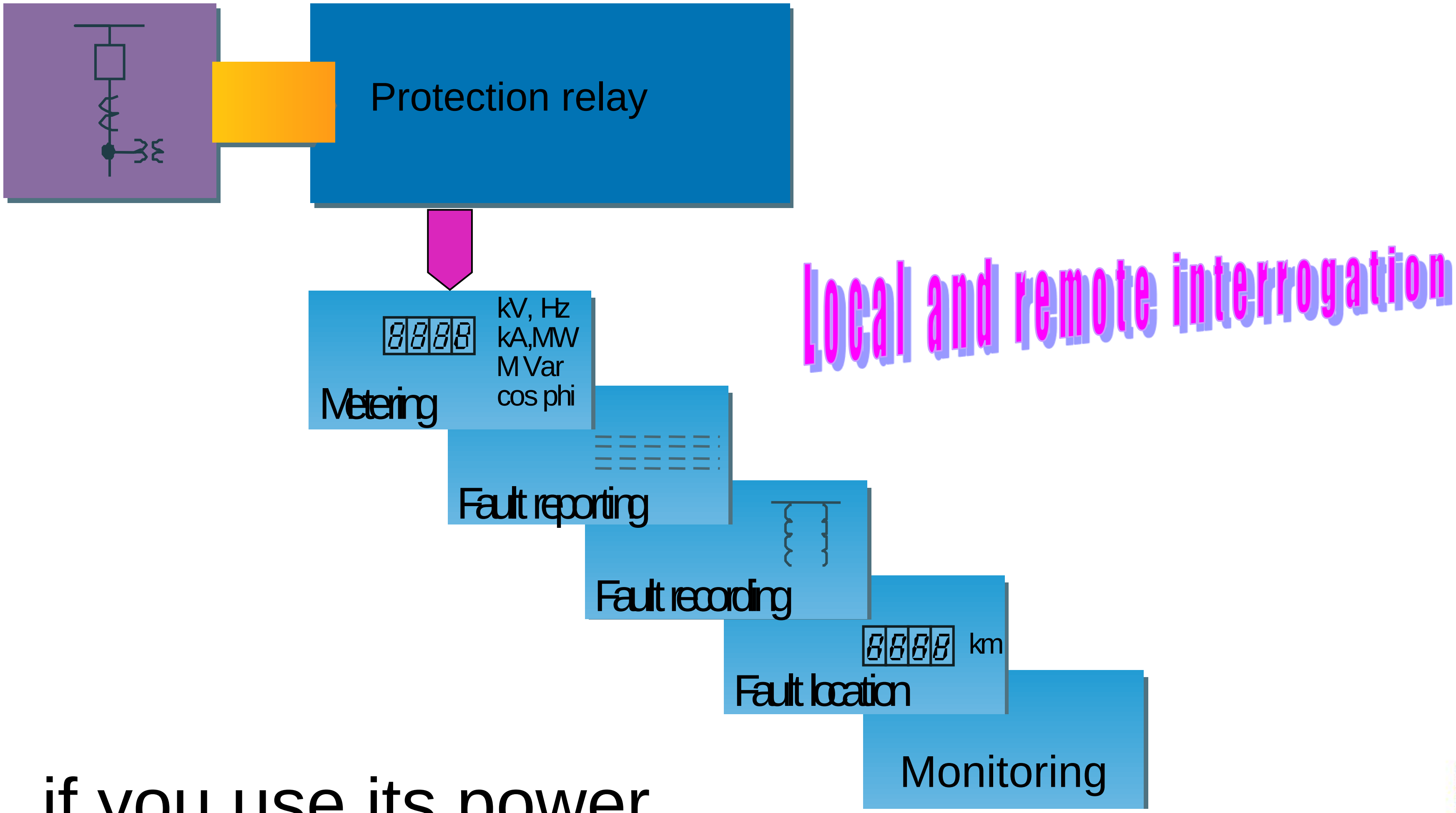
Does numerical protection & control relays (IEDs) solve your DG problems?



Or just give you more panel space!

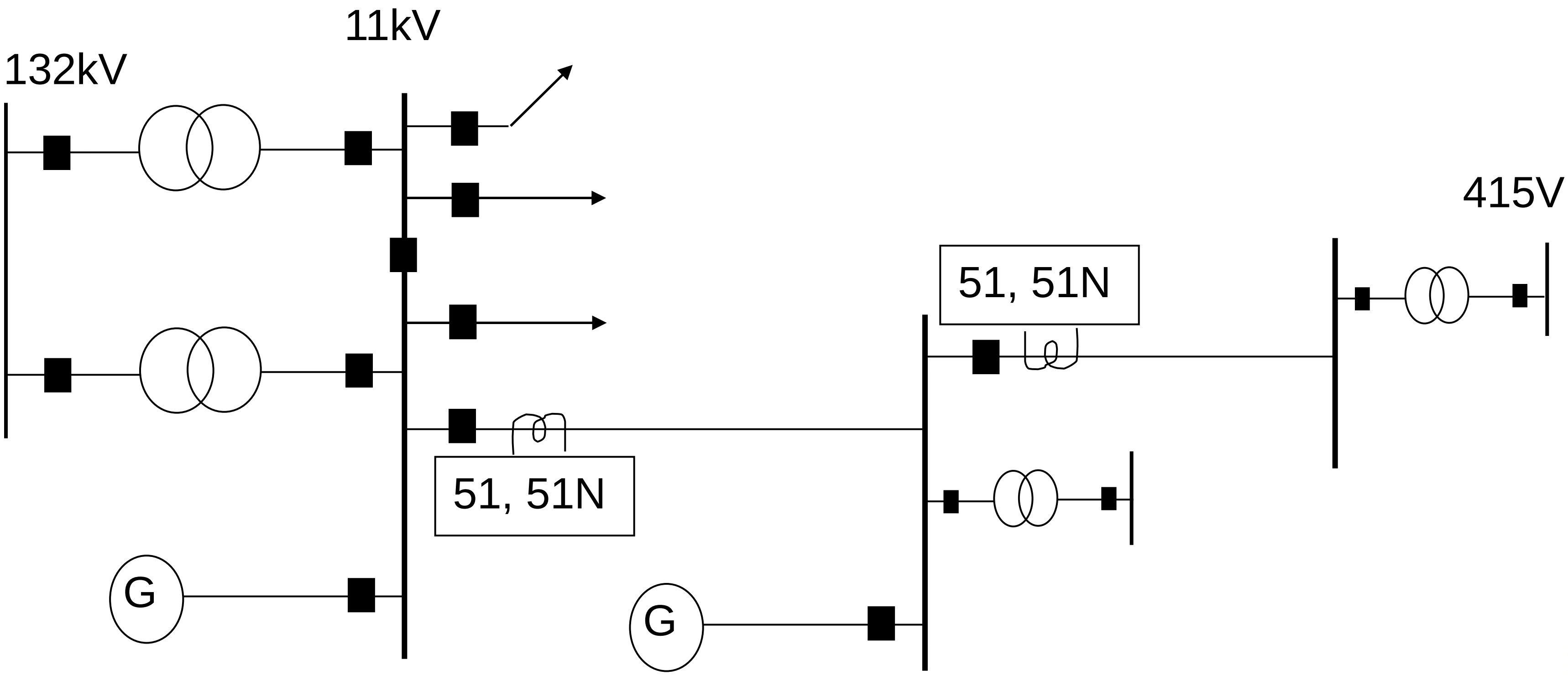
You have a lot of options, but can they deliver the solution?

An IED is much more than a relay !



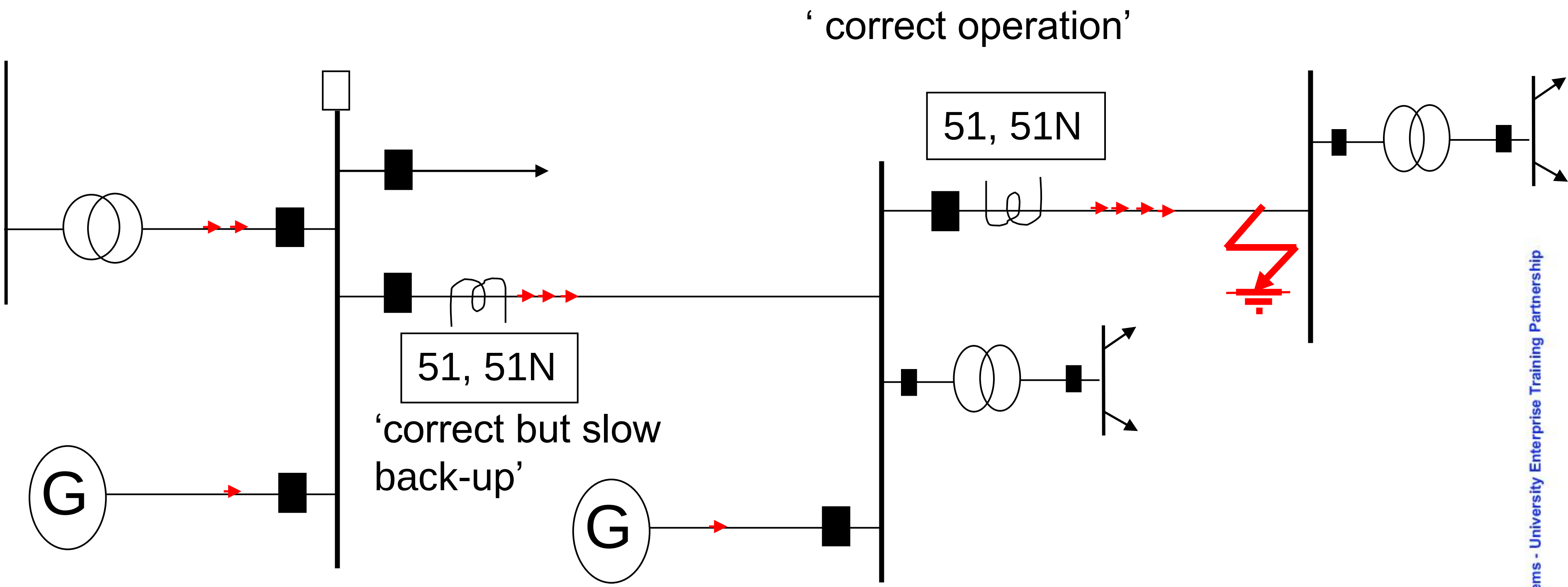
if you use its power

Overcurrent protection of radial network with distributed generators



Overcurrent protection:

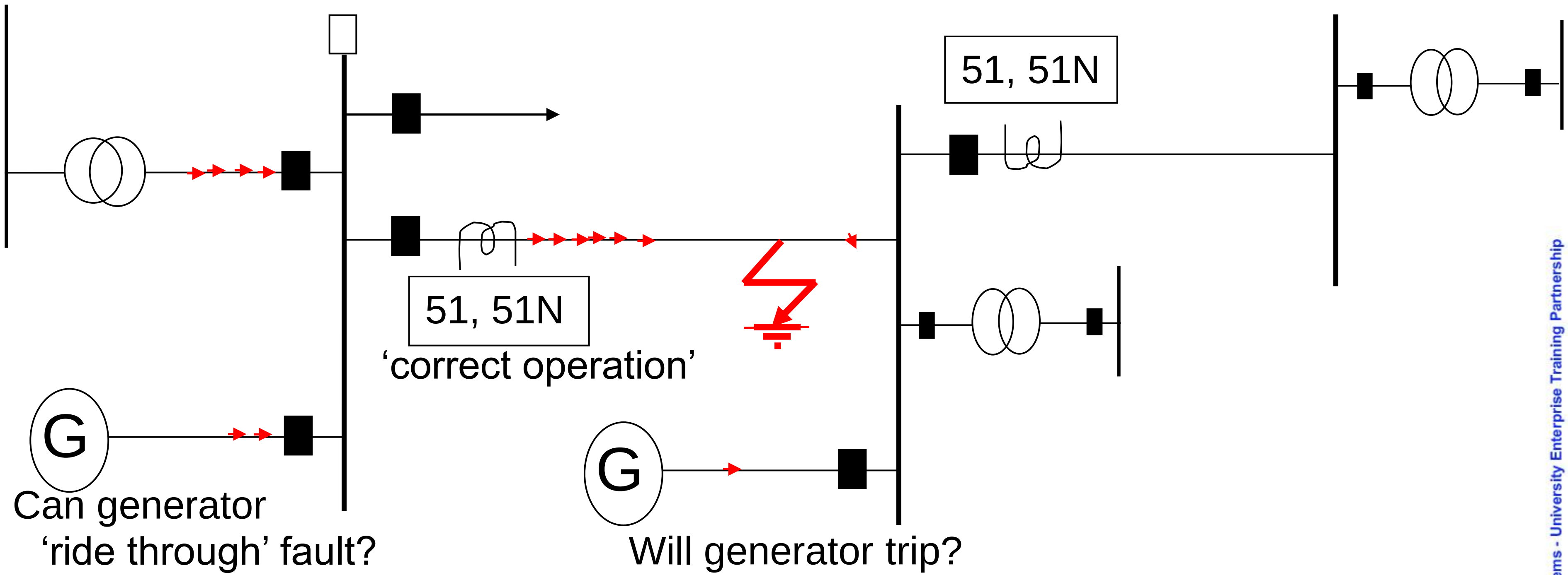
- radial network with distributed generators



Can generator “ride through” fault ?

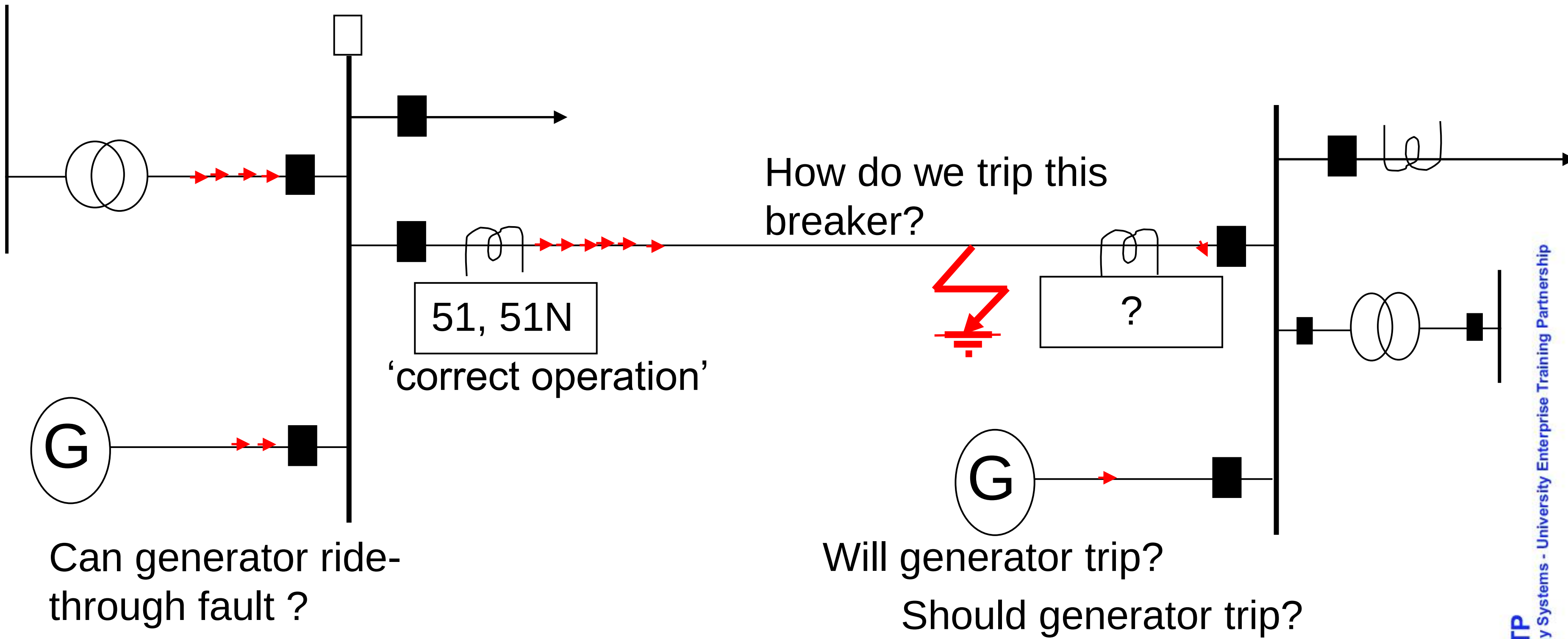
Overcurrent protection:

- radial network with distributed generators

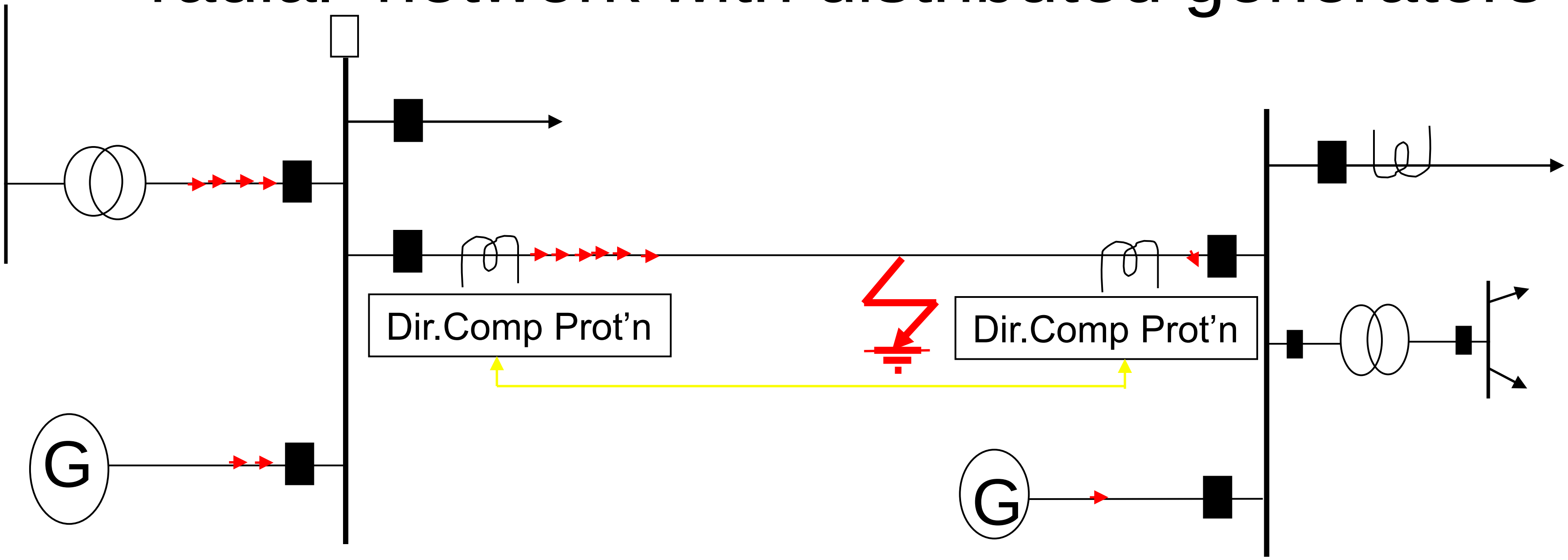


Overcurrent protection:

- radial network with distributed generators



Directional Comparison Protection:
- radial network with distributed generators



Can generator supply local utility load?

If yes; should it?

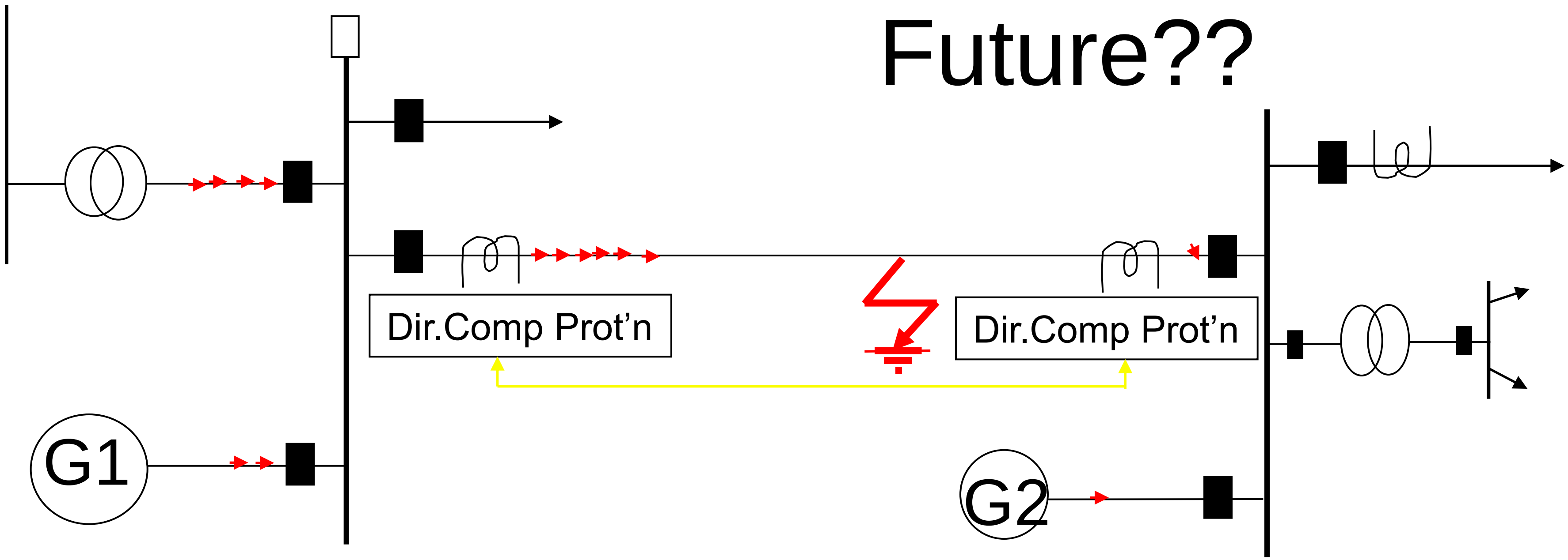
If no; can we shed load ?

What about protection of island?

Is fault current sufficient to operate protection?

How do we reconnect island?

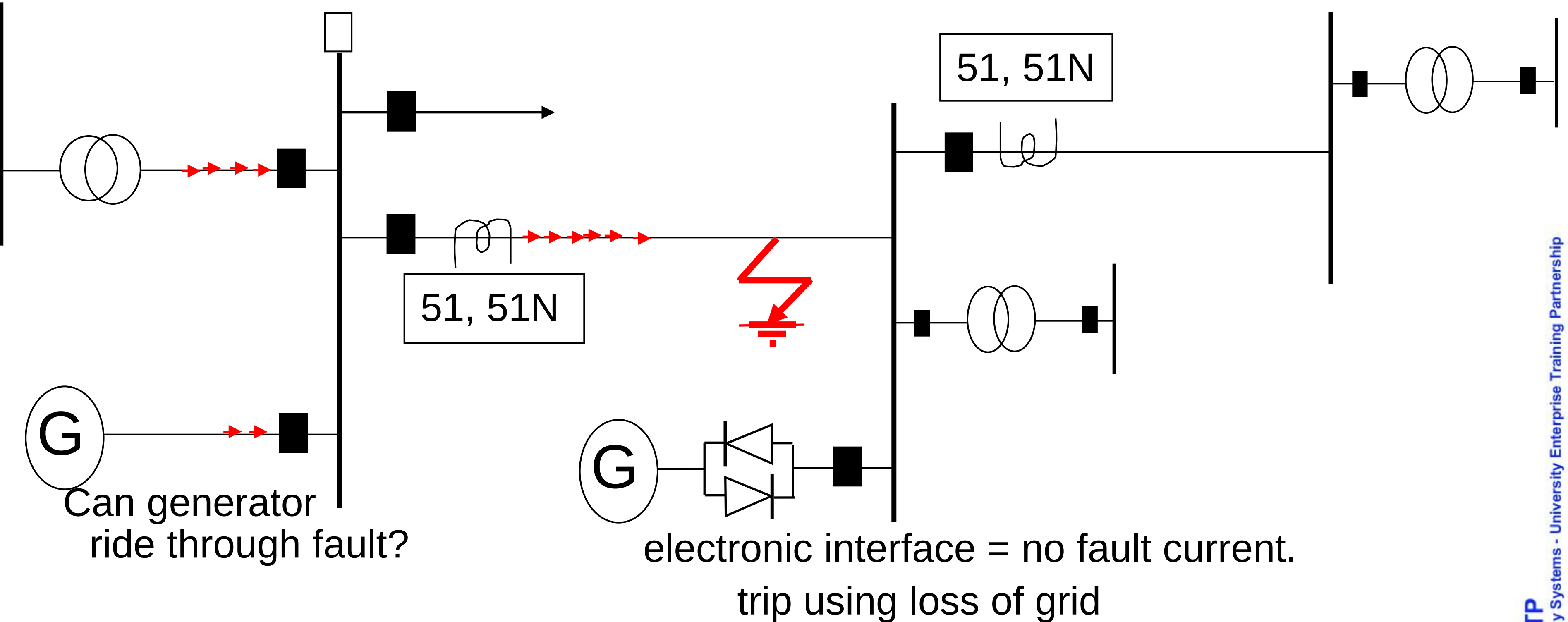
Future??



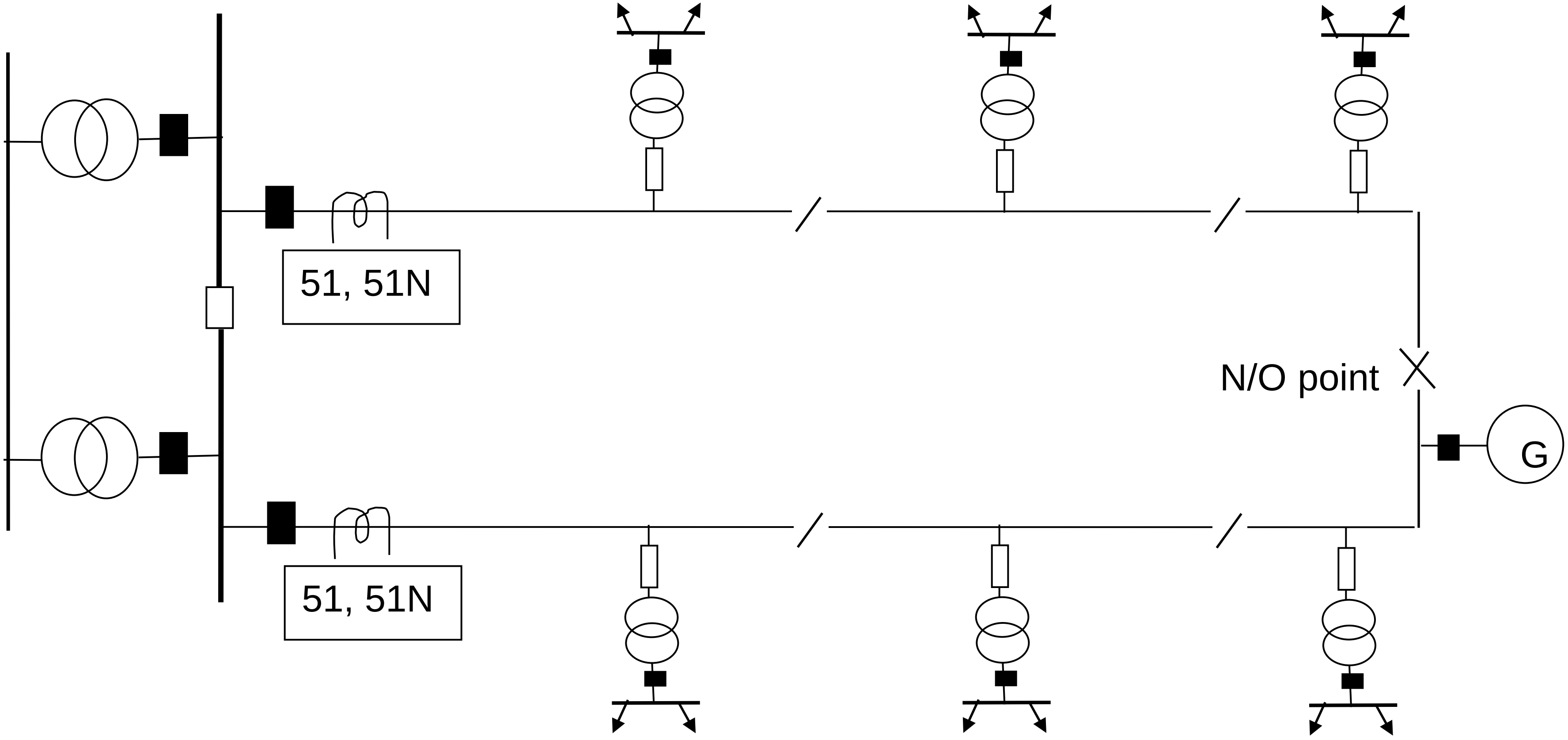
- Dir. Comp Prot'n = high speed fault clearance
- Sync. generator G1 remains in sync & connected
- After fault clearance:- sync. gen. G2 governor picks up load (and if necessary sheds load) . G2 then supplies local 'island' at statutory volts & freq.
- Faulted line restored; requires sync check on breakers

Overcurrent protection:

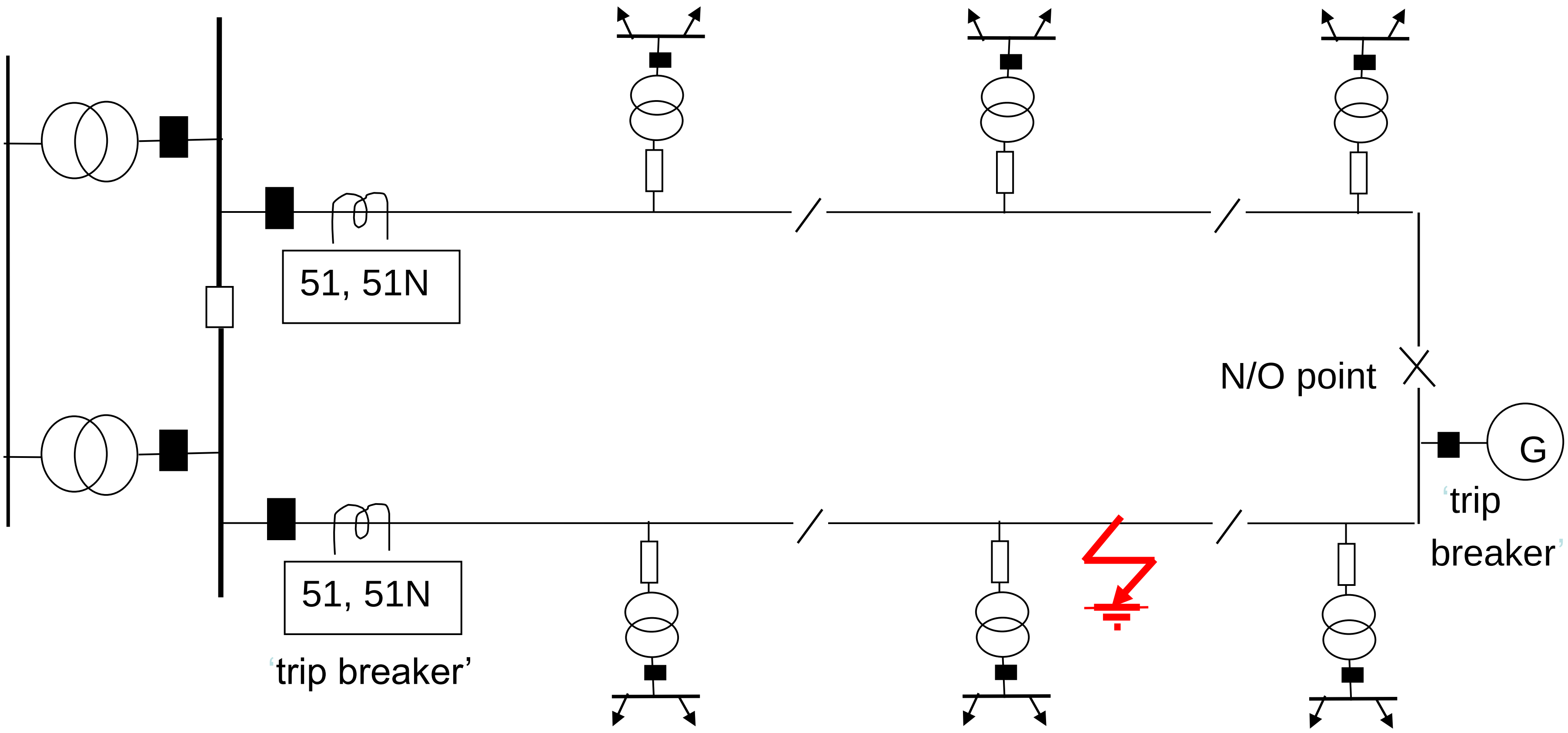
- radial network with distributed generators



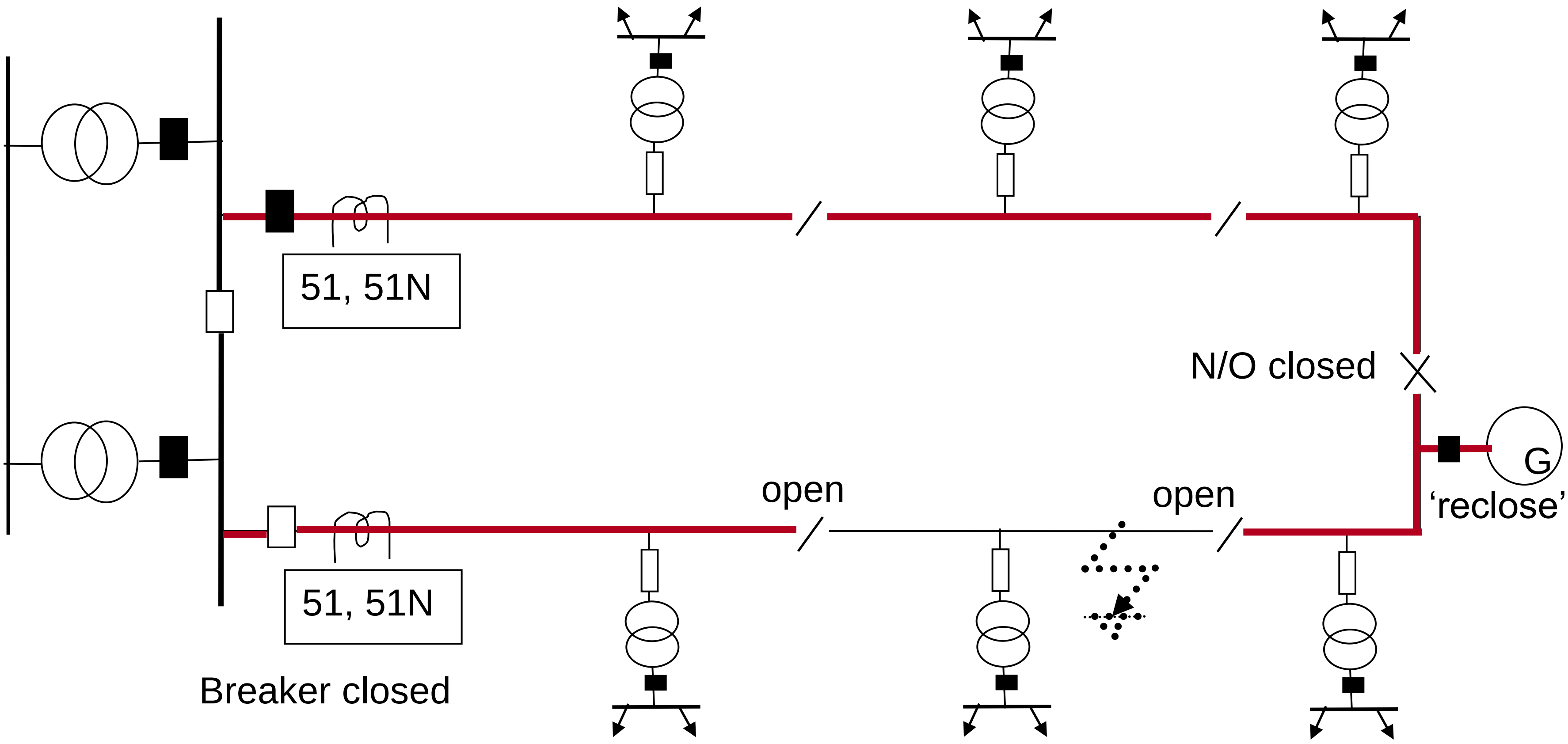
Protection & restoration of rural active radial network



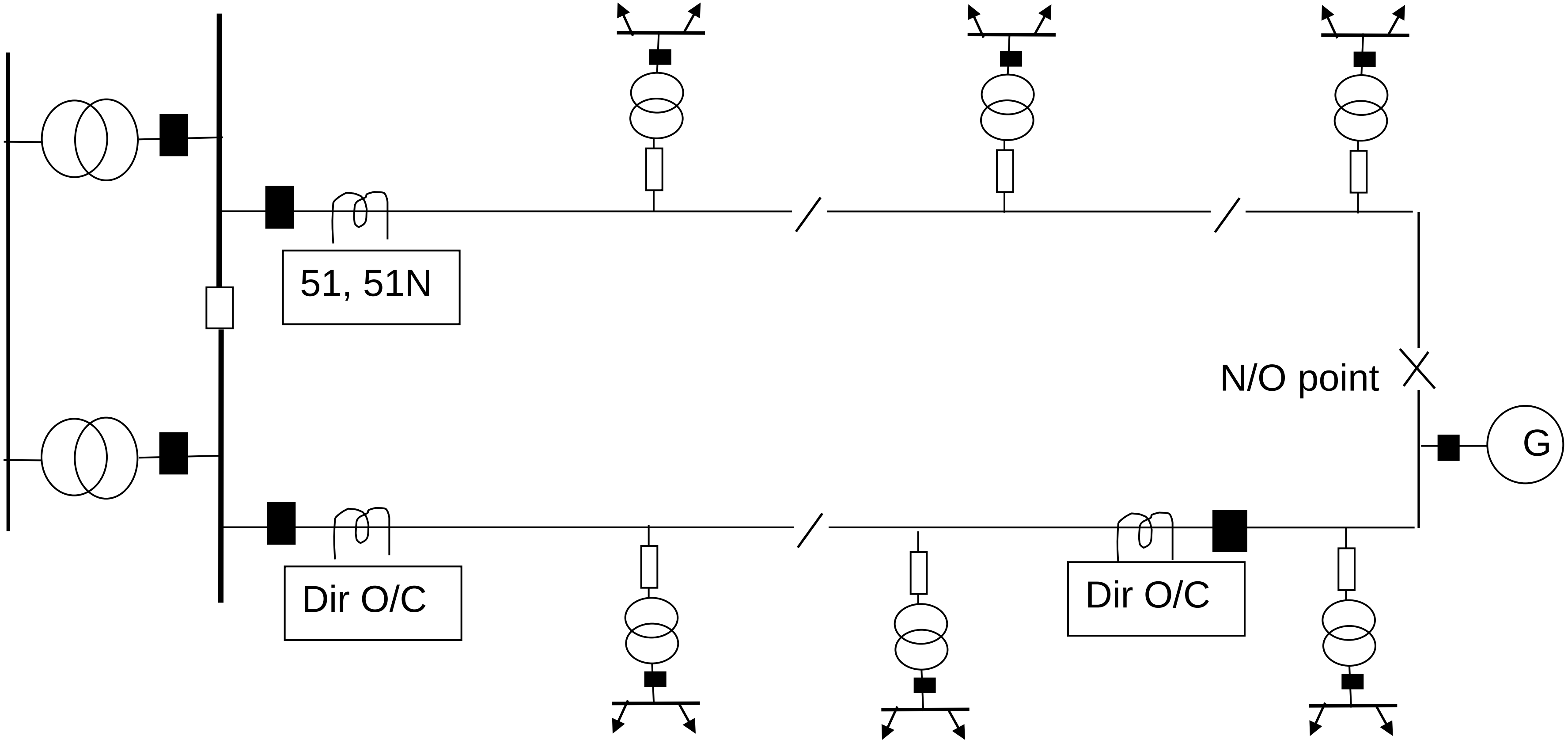
Protection of rural active radial network:- assumes G59



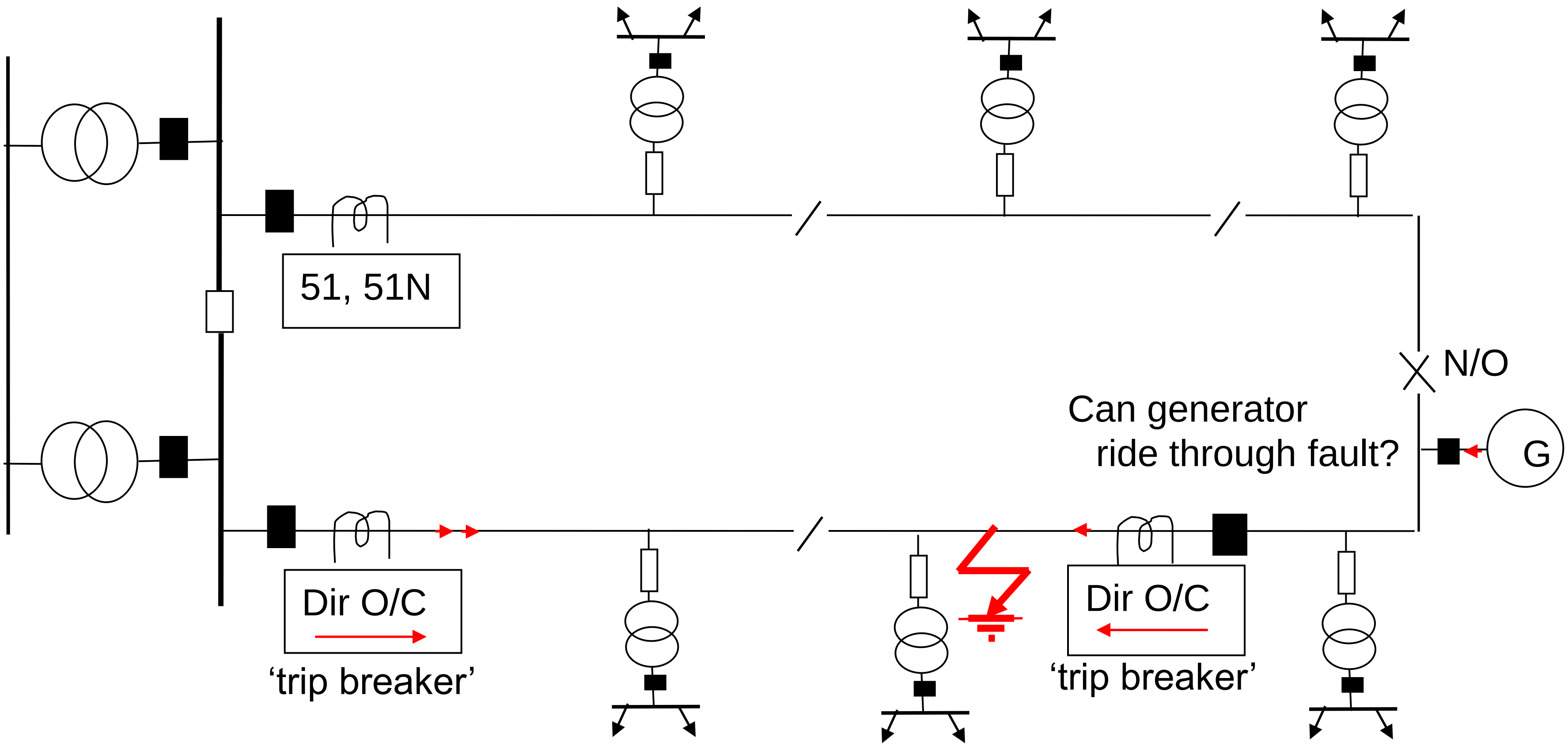
Active radial network:- restoration:



Protection & restoration of rural active radial network

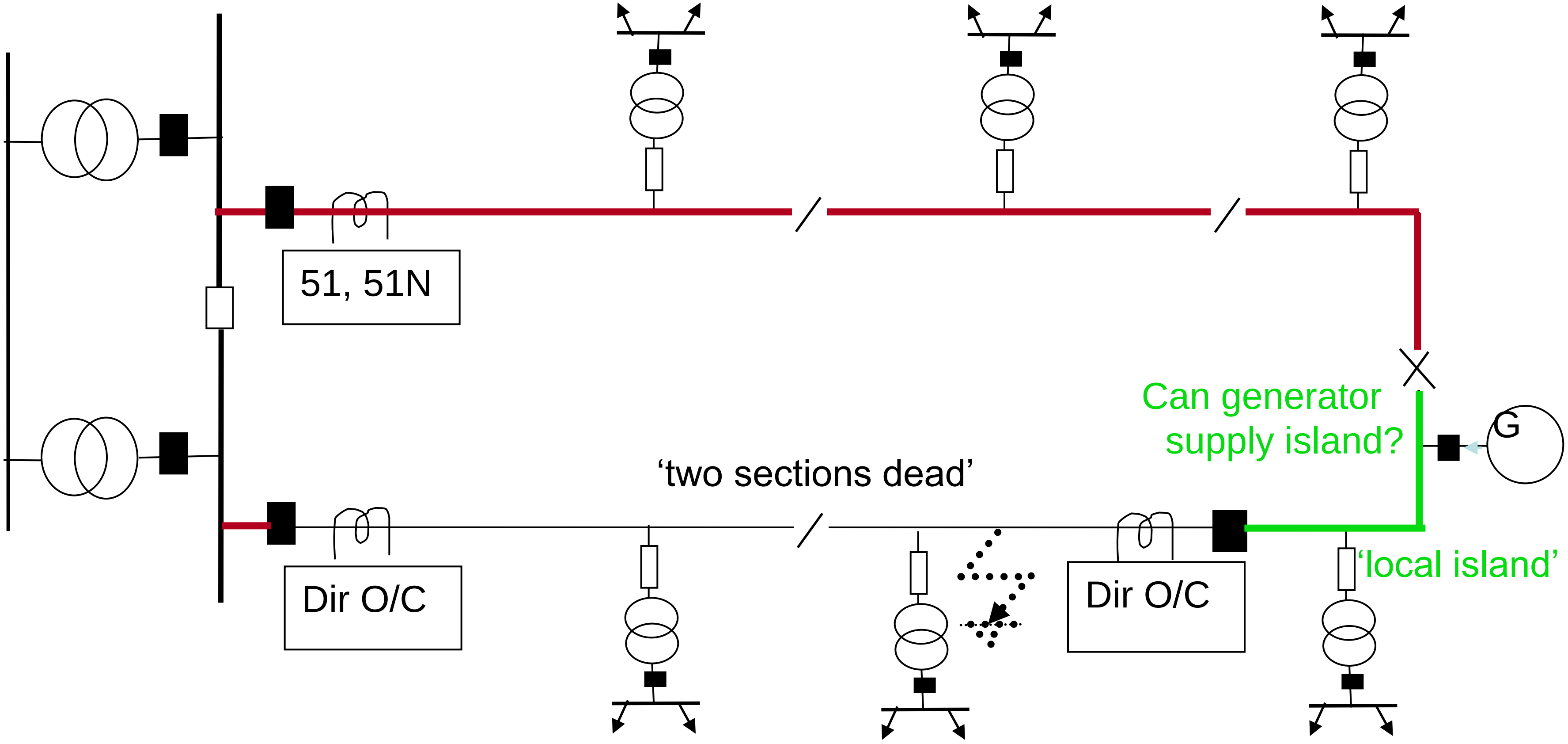


Protection of active radial network:- permanent fault

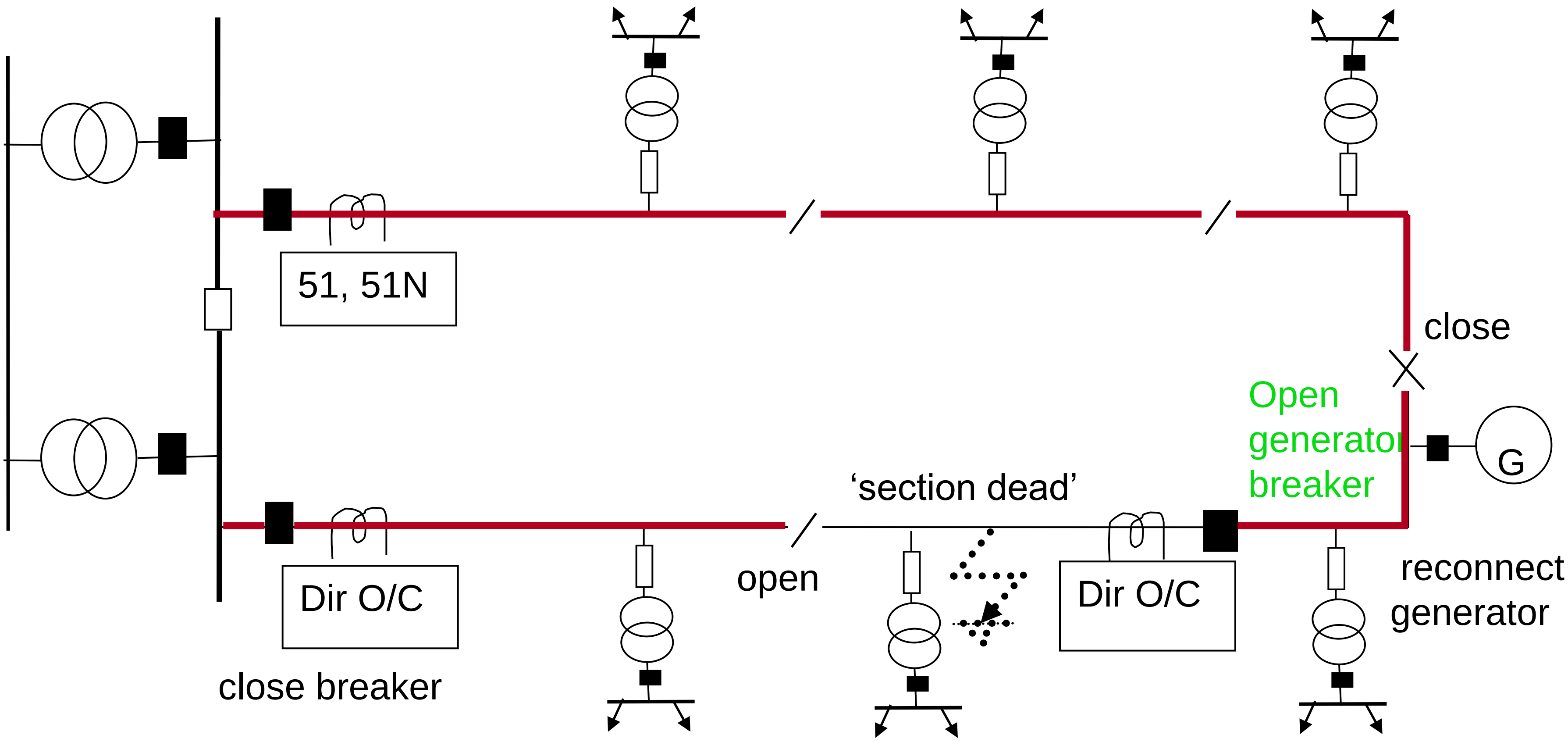


Problem:- is I_{fault} sufficient?

Restoration of rural active radial network:



Restoration of rural active radial network:

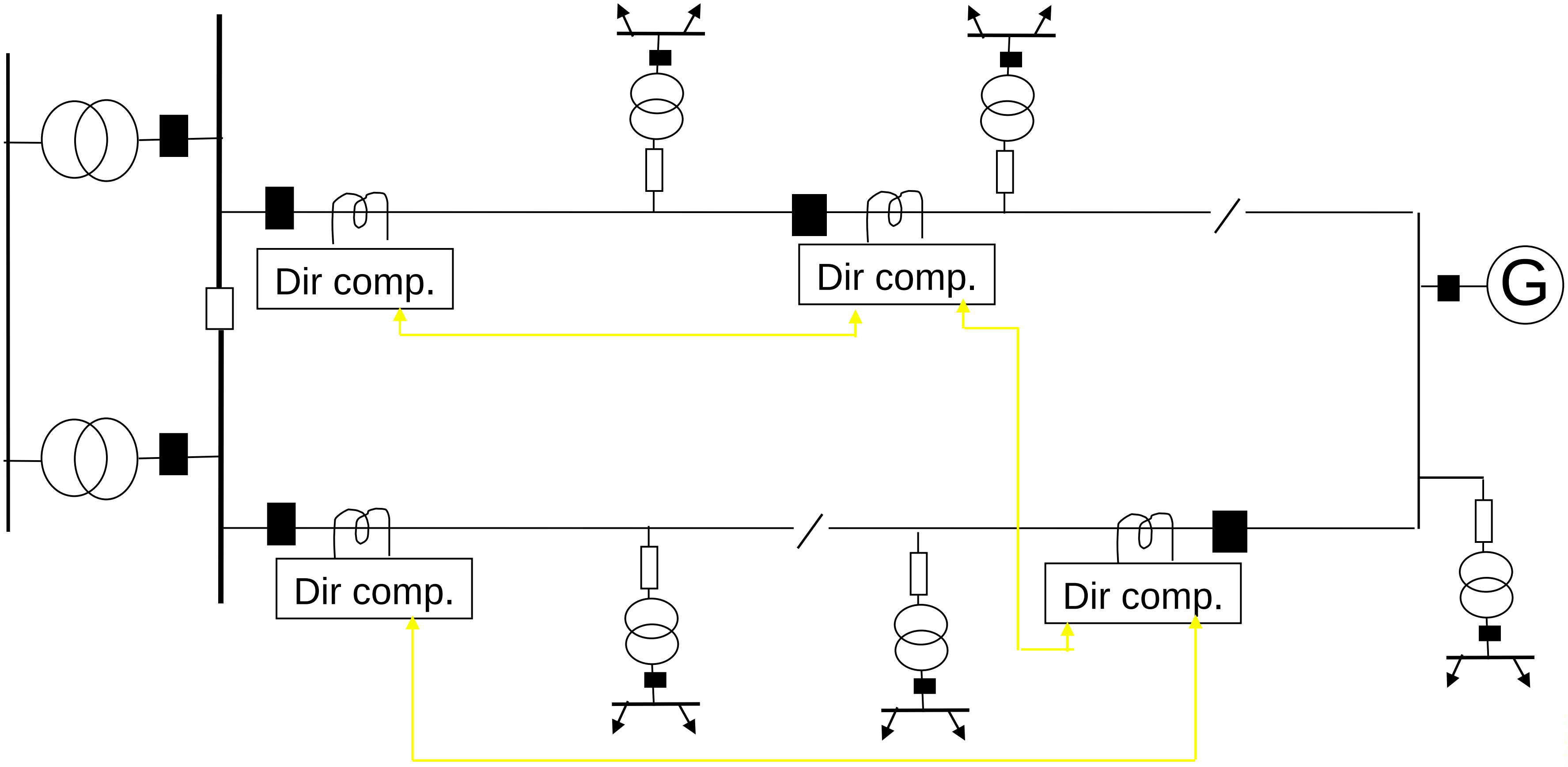


Dir.comp protection of rural active radial network

advantages:- high speed fault clearance (100ms)

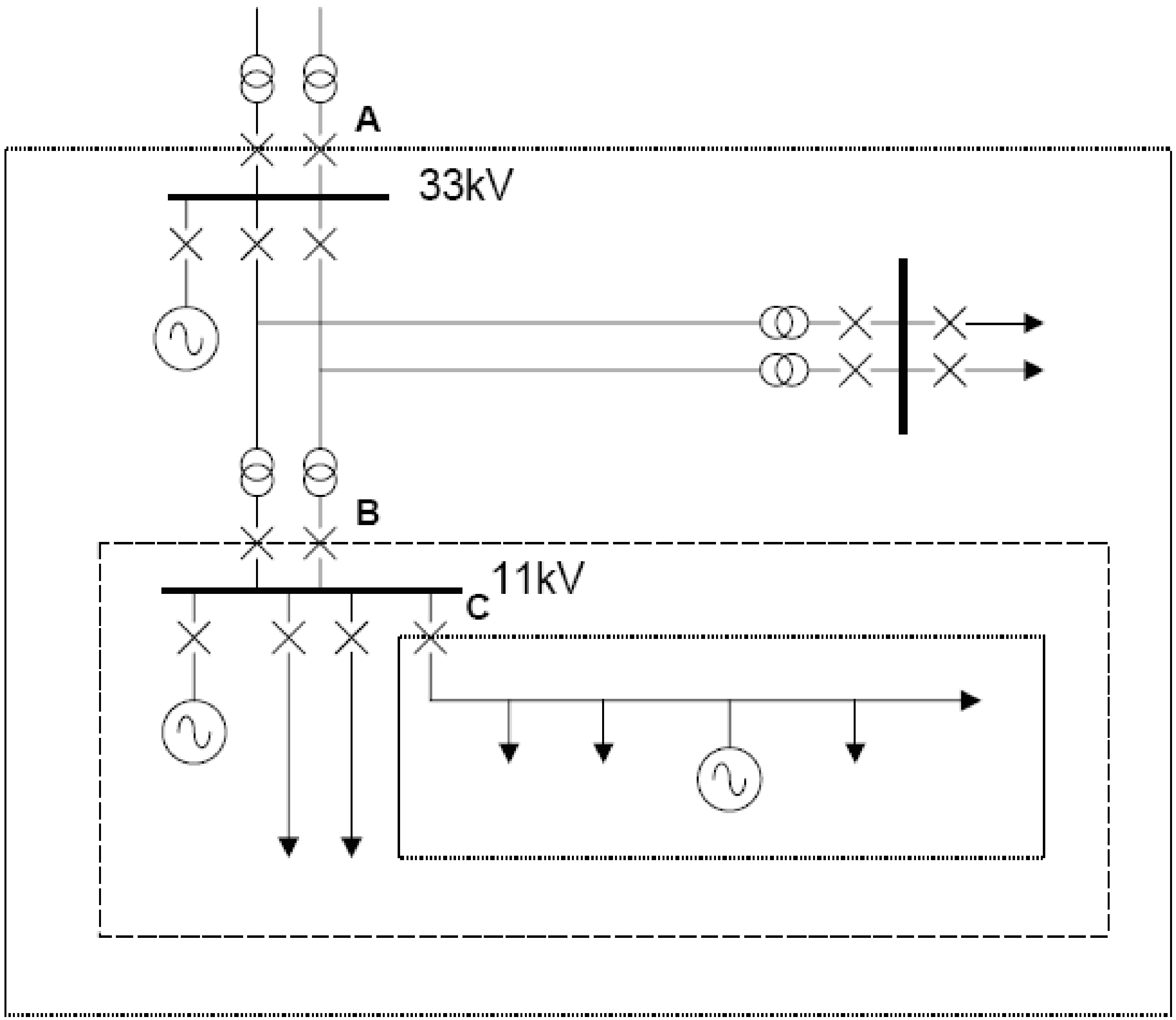
limited impact of ext. faults on generator stability

disadvantages:- needs circuit breakers and communications

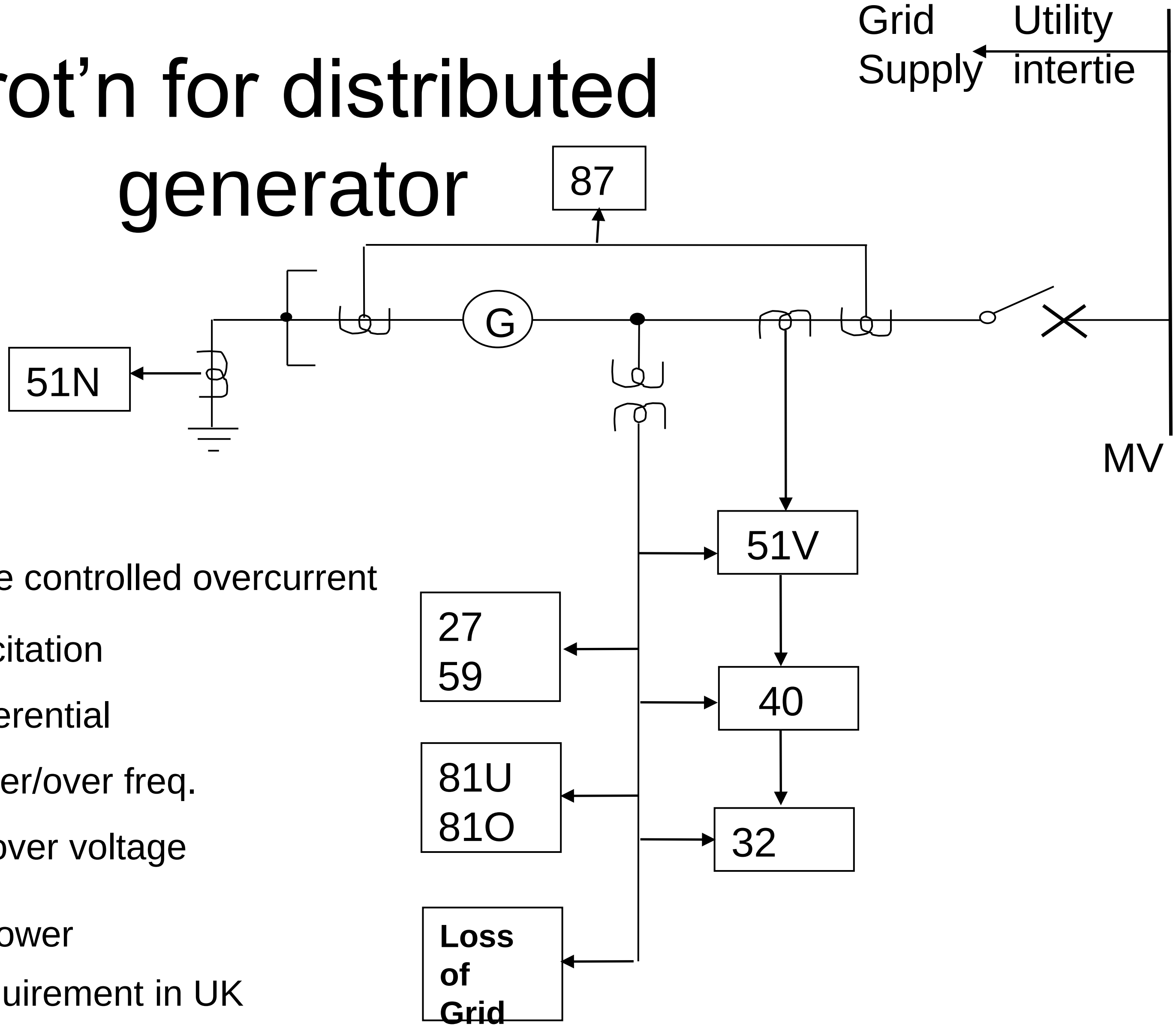


Formation of an Island

Cause:- opening of a circuit breaker in response to a downstream fault
Ideally:- DG protection should detect the fault and trip DG before island formed
If protection fails to detect the fault, or breaker is manually tripped, islanding can occur.



Prot'n for distributed generator



51V = voltage controlled overcurrent

40 = loss of excitation

87 = phase differential

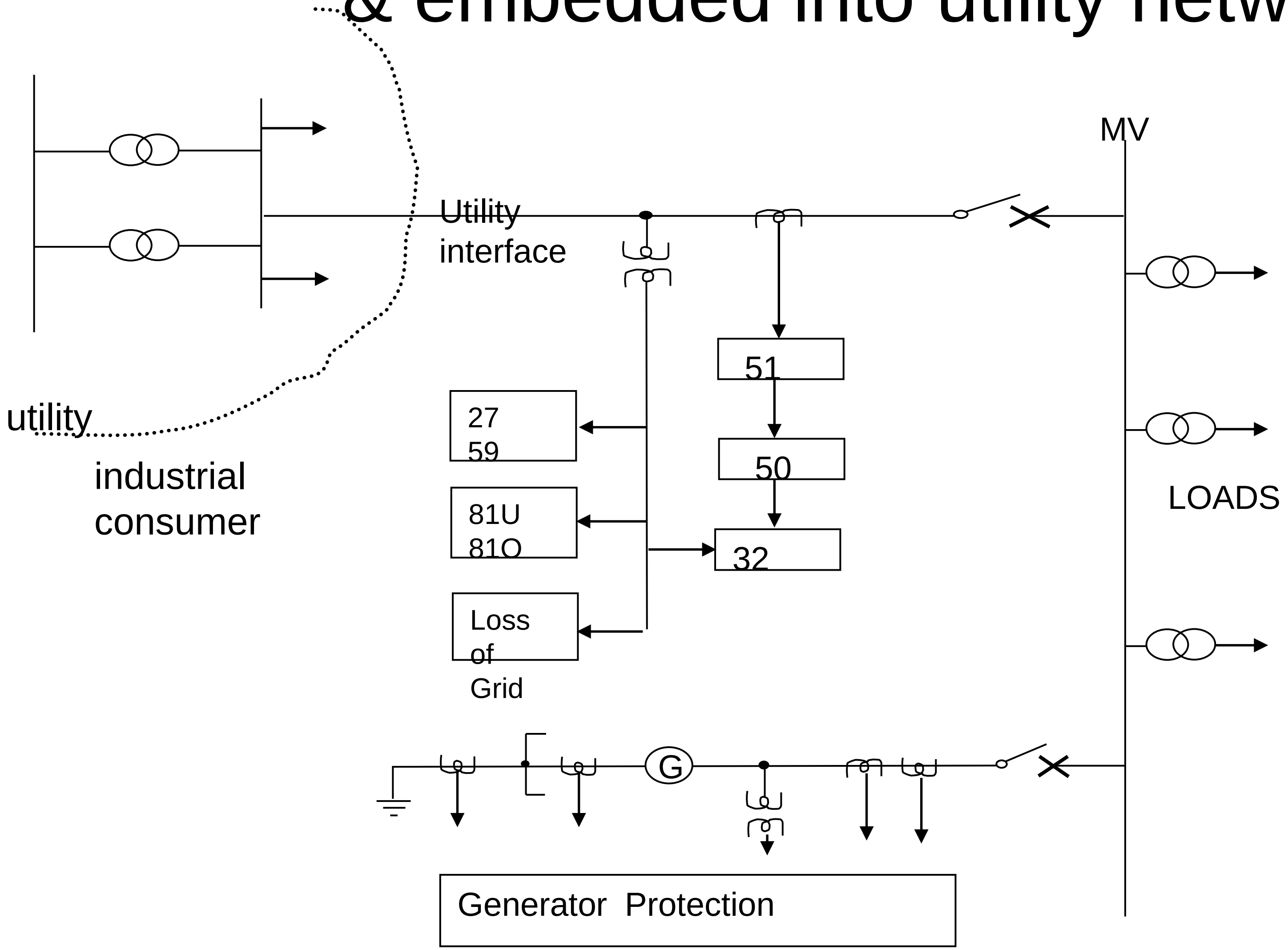
81U/81O = under/over freq.

27/59 = under/over voltage

32 = reverse power

Loss of grid:- requirement in UK

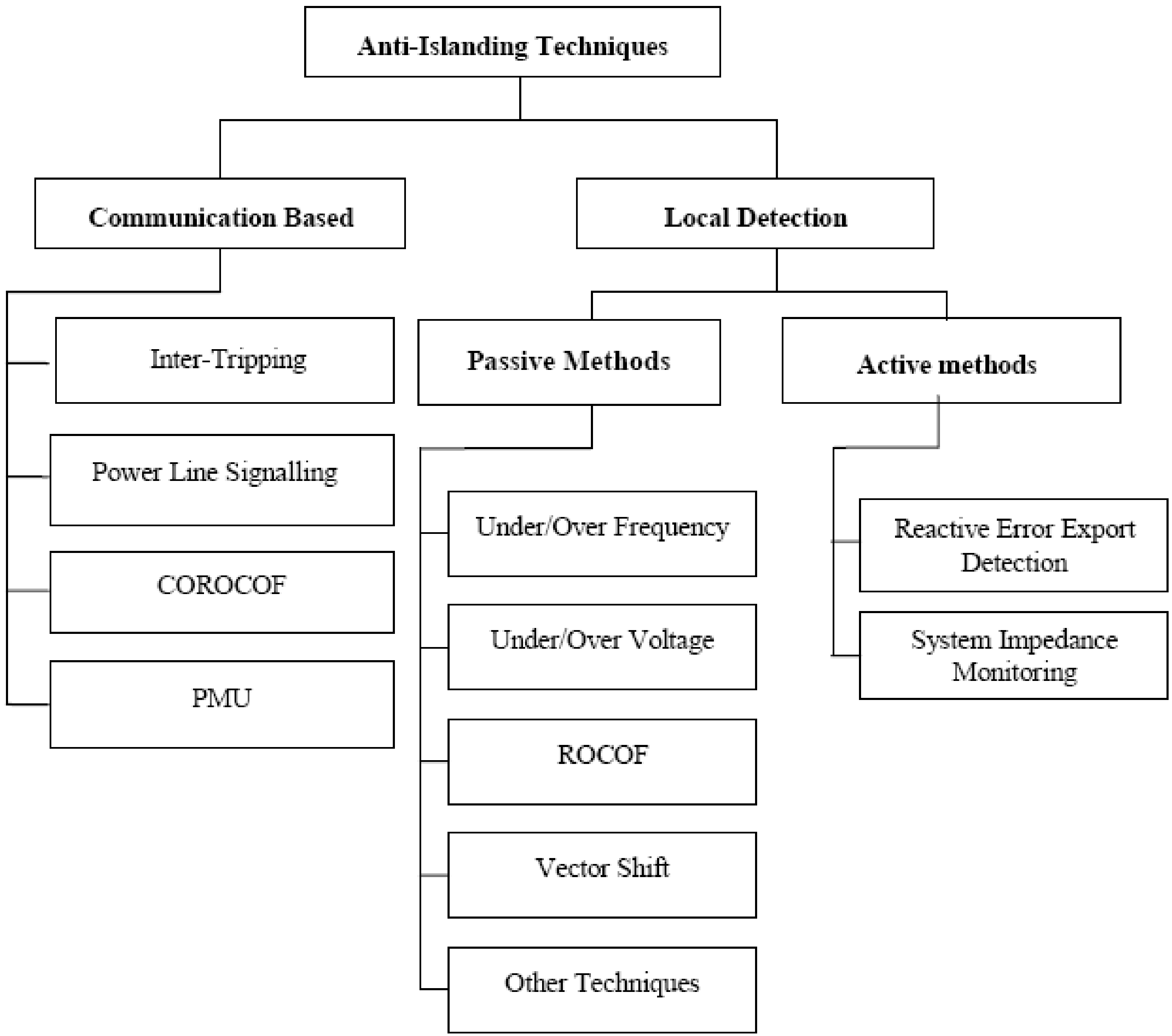
Prot'n for generator supplying industrial load & embedded into utility network



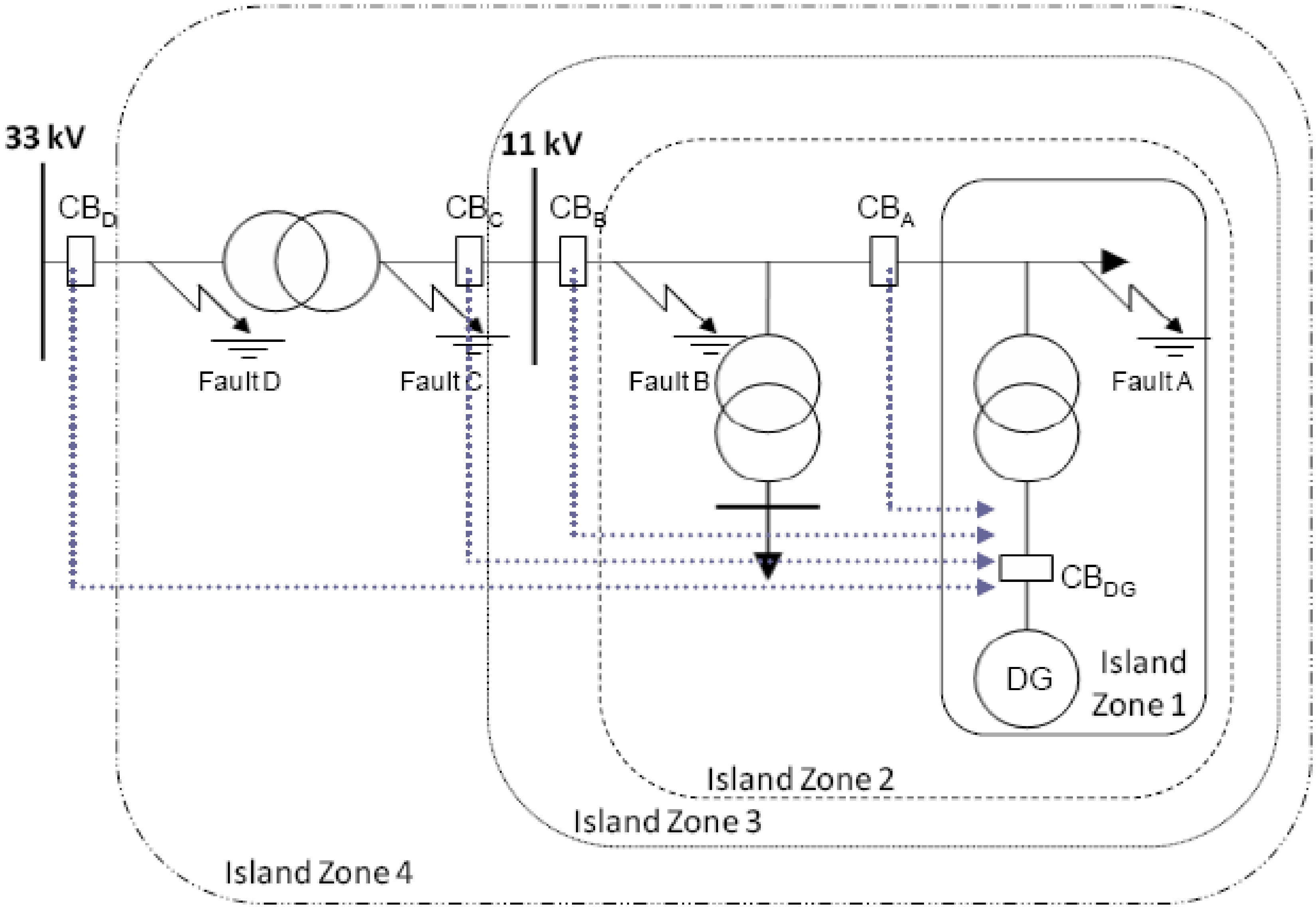
Loss of grid protection

- Faults on utility network cleared by local relays:
  - hence:- distributed generators may attempt to supply parts of network islanded from grid
  - for safety:- protection on distributed generator intertie must detect “loss of grid” and trip intertie breaker
- Islanding of distributed generator:
  - may leave section of network without earth
  - fault level inadequate to operate protection relays
  - distribution breakers do not include check synchronising
  - hence:- reclosing of breaker could result in its destruction
- Immediately after removal of grid supply, G59 states:
  - all distributed generators connected to island must be disconnected
  - remain disconnected until grid supply restored

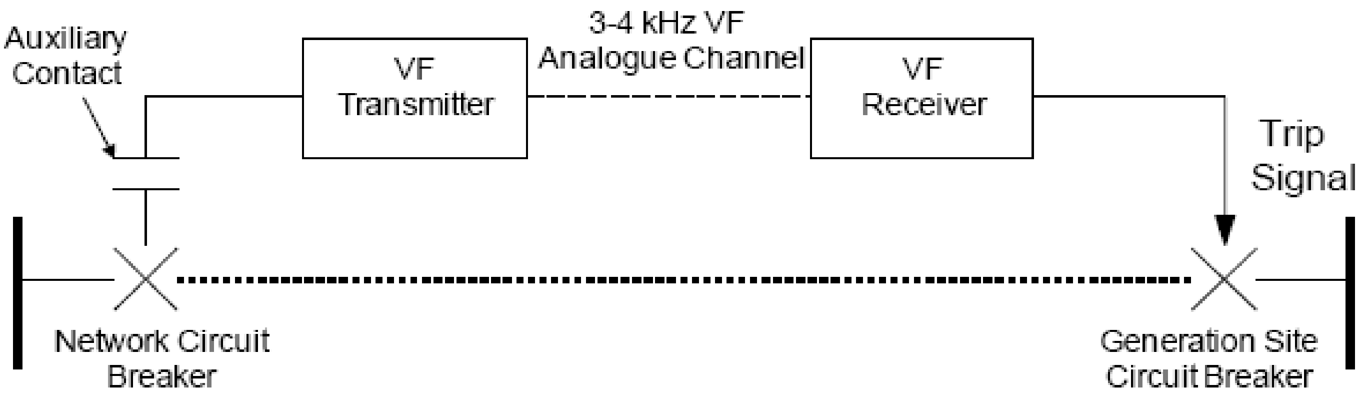
Islanding Detection Techniques



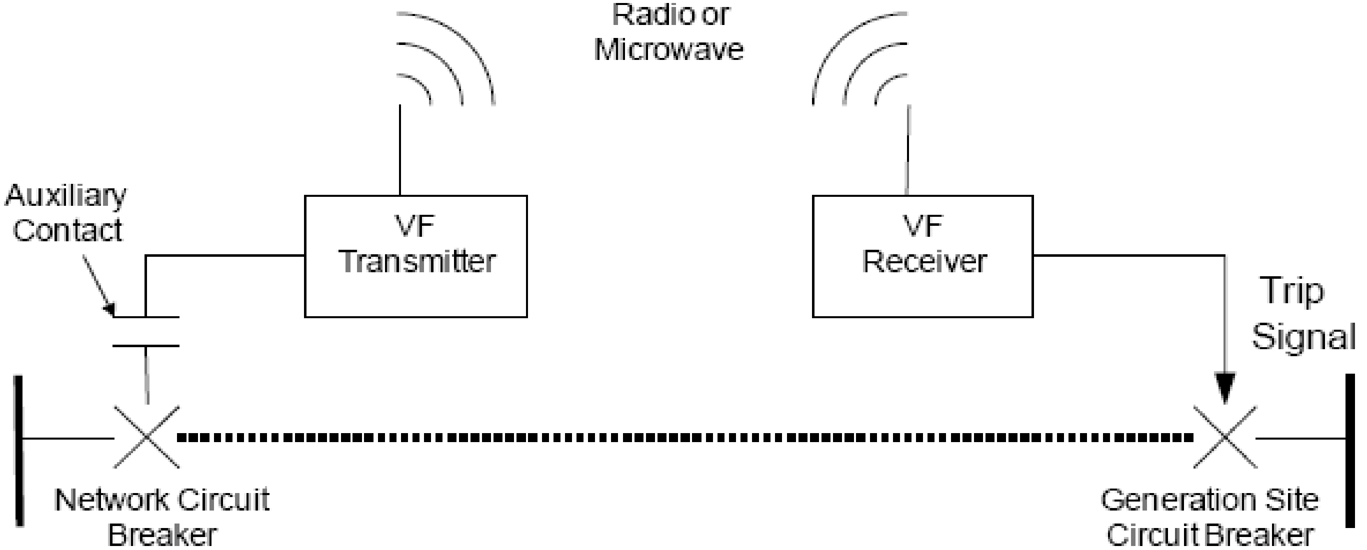
Island Detection Inter-tripping Schemes



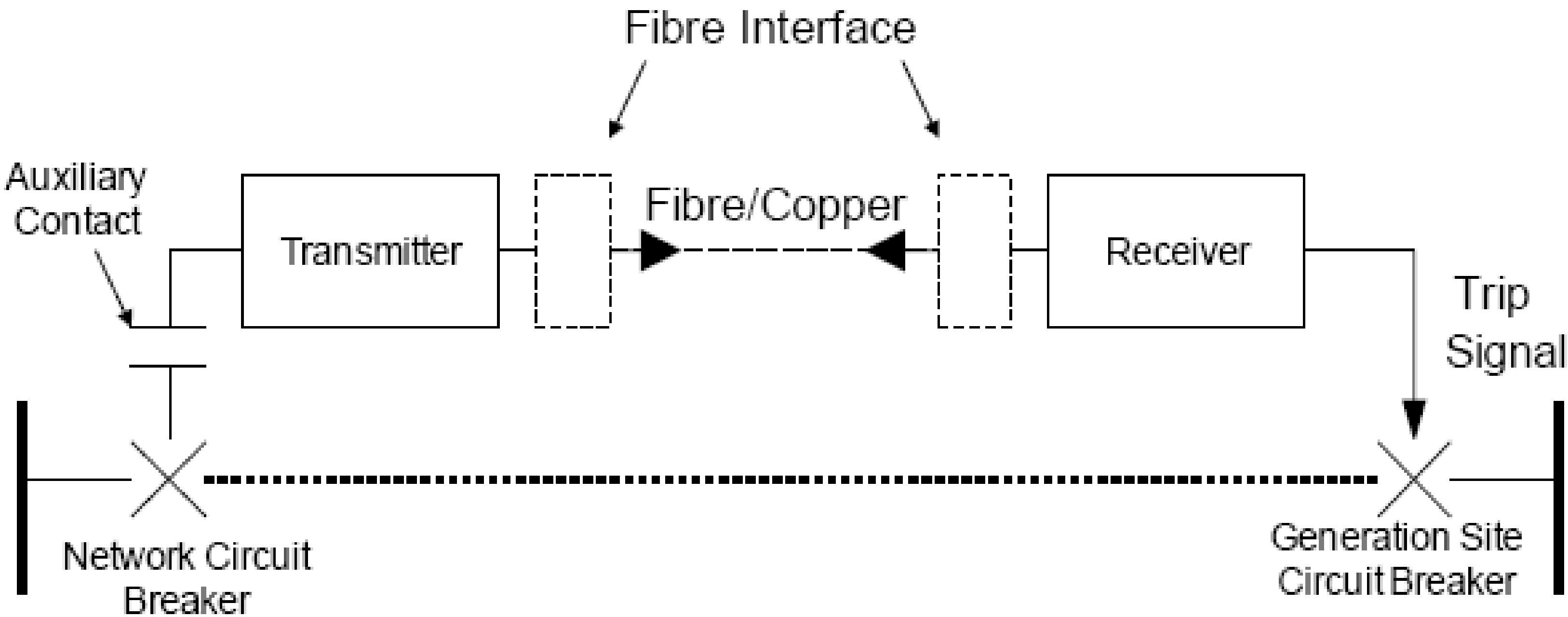
Mediums of Inter-tripping Schemes:
(a) leased line, (b) radio/microwave



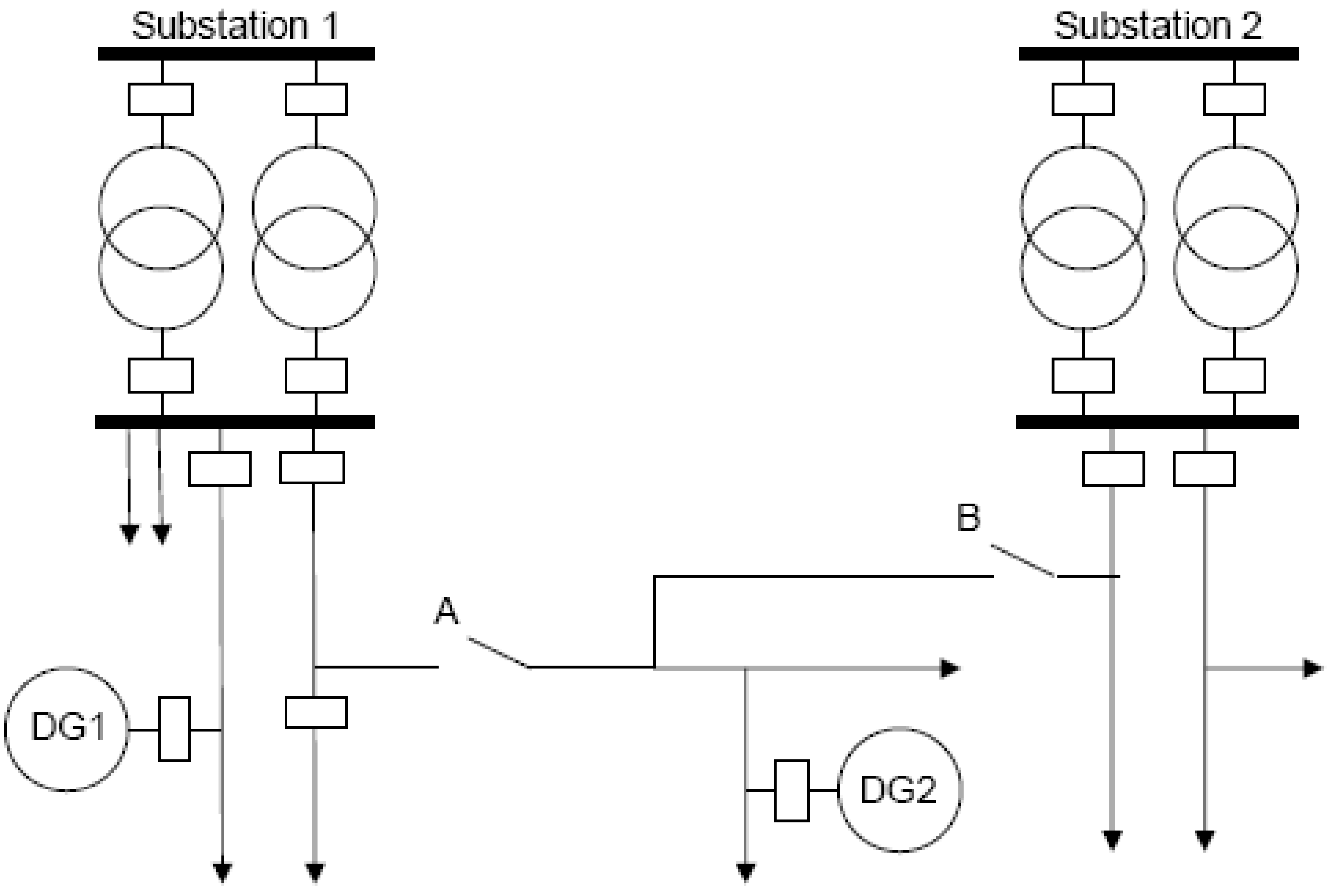
(a)



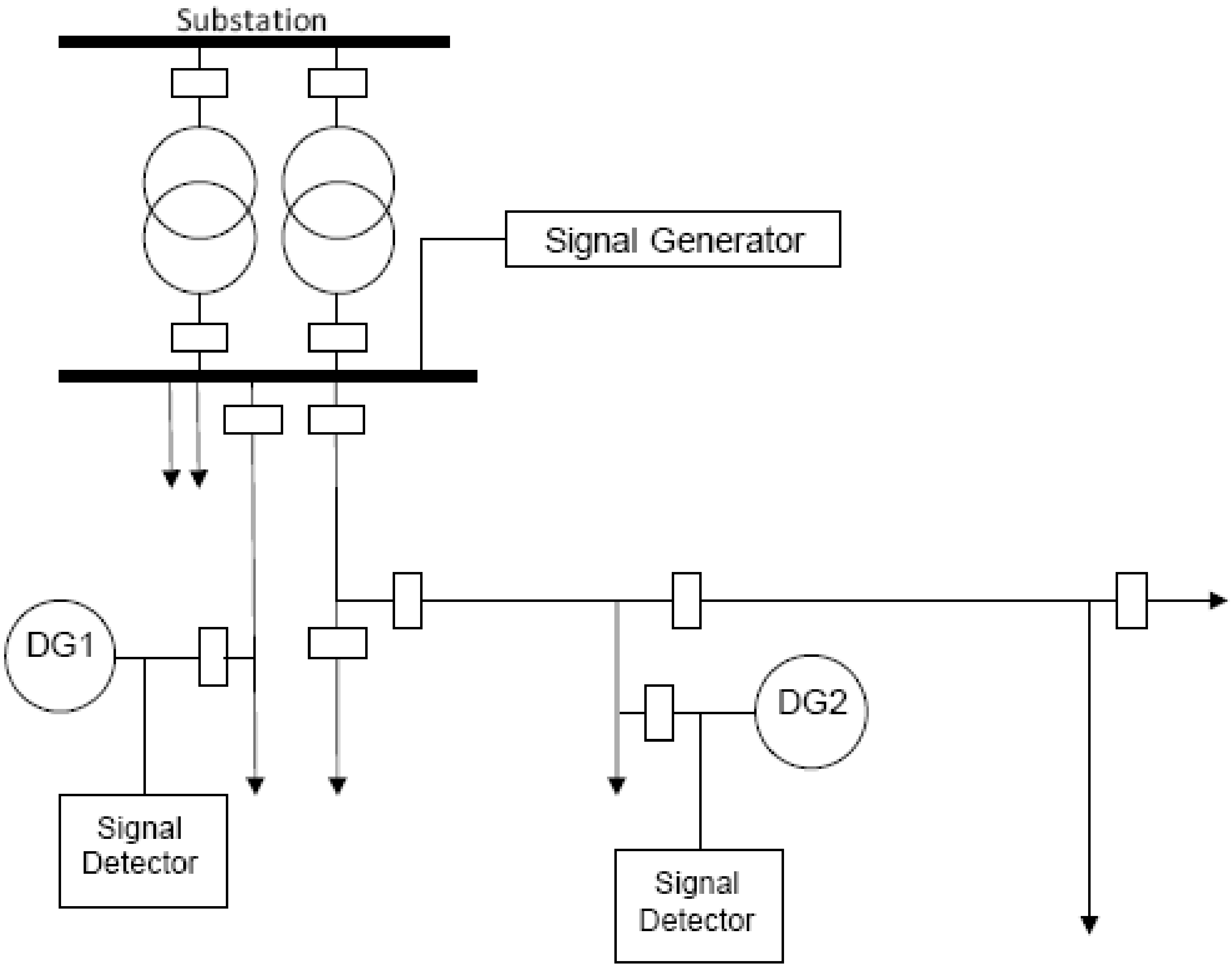
Mediums of Inter-tripping Schemes:
fibre/copper cables



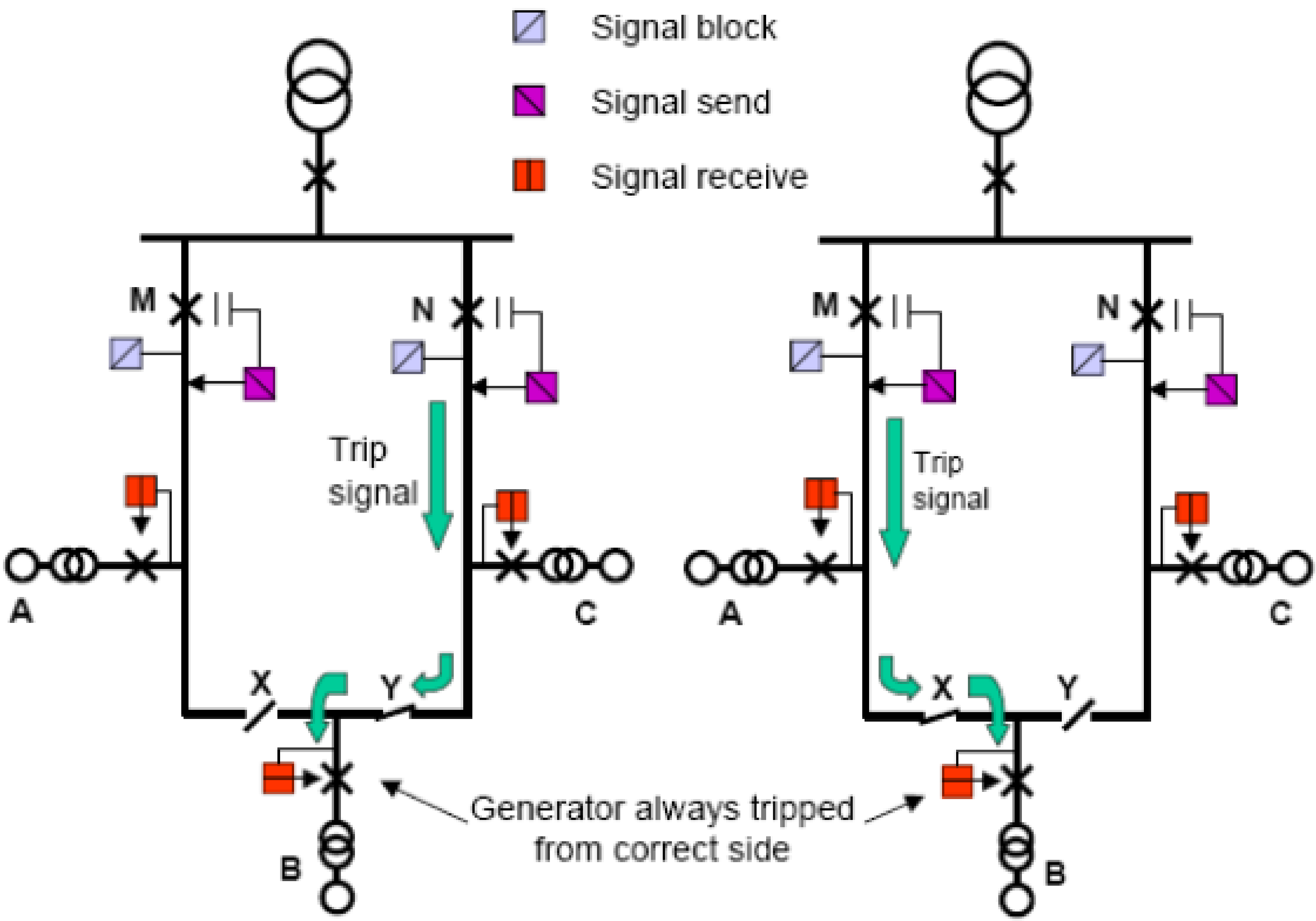
Network with changeable feeder topology:



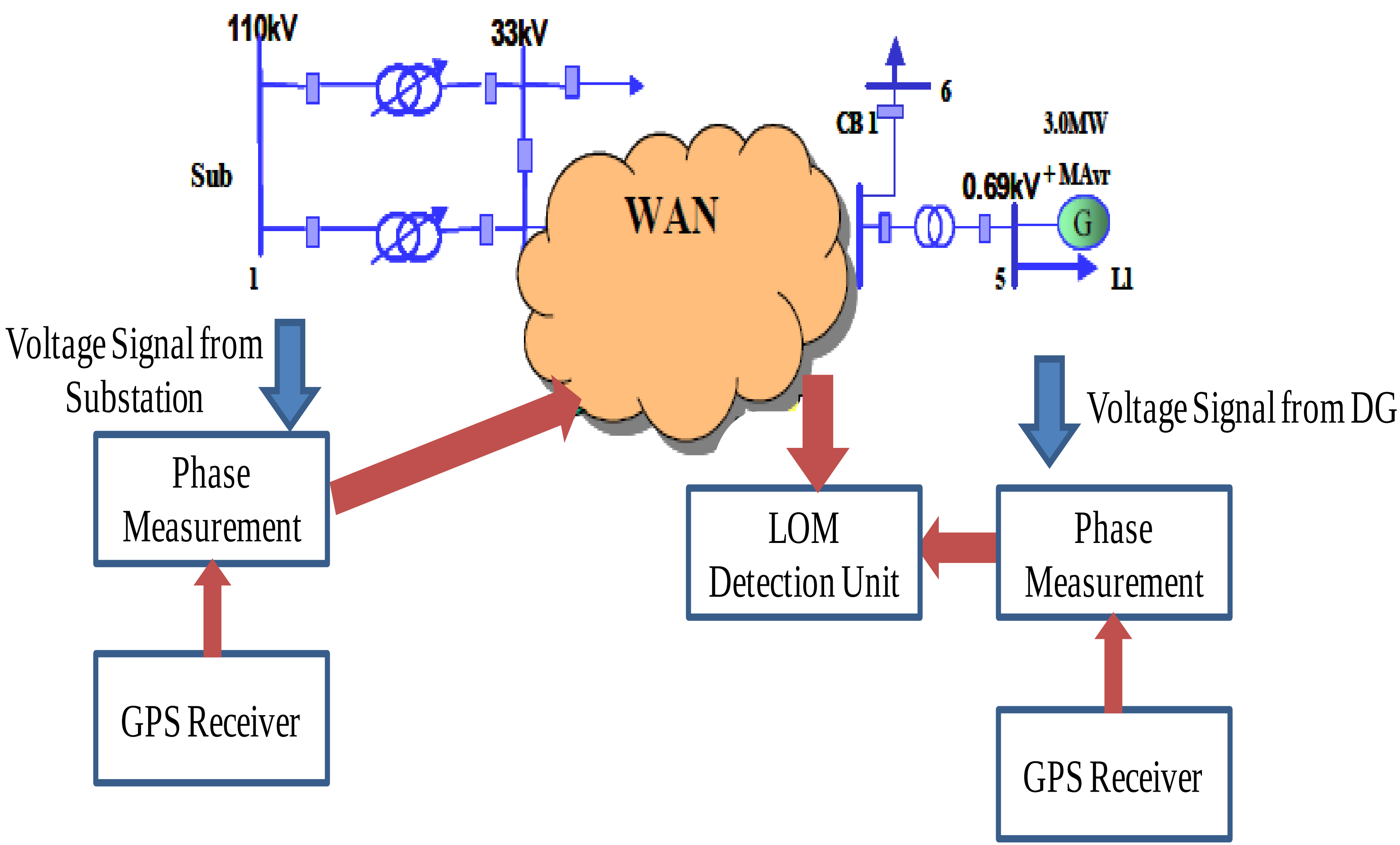
Power-line Signalling Scheme:



Operation of Power-line Signalling Scheme:



Phasor Measurement Unit based LOM:



Loss of mains protection

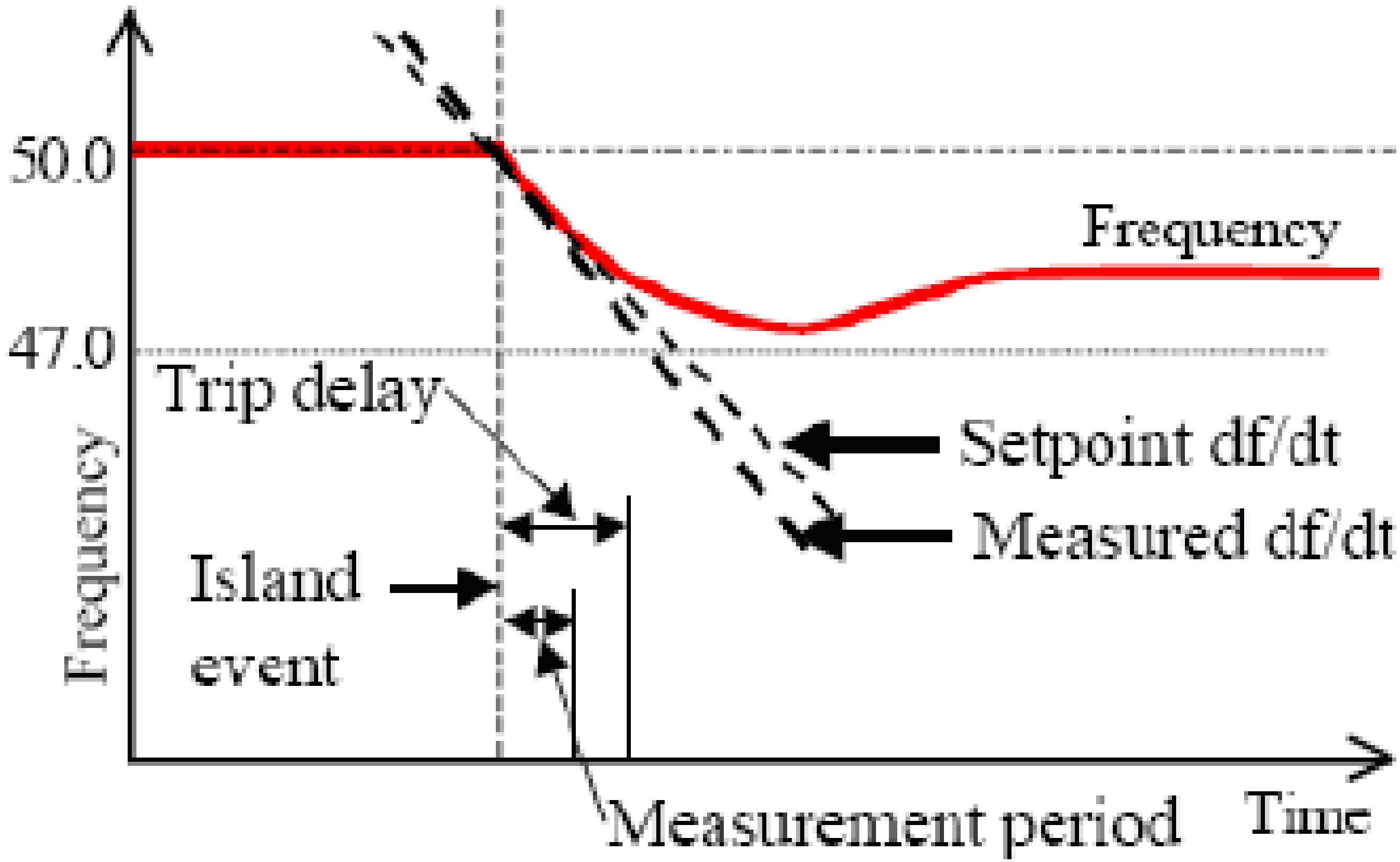
- Two techniques used to detect loss of mains:
  - rate of change of frequency (ROCOF)
  - vector shift
- ROCOF
  - assumes most 11kV feeders loaded up to about 5MW
  - loss of grid:- part of load supplied by embedded generator
  - generation deficit, causes rate of change of frequency
    - $df/dt = -(P_{LO} \times f_r^2 - P_{TO} \times f_r^2)/(2 \times H \times P_{TNOM} \times f_r)$
      - » P_{LO} **= load at rated frequency**
      - » P_{TO} **= output of distributed generator**
      - » P_{TNOM} **= rated capacity of generating plant**
      - » H **= inertia constant of generating plant**
      - » f_r **=** rated frequency

ROCOF

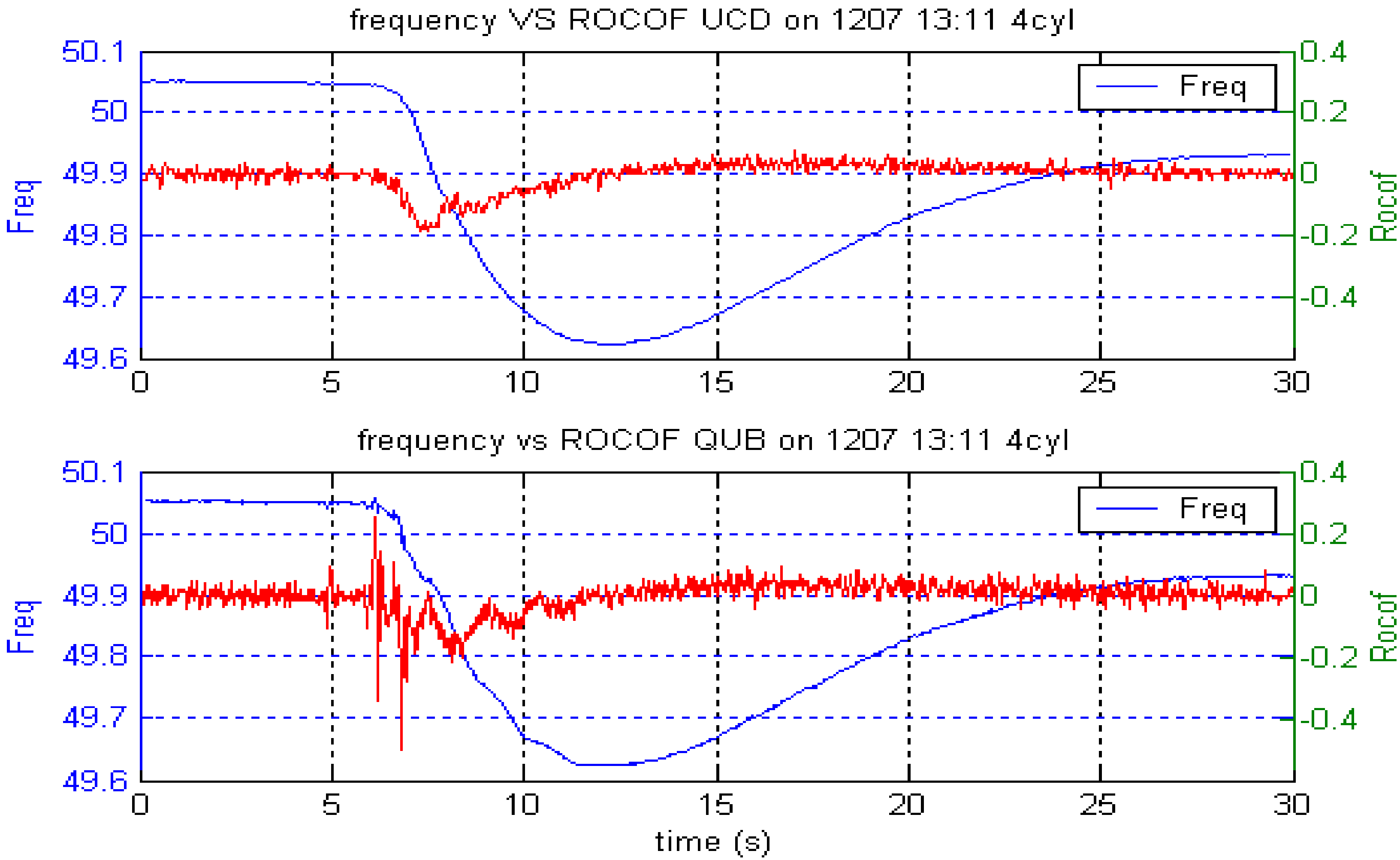
- Example:
  - consider 800kW 1MVA generator with inertia constant H of 1.2s operating at 615kWwhen loss of grid occurs
  - if load on generator suddenly increases to 677kW
  - the initial rate of change of frequency is:
    - $df/dt = -(0.677 \times 50^2 - 0.615 \times 50^2)/(2 \times 1.2 \times 0.800 \times 50) = -1.6Hz/s$
- Relay operating threshold = 0.1 - 10Hz/s (typ.:- 0.2 - 0.5Hz/s)
- Relay operating time = 0.04 - 2.0s (typ :- 0.2 - 0.5s)
- ROCOF sensitive and dependable method of detecting LOG
- concern about nuisance trips caused by loss of bulk generation
- UK:- loss of bulk generation regularly causes 0.2Hz/s, occasionally 1Hz/s

- incorrect tripping of large amounts of distributed generation risks integrity of national network

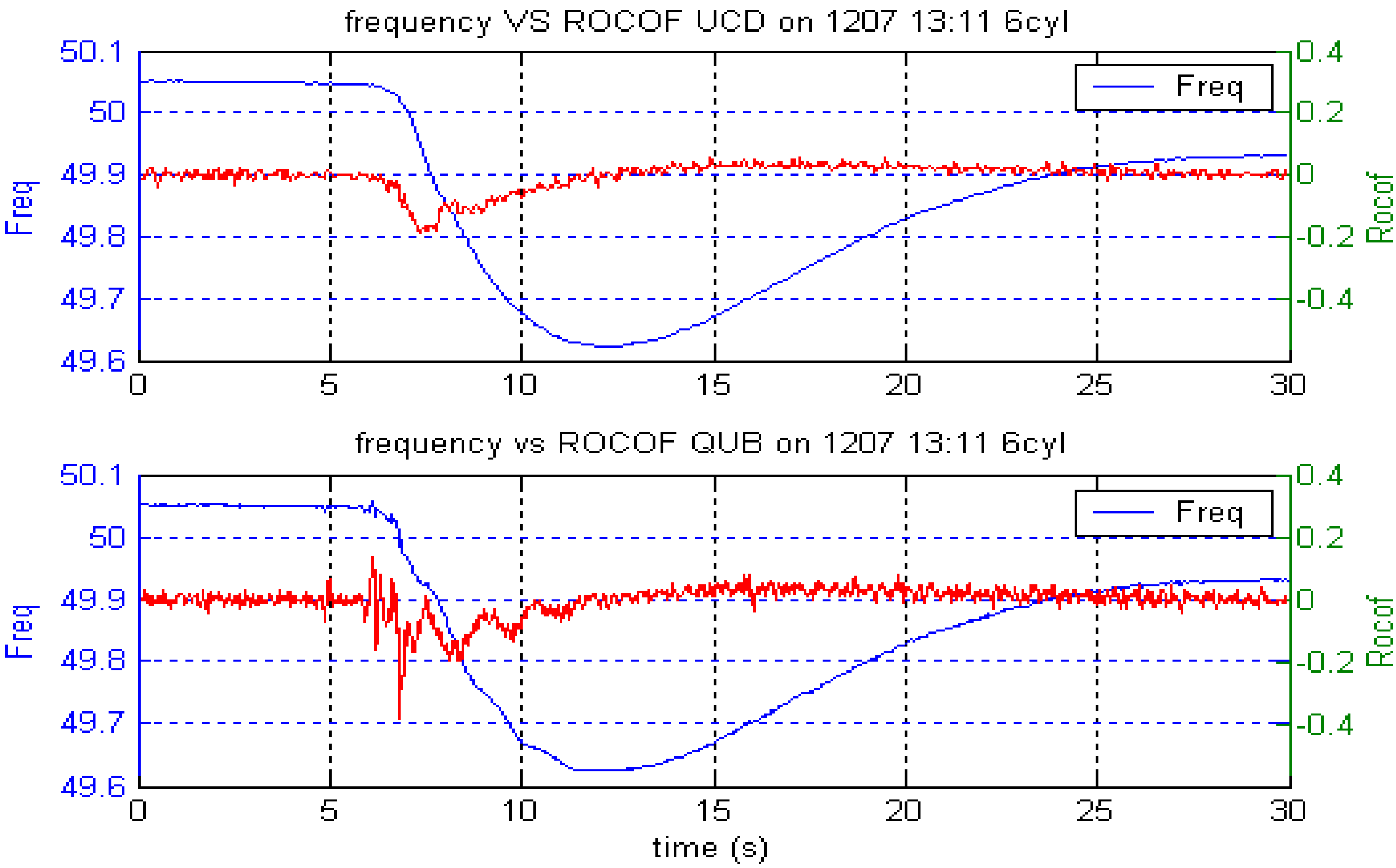
ROCOF Detection Method:



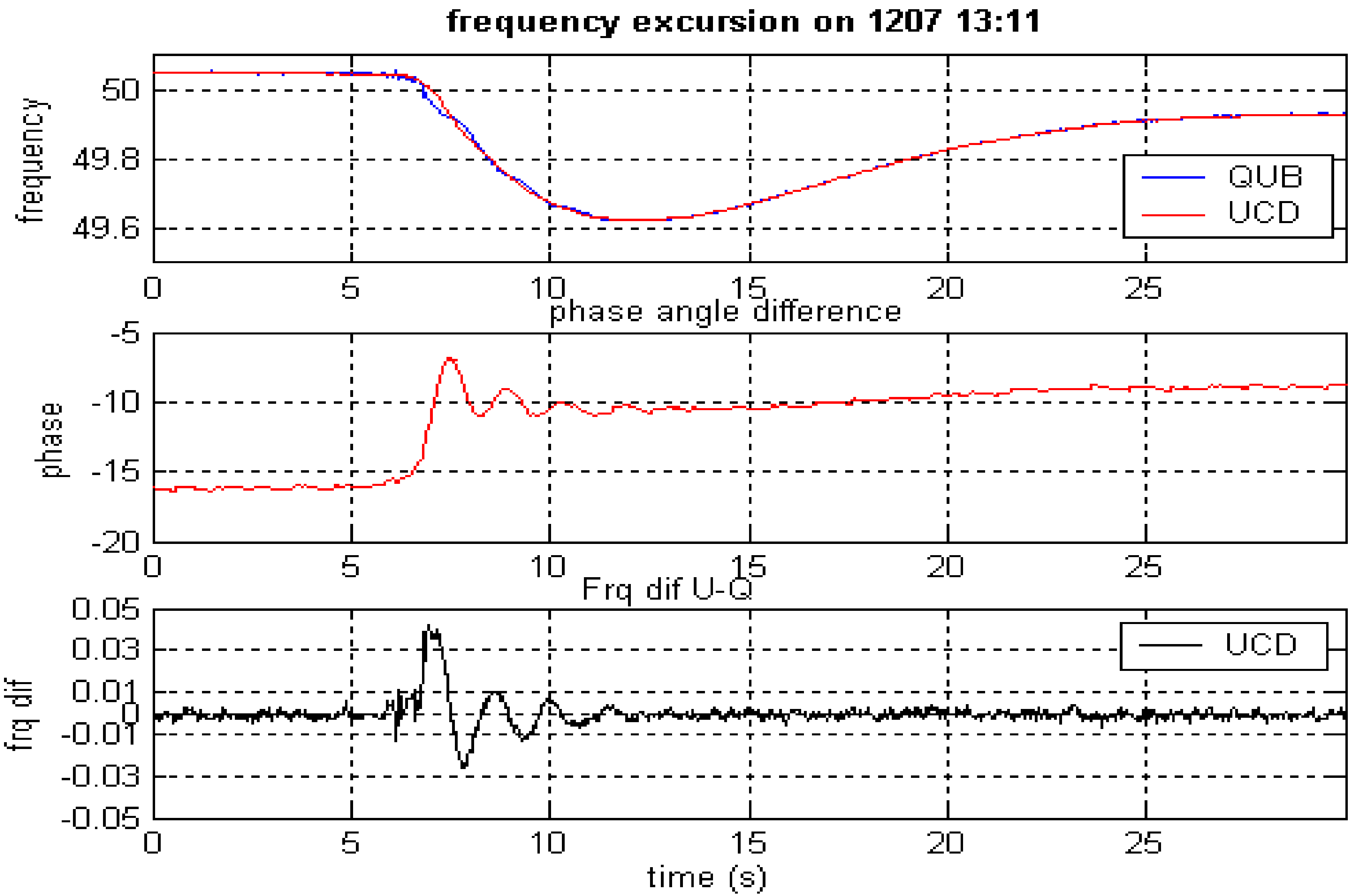
Impact of a freq dip on a ROCOF relay



Impact of a freq dip on a ROCOF relay

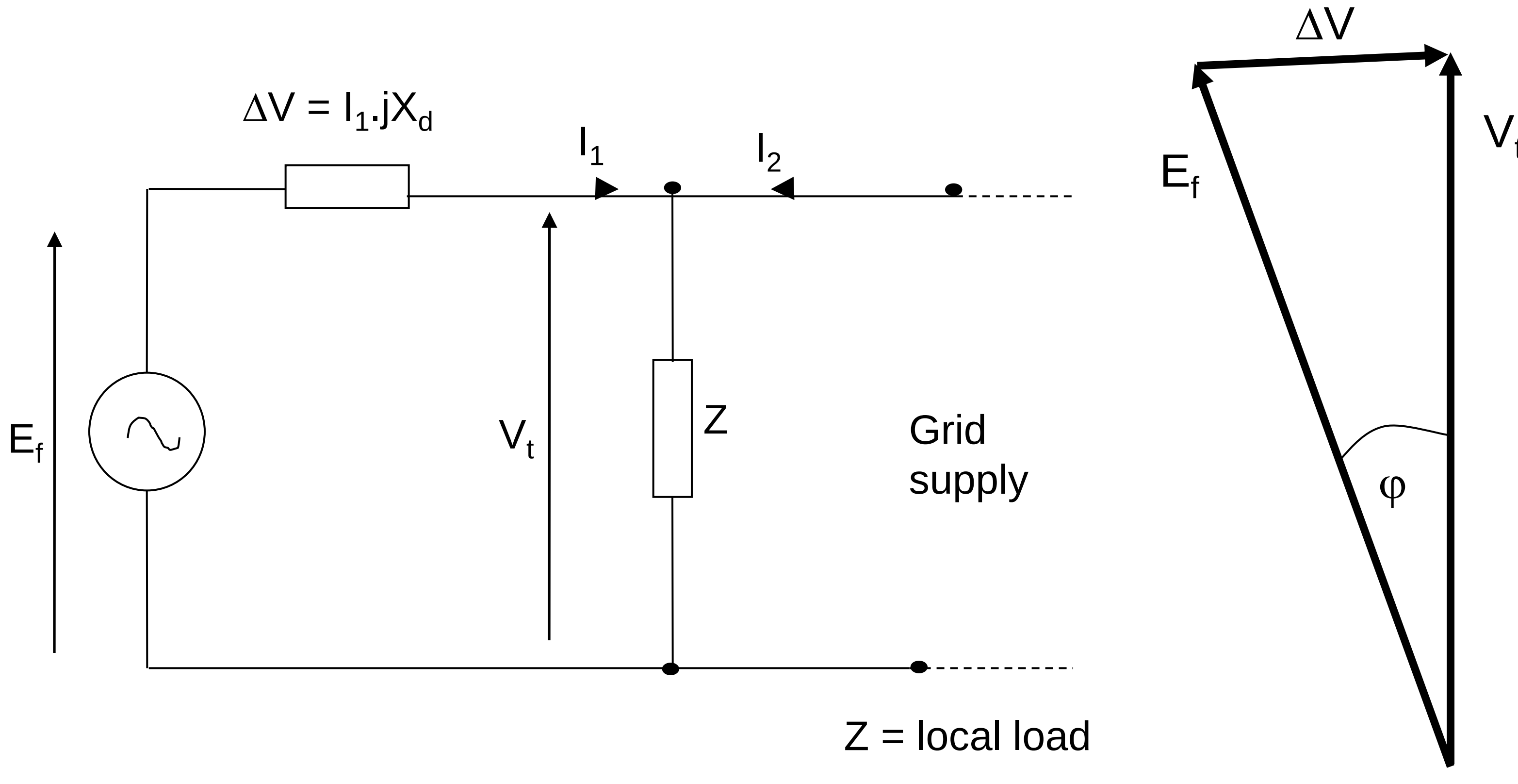


For those interested in stability!



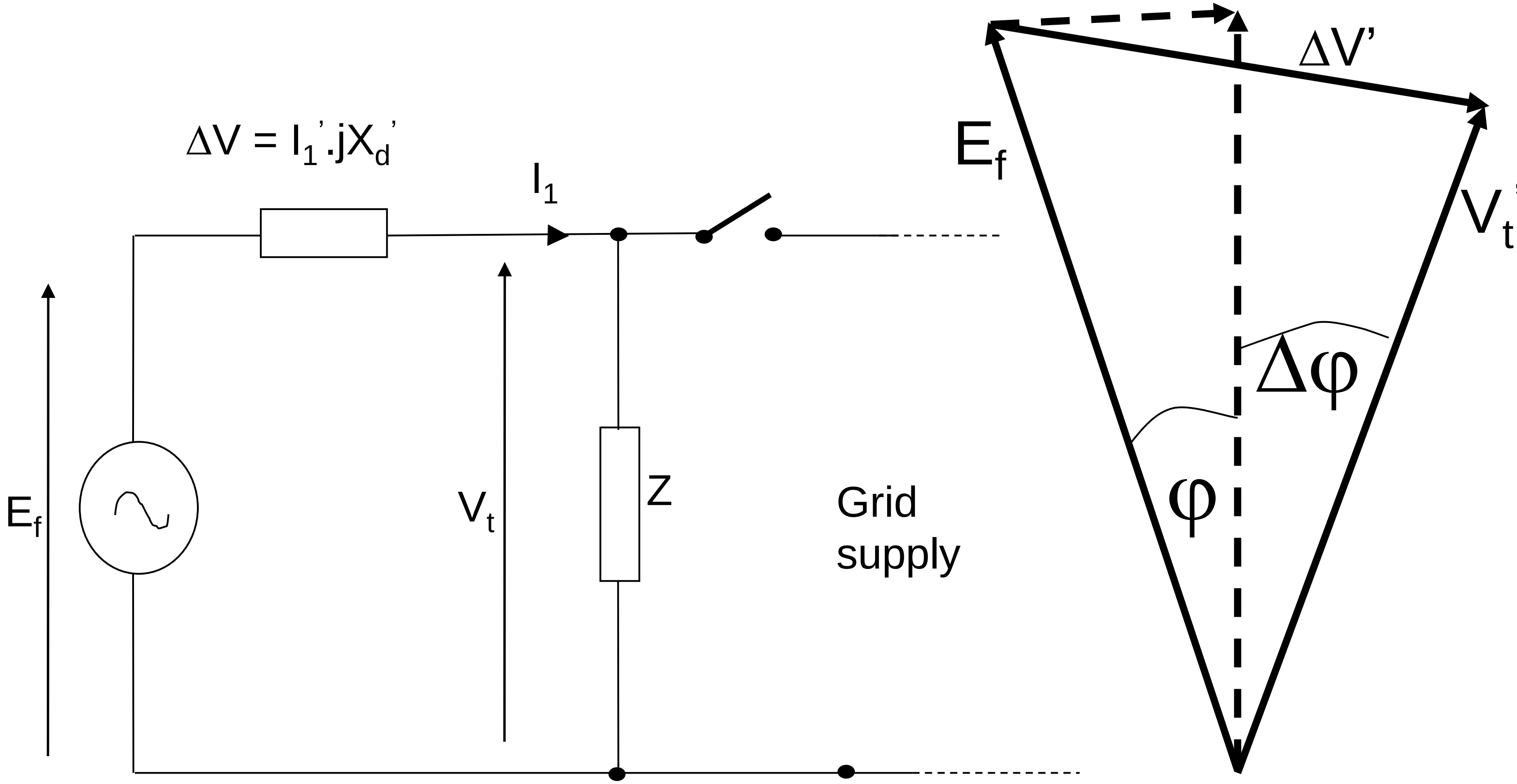
Vector Shift

- normal operation:- terminal voltage of embedded generator (V_t) lags the synchronous emf (E_f) by rotor displacement angle (φ)

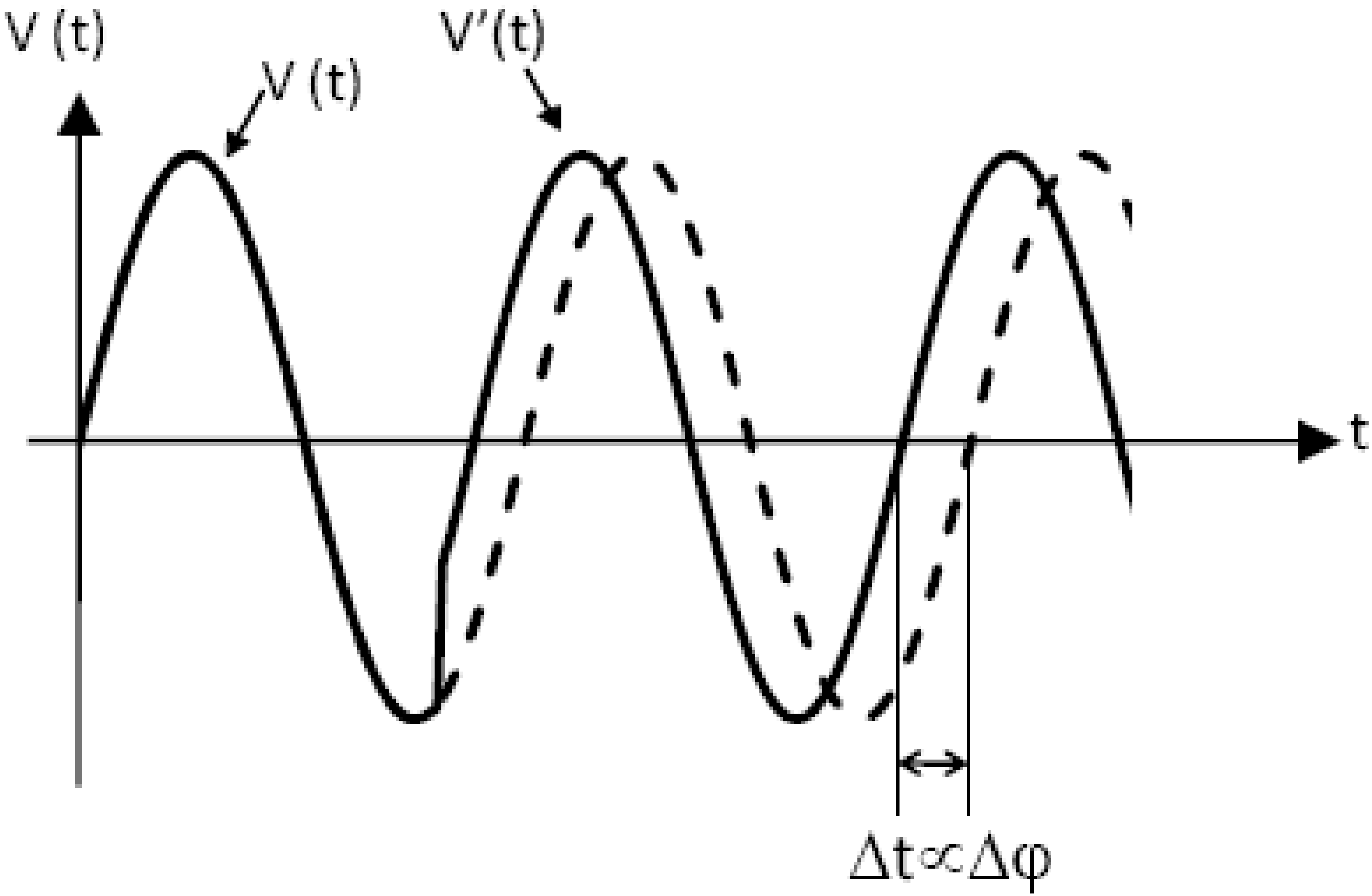


Vector Shift

- If grid lost:- load on generator increases; hence sudden increase in φ



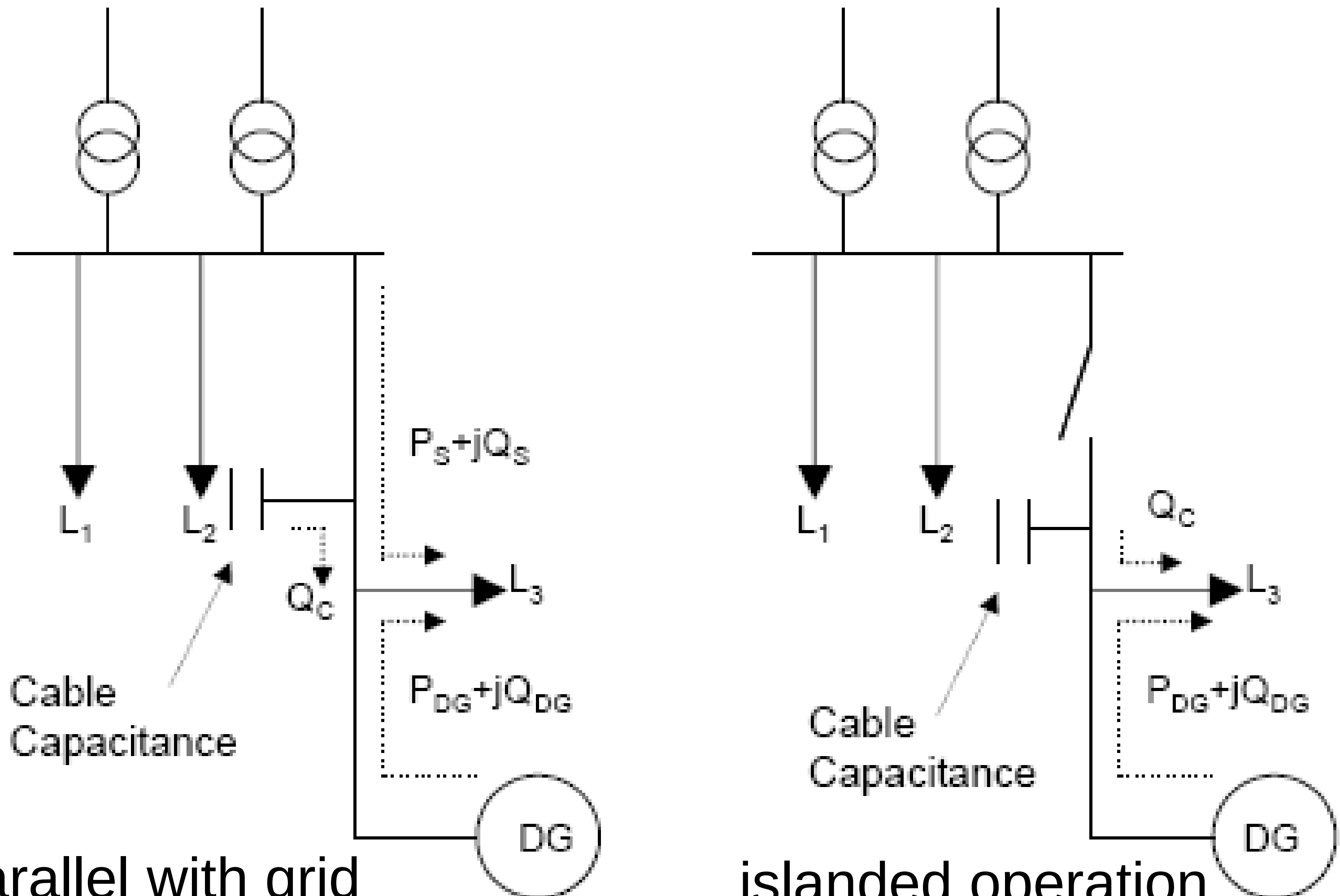
Voltage waveform of DG at instant of islanding:



Loss of grid protection

- Problem:- sensitivity .vs. stability
  - can ROCOF/vector shift always detect loss of grid?
  - can appropriate “loss of grid” setting prevent nuisance trips
  - Nuisance trips often caused by bulk loss of generation
  - Impact depends on ‘strength’ of power system
- European network:- loss of bulk generator =
  - negligible change in df/dt or voltage angle
- Great Britian network:- loss of bulk generator =
  - occasional significant change in df/dt or voltage angle
- Ireland network:- loss of bulk generator =
  - significant change in df/dt or voltage angle

LOM detection:- reverse reactive power scheme:



parallel with grid

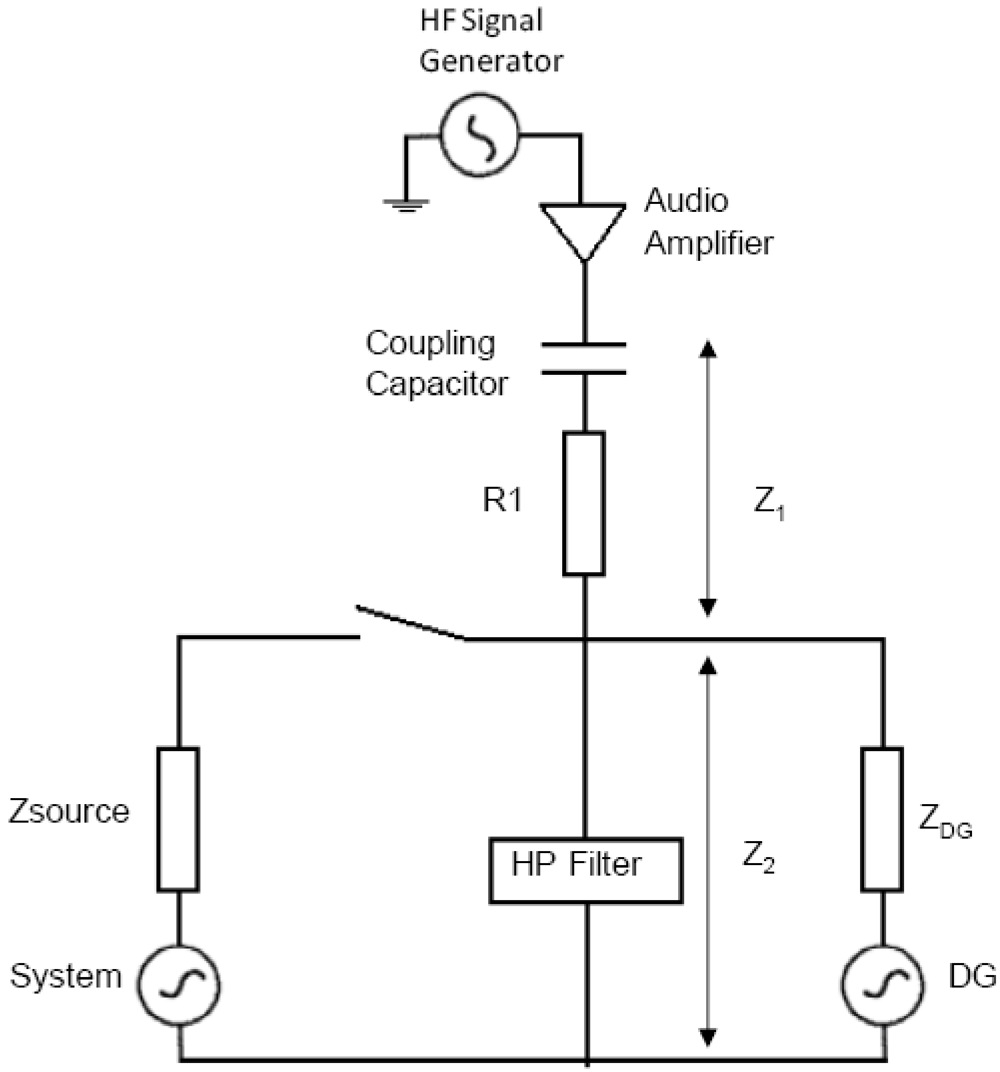
DG operates close to unity power factor
Reactive demand mainly supplied by utility

islanded operation

DG must now supply reactive demand

reverse reactive power relay detects change of reactive power flow and trips DG after a time delay.

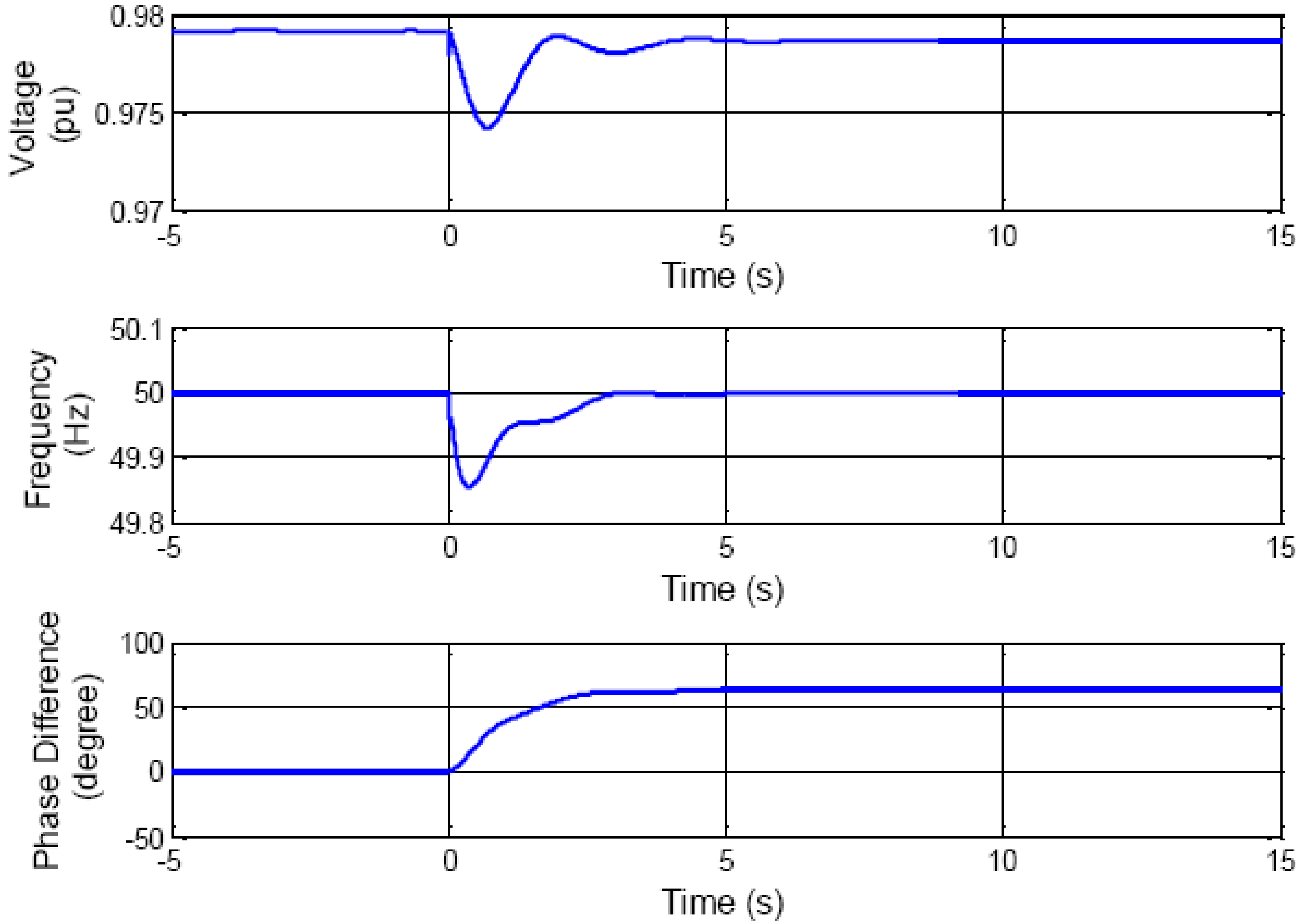
LOM detection: system impedance monitoring



utility connected:- measured impedance low
impedance increases significantly after islanding
= fast operation, immune to network instigated nuisance trips

Islanded operation:- impact of load disturbance

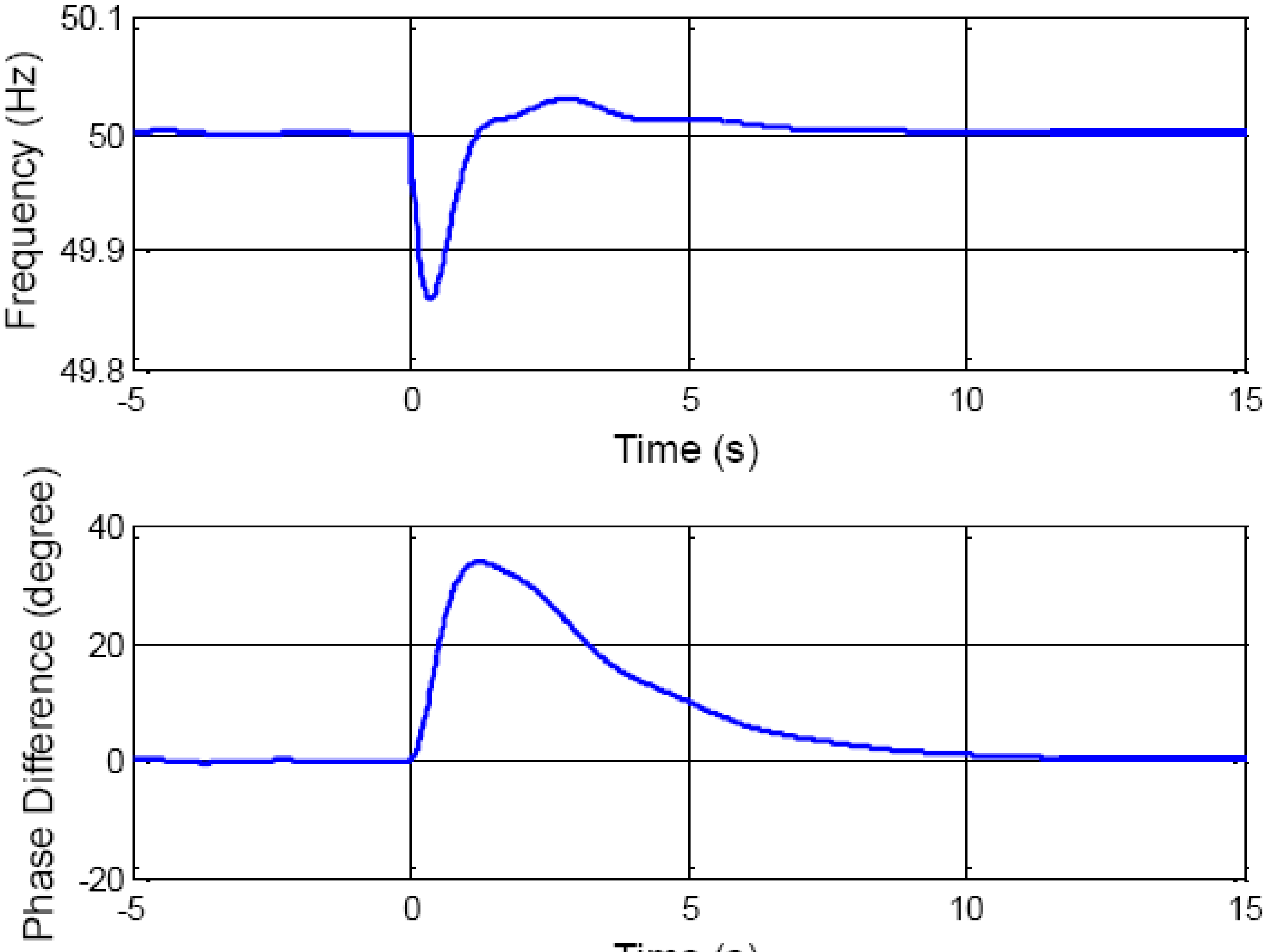
synchronous DG with appropriate governor and AVR control



Voltage and frequency restored within recommended synchonisation limits
Problem = phase deviation between utility and island systems

Control of frequency and phase of islanded network

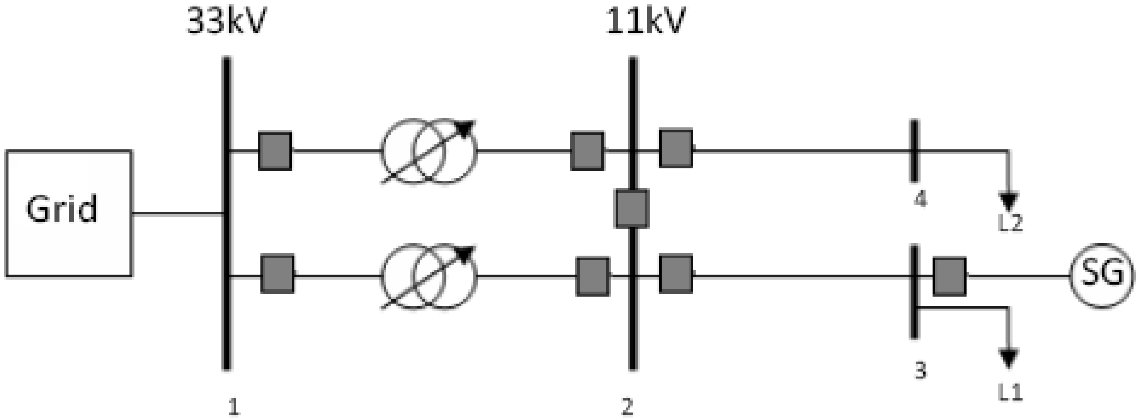
phase difference control added to conventional DG governor control



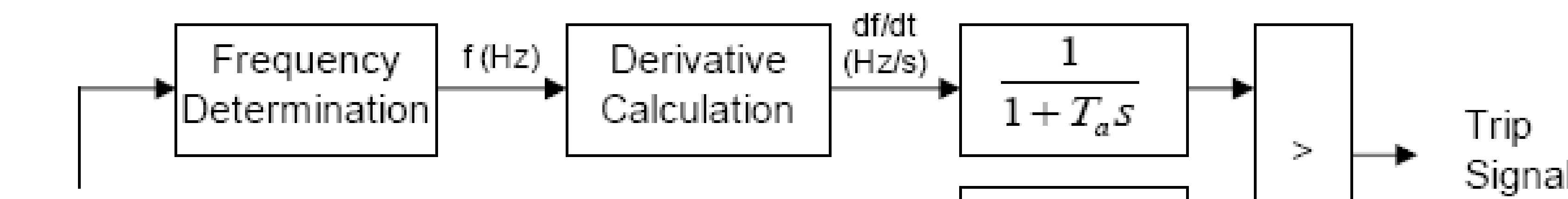
phase deviation regulation effective if island has one sync.generator

What happens with multiple generators in the island?

Problems with existing LOM detection schemes



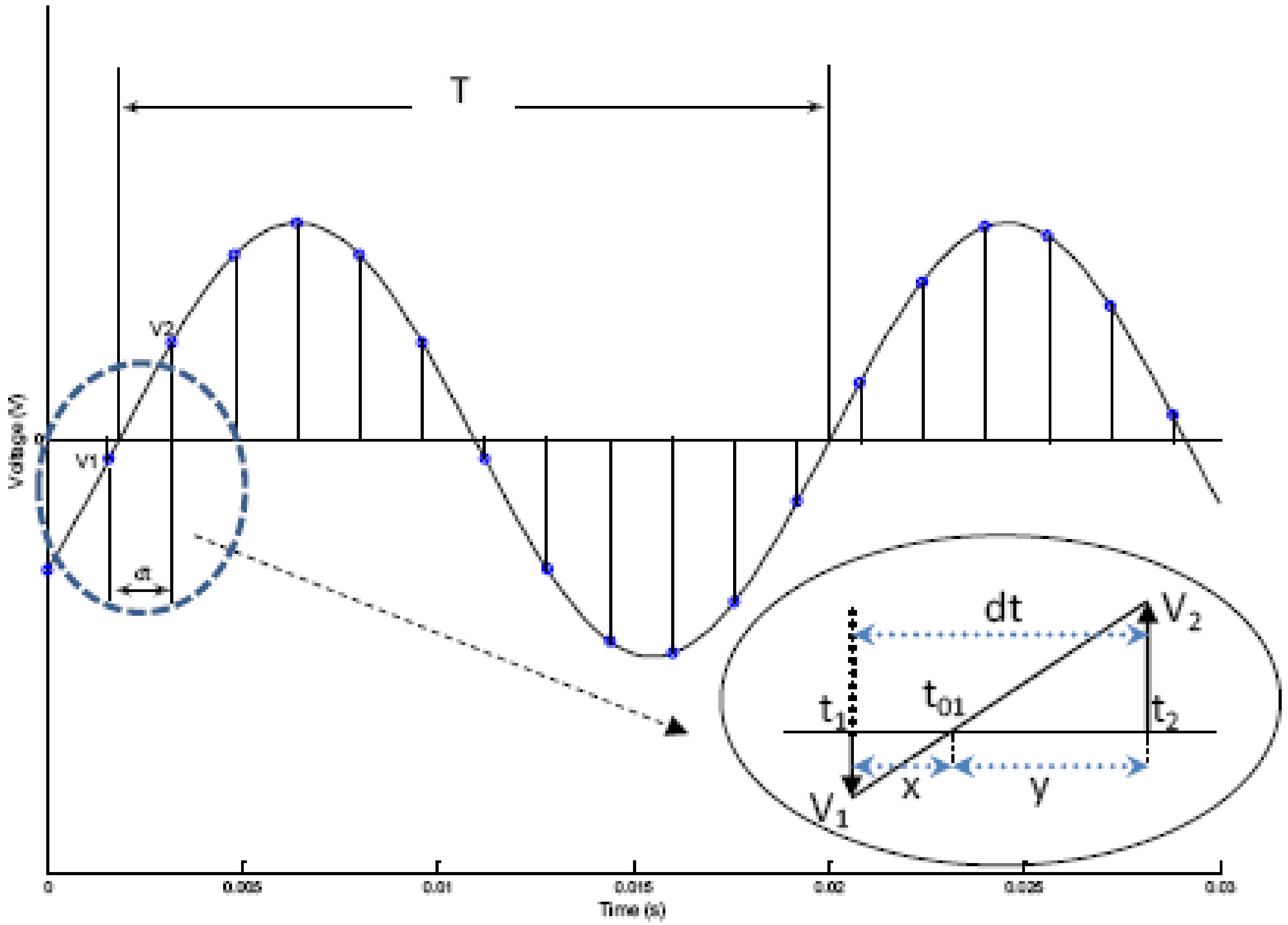
EMTDC/PSCAD distribution network model



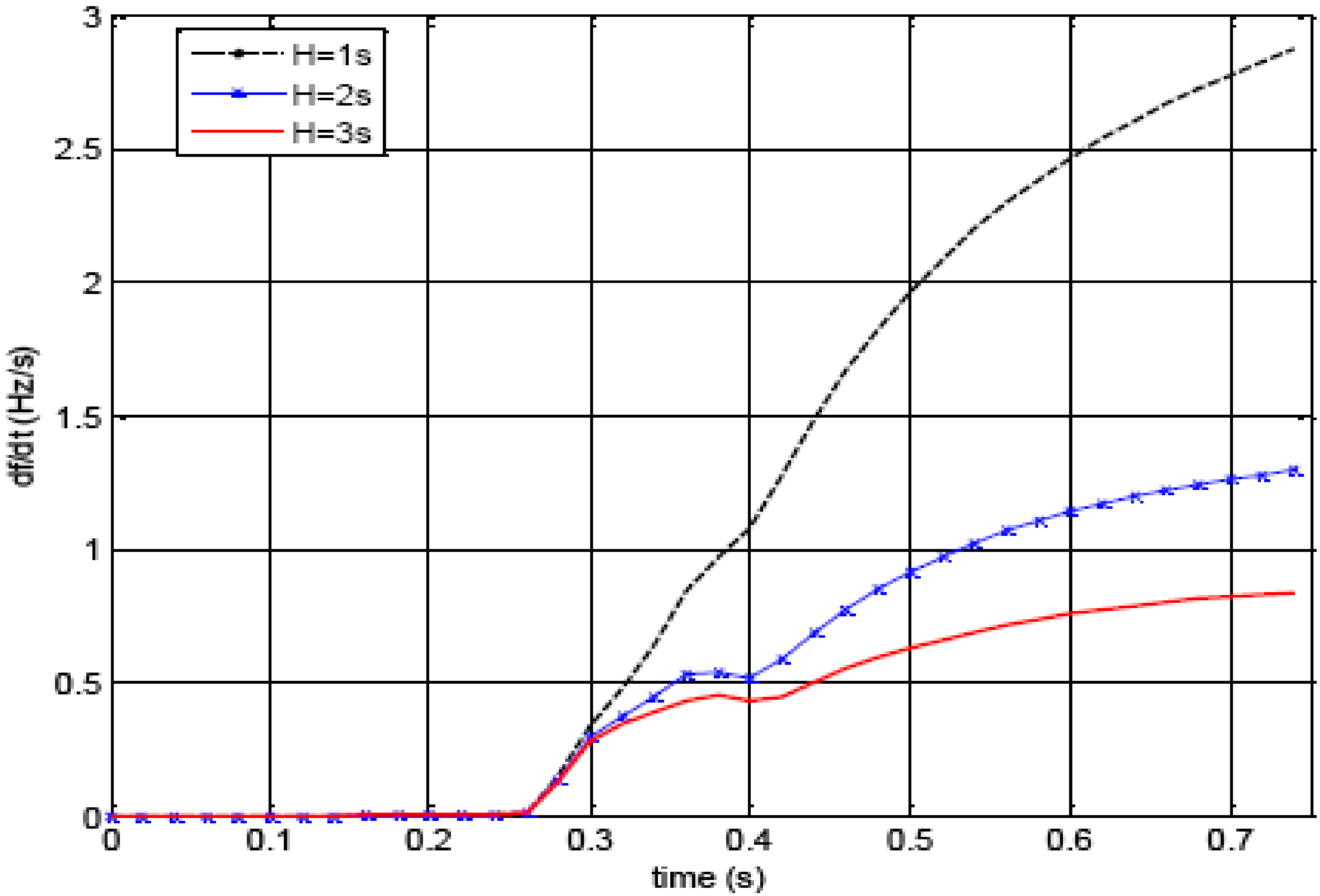
$$\frac{df}{dt} = \frac{1}{5}\sum_{i=1}^{5}\frac{\Delta f_i}{\Delta t_i}$$

ROCOF relay model
(100ms moving window)

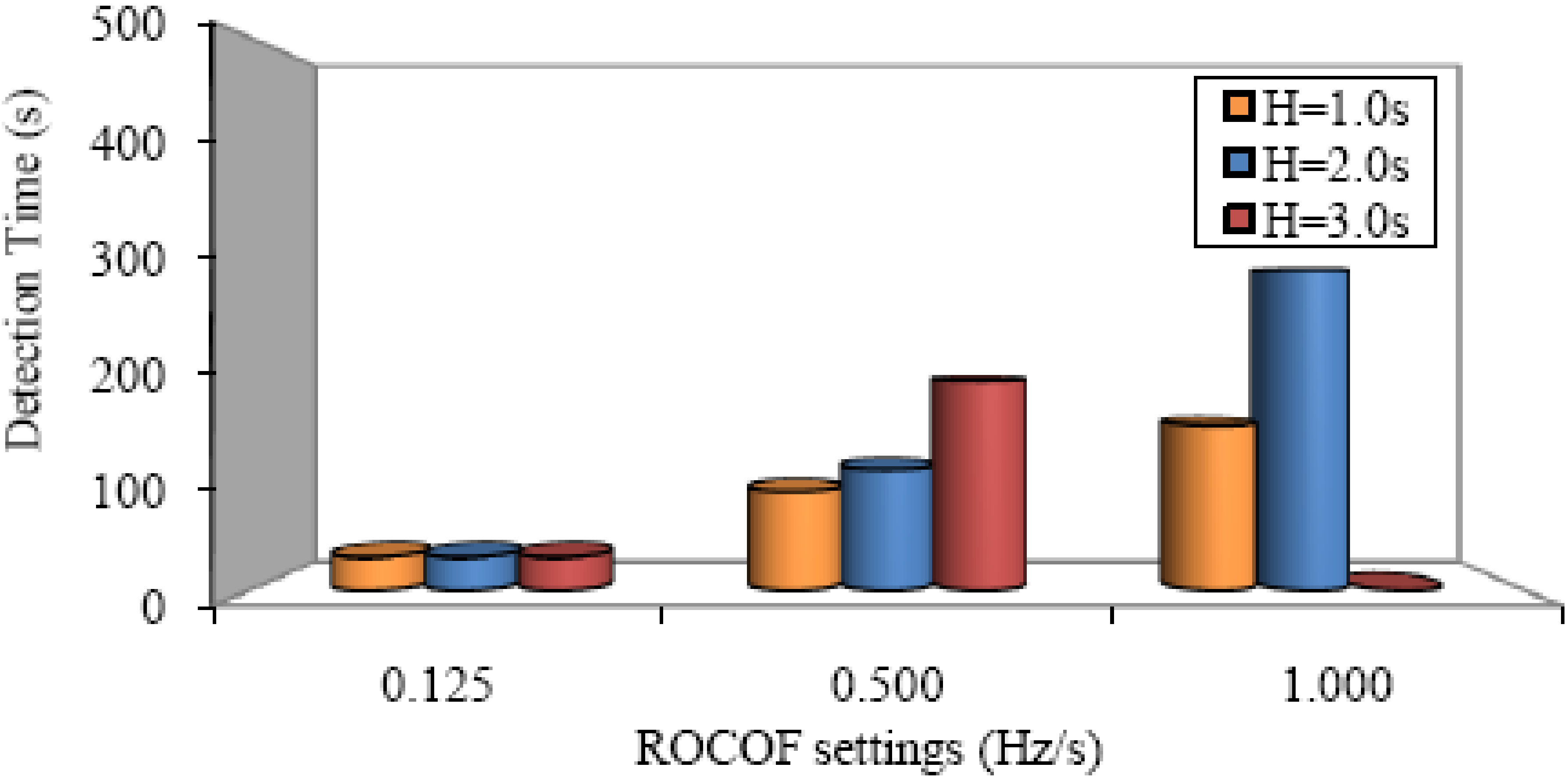
Zero-crossing LOM detection technique



Impact of DG inertia constant on rate of change of freq.



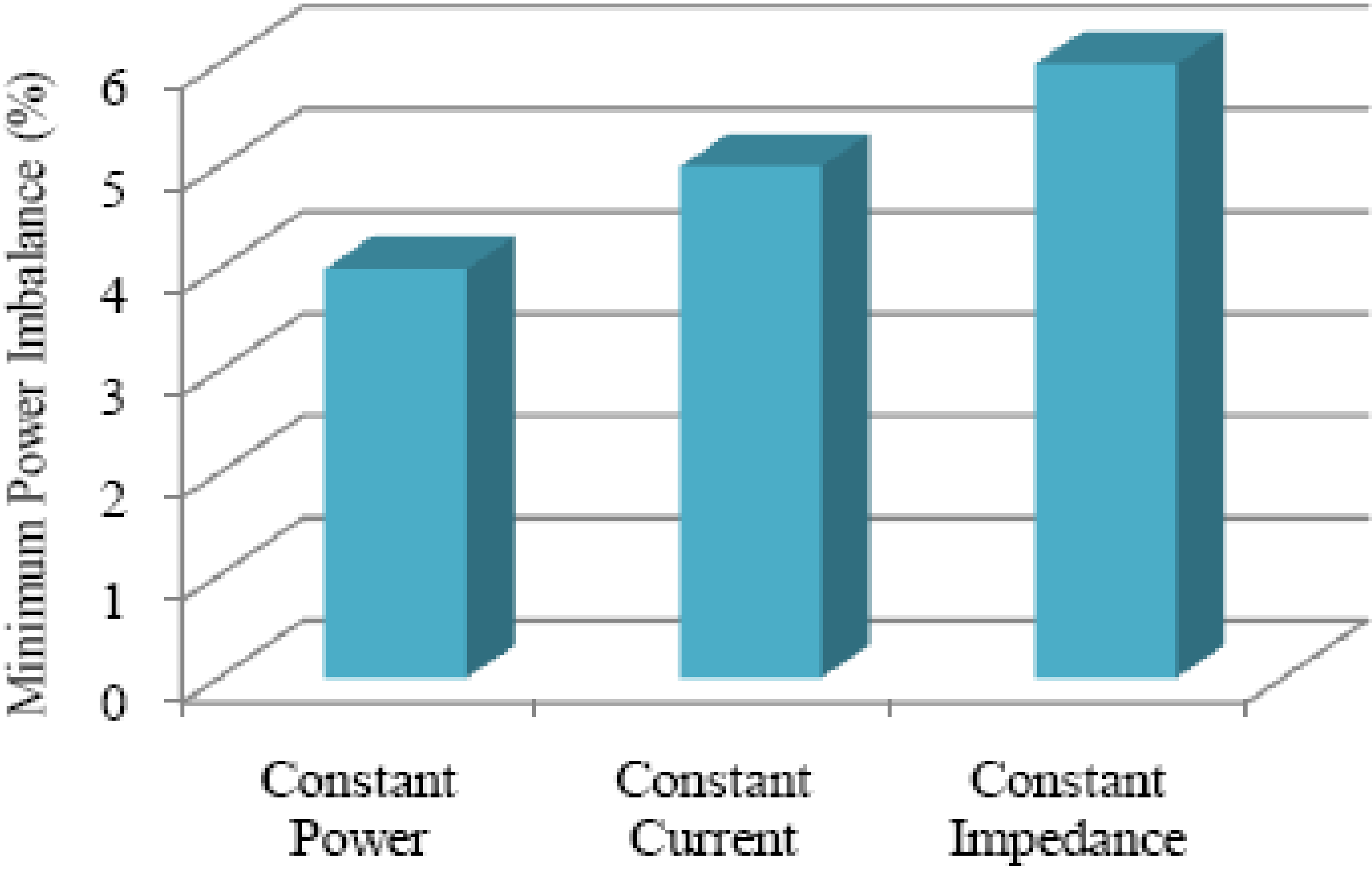
Impact of DG inertia constant on ROCOF LOM detection



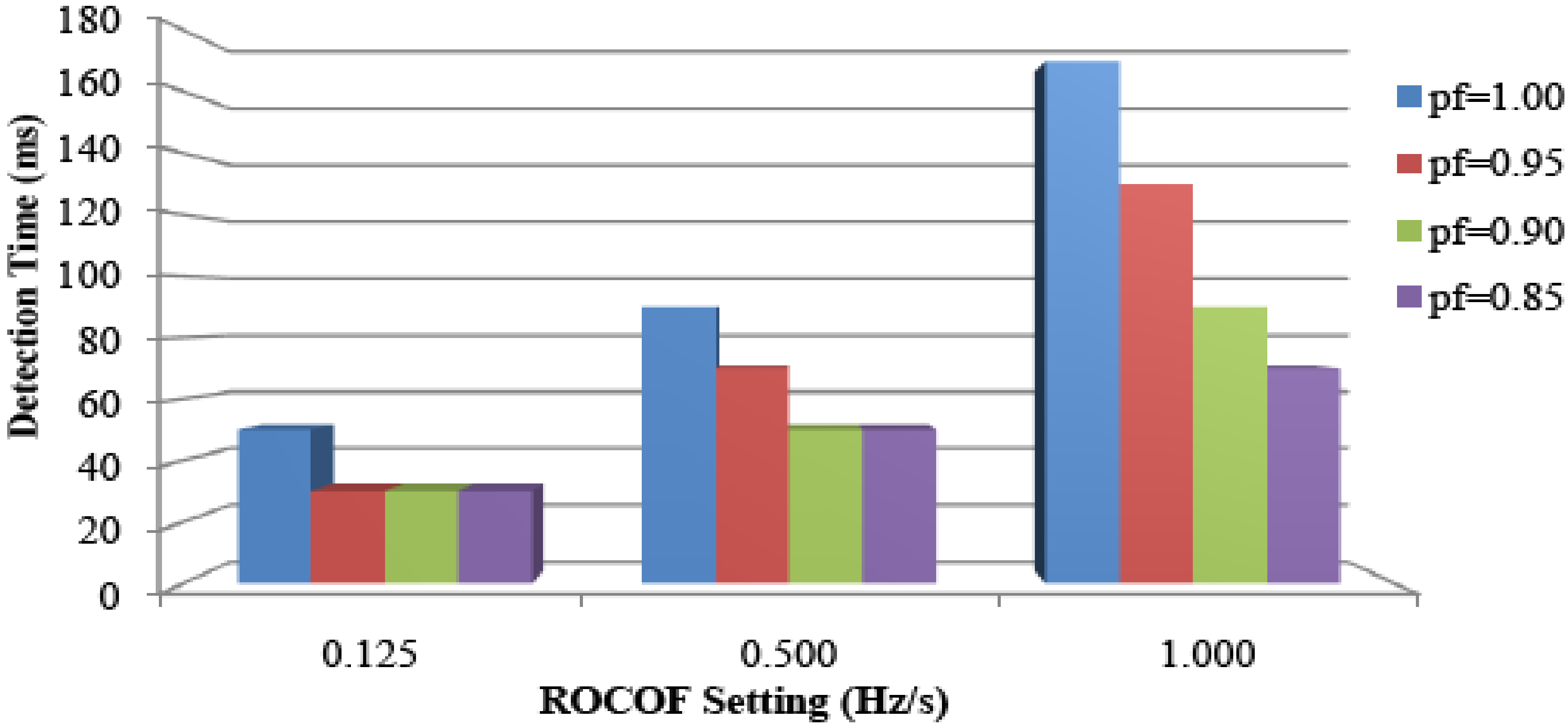
A ROCOF relay with a typical "maximum" setting of 1Hz/s failed to detect LOM when H of DG is high (3.0s)

Recommended setting in GB is 0.125Hz/s, in N.Ireland is 0.45 - 0.5Hz/s

Effect of voltage dependant loads on ROCOF LOM detection (insensitive setting of 1Hz/s)



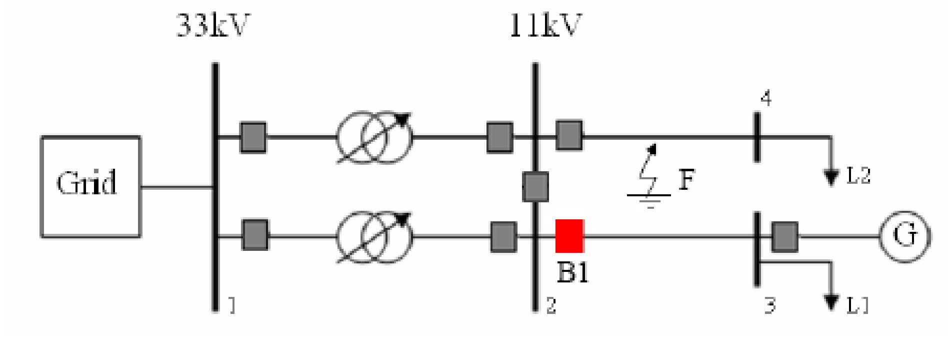
Impact of load power factor on ROCOF LOM detection

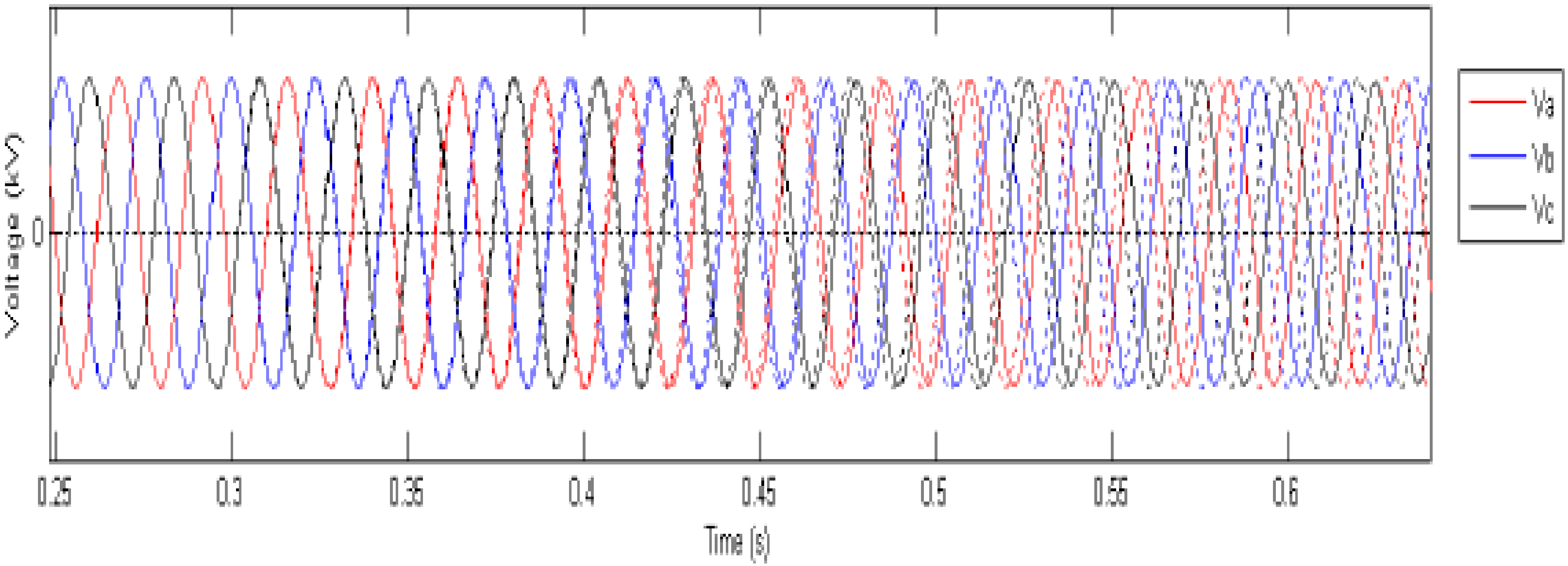


Load power factor changes the voltage profile and affects the dynamic behaviour of a voltage dependent load

The smaller the load power factor the greater the voltage reduction at instant of islanding

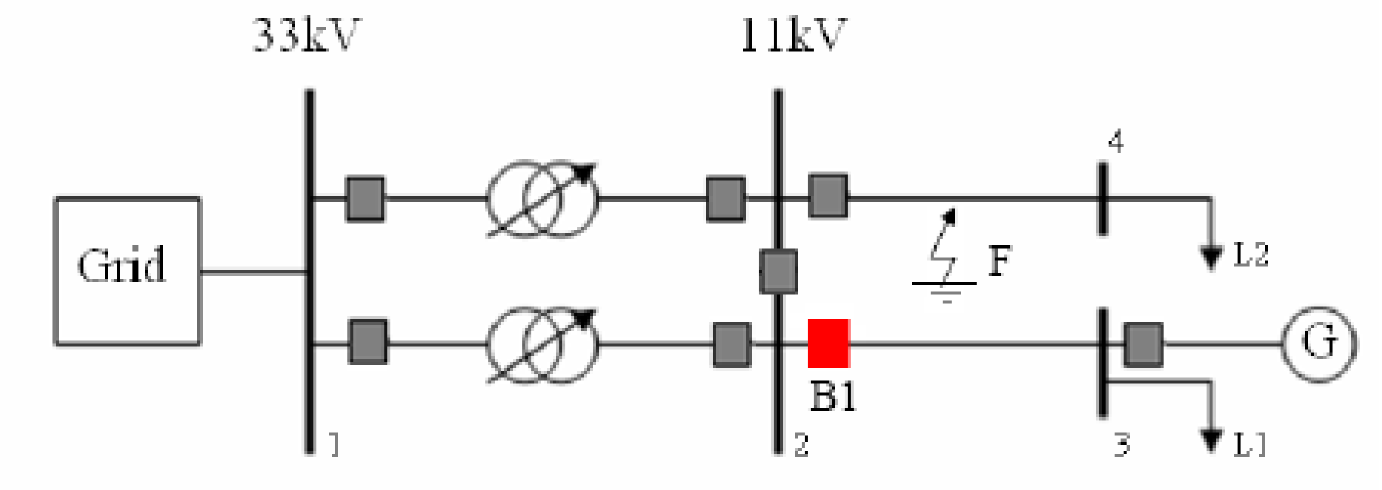
Impact on ROCOF of islanding and system disturbances





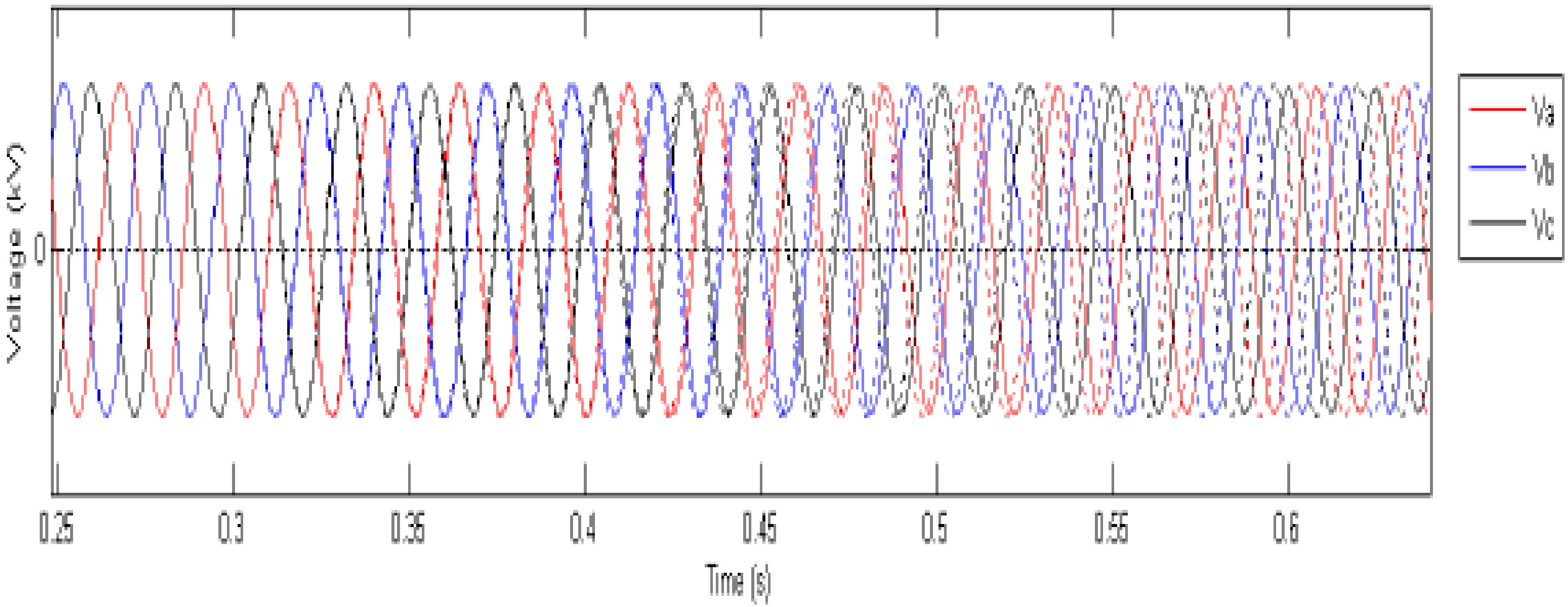
Impact on ROCOF of islanding and system disturbances

Network model used in simulation studies:



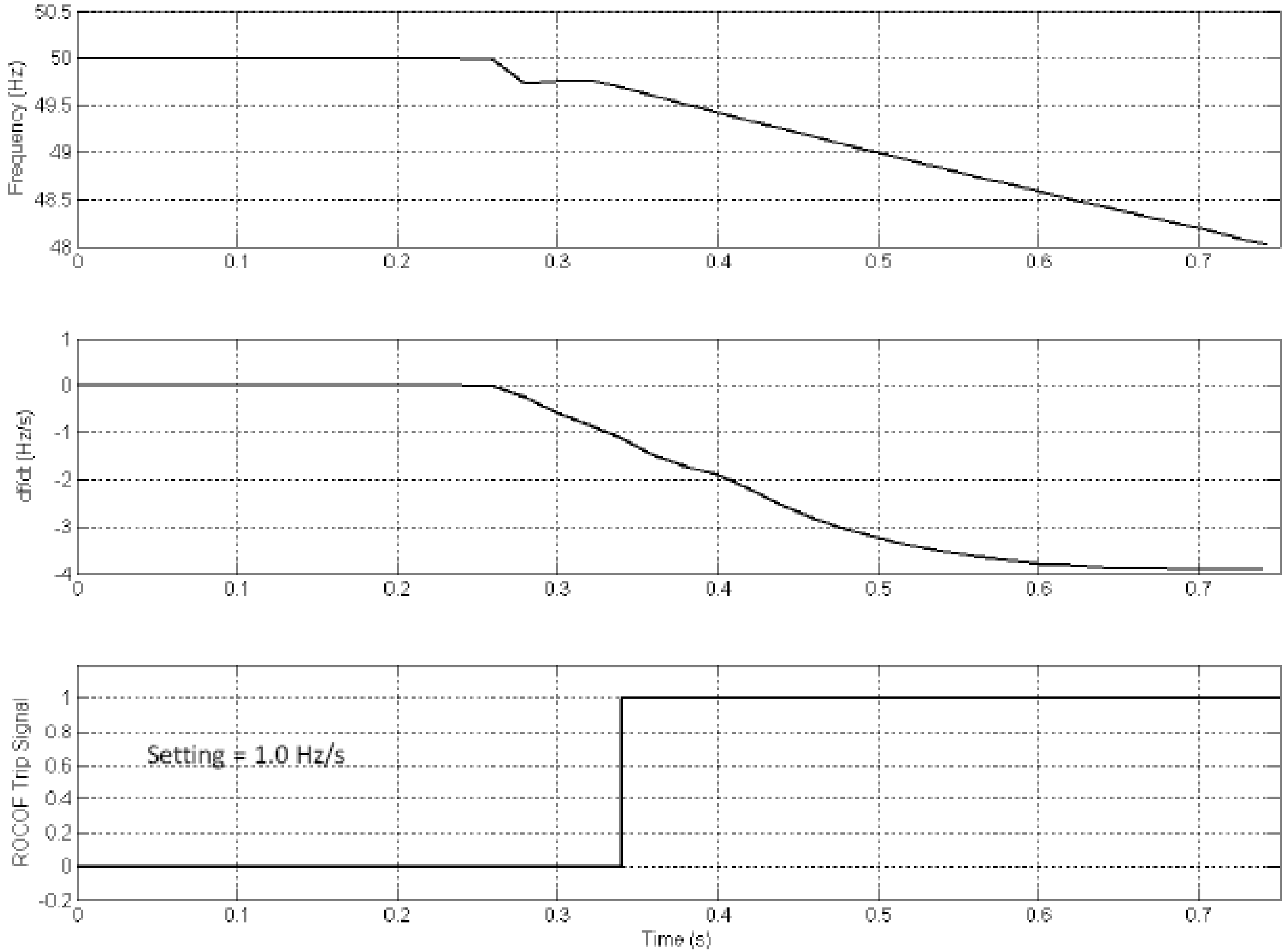
Case 1:- islanding with 0.2pu power imbalance; B1 opened at 0.25s.
Case 2:- islanding when load and generation are closely matched
Case 3:- network disturbance, effect of switching action on ROCOF
Case 4:- impact on ROCOF relay of network fault conditions

Case 1: islanding with 0.2pu power imbalance; B1 opened at 0.25s

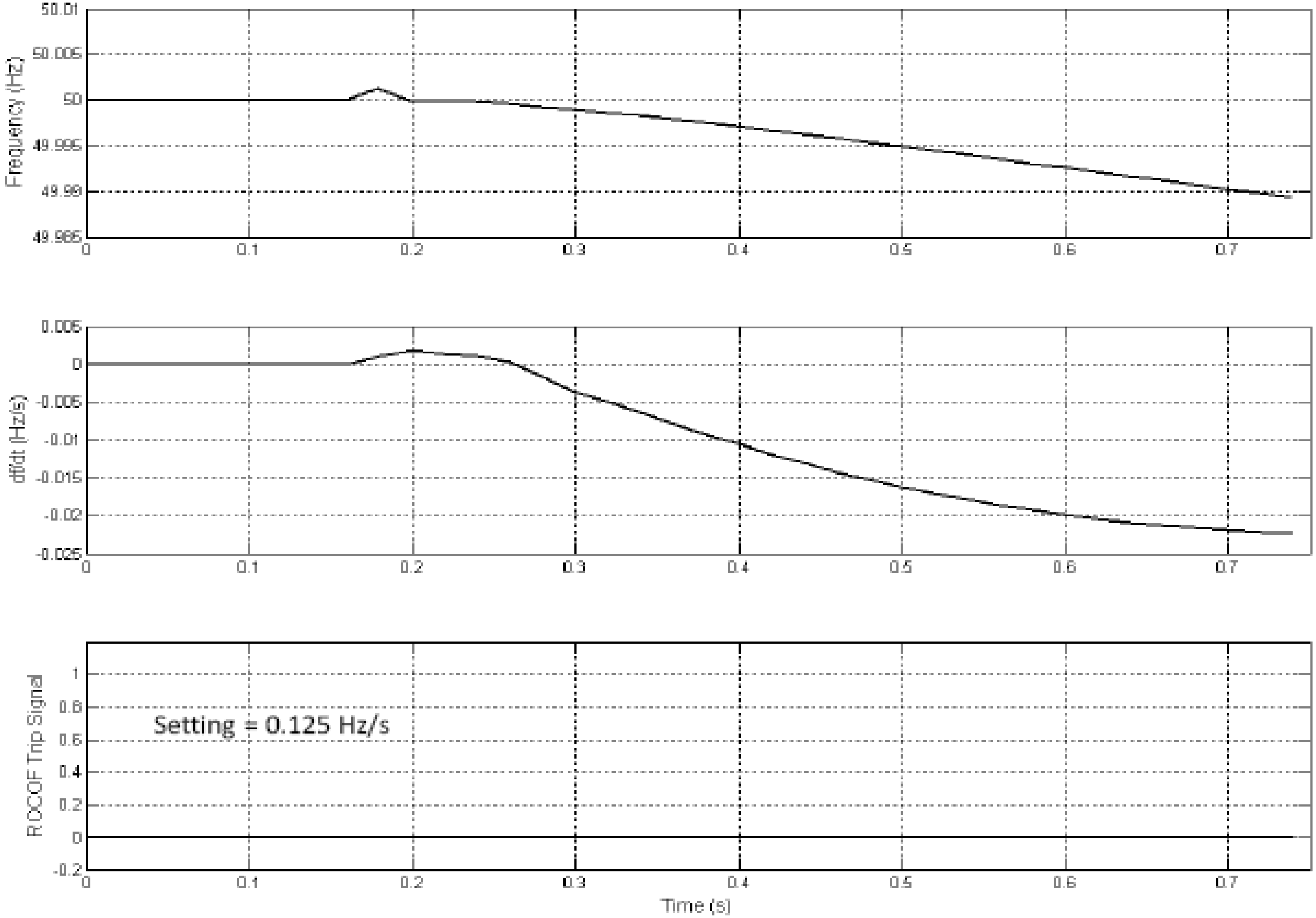


Immediately after islanding, voltage decreases and frequency starts to reduce (dotted lines represent voltages if islanding had not occurred).

Case 1: response of ROCOF relay to islanding with 0.2pu power imbalance; B1 opened at 0.25s (relay setting = 1.0Hz/s)

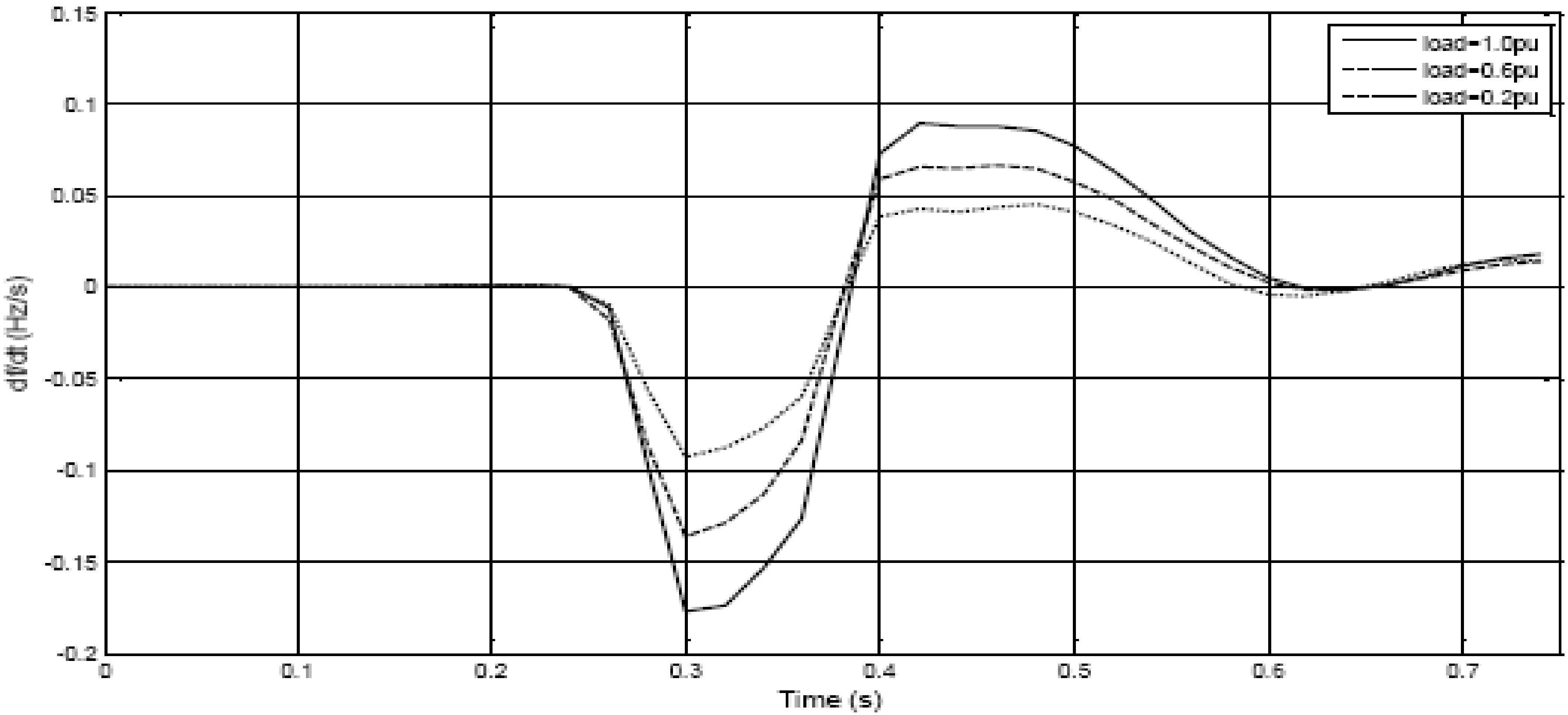


Case 2: islanding when load and generation are closely matched



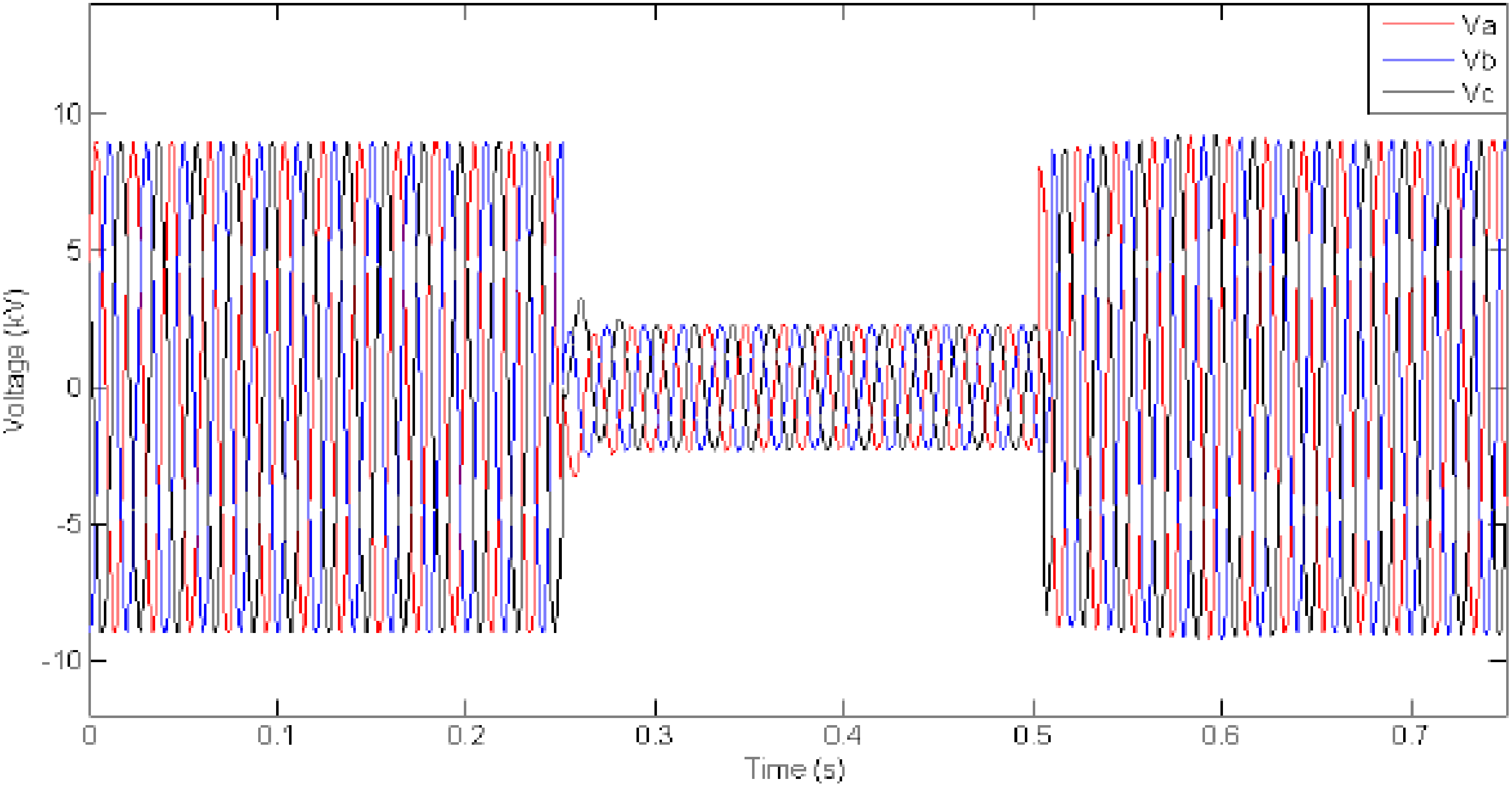
Frequency deviation is very small, hence
ROCOF relay, set at 0.125Hz/s, failed to detect islanding

Case 3: Network disturbance, effect of switching action on ROCOF relay (LOM relay should not operate)

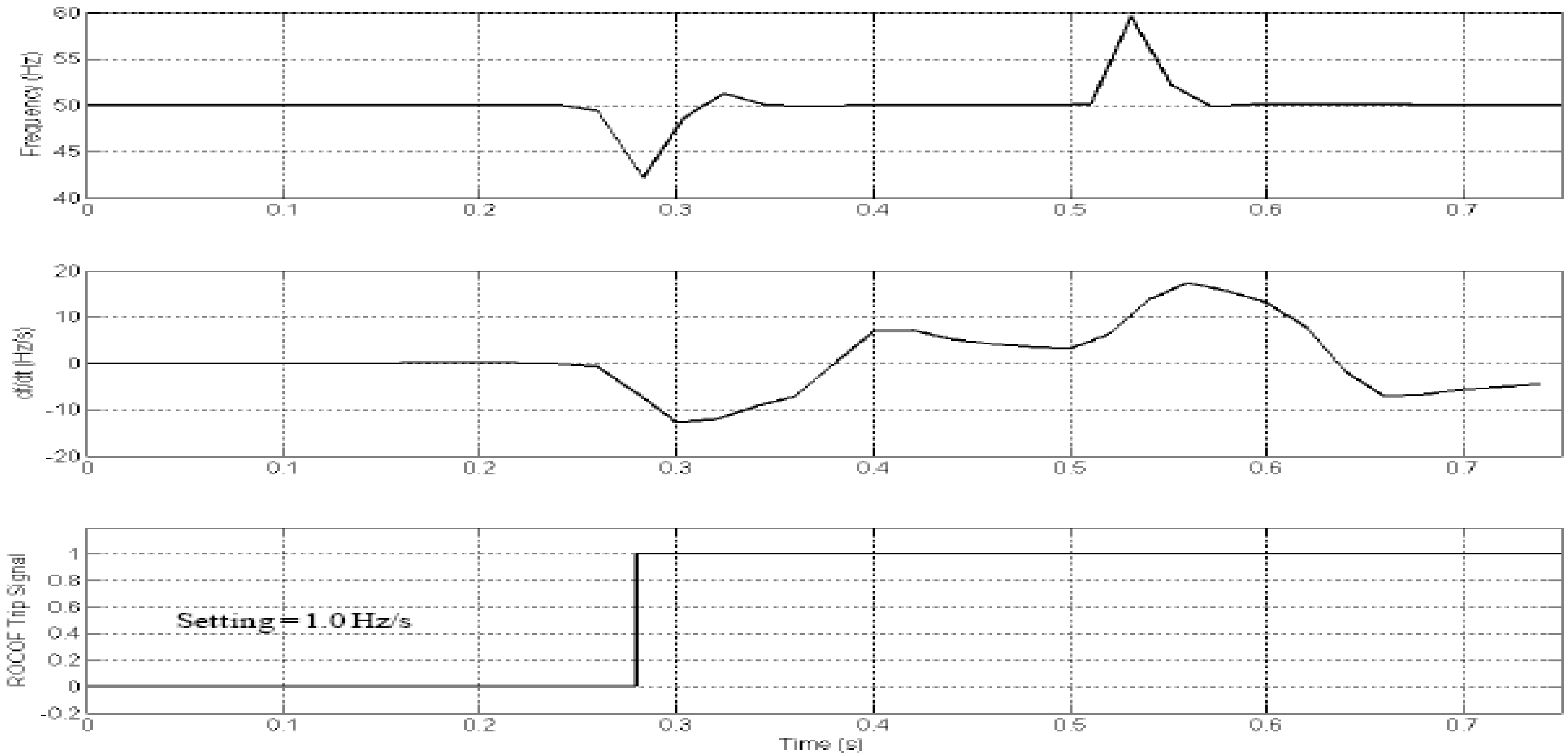


higher the DG's loading, greater the effect of switching on ROCOF
ROCOF relay set at 0.125Hz/s, incorrectly operated
ROCOF relay set at 0.2Hz/s, correctly remained stable

Case 4: ROCOF relay behaviour during network fault conditions. 3Φ fault on adjacent feeder 2-4, fault removed after 0.25s

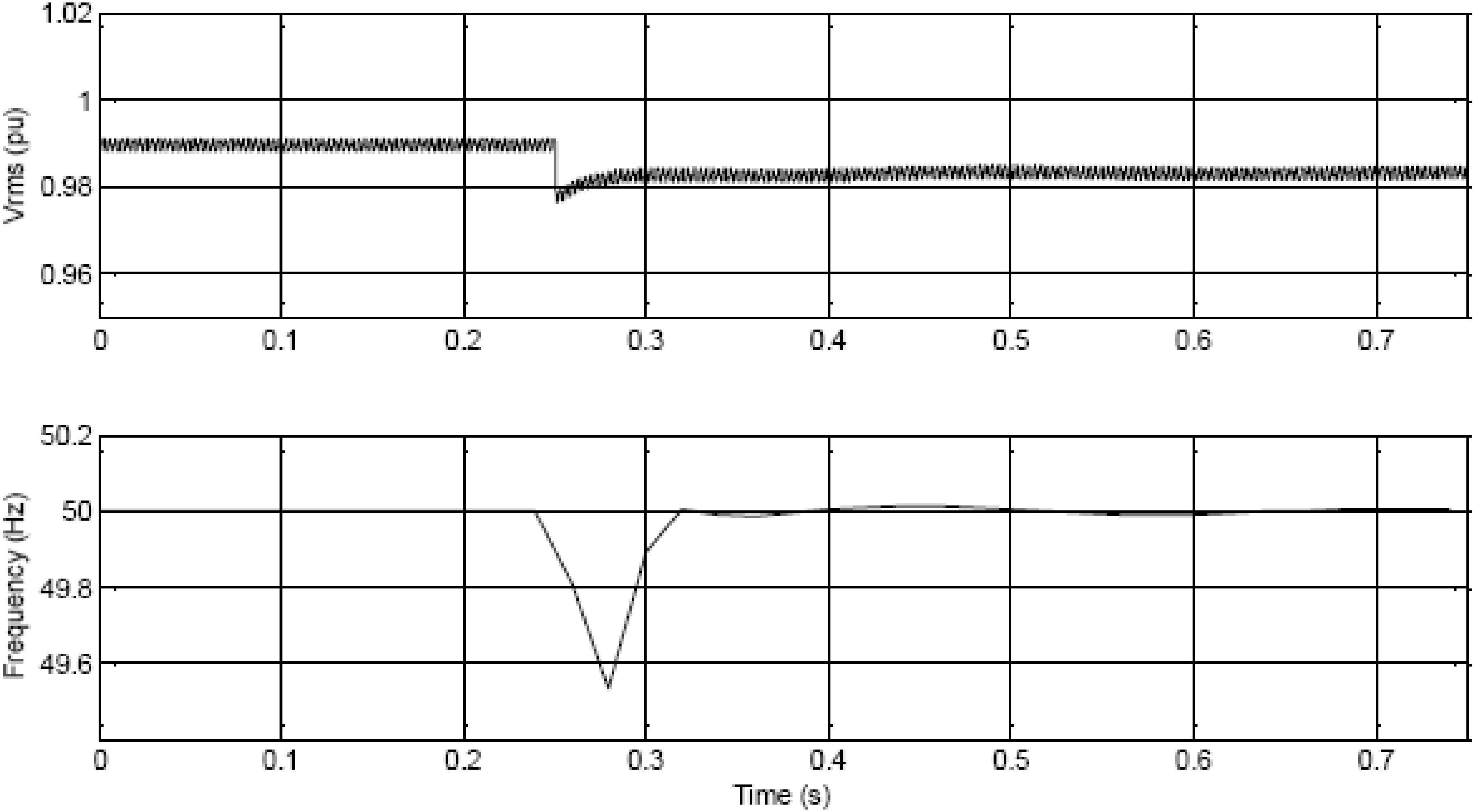


Case 4: ROCOF relay behaviour during network fault conditions. 3Φ fault on adjacent feeder 2-4, fault removed after 0.25s. ROCOF relay not expected to operate (not islanding event)



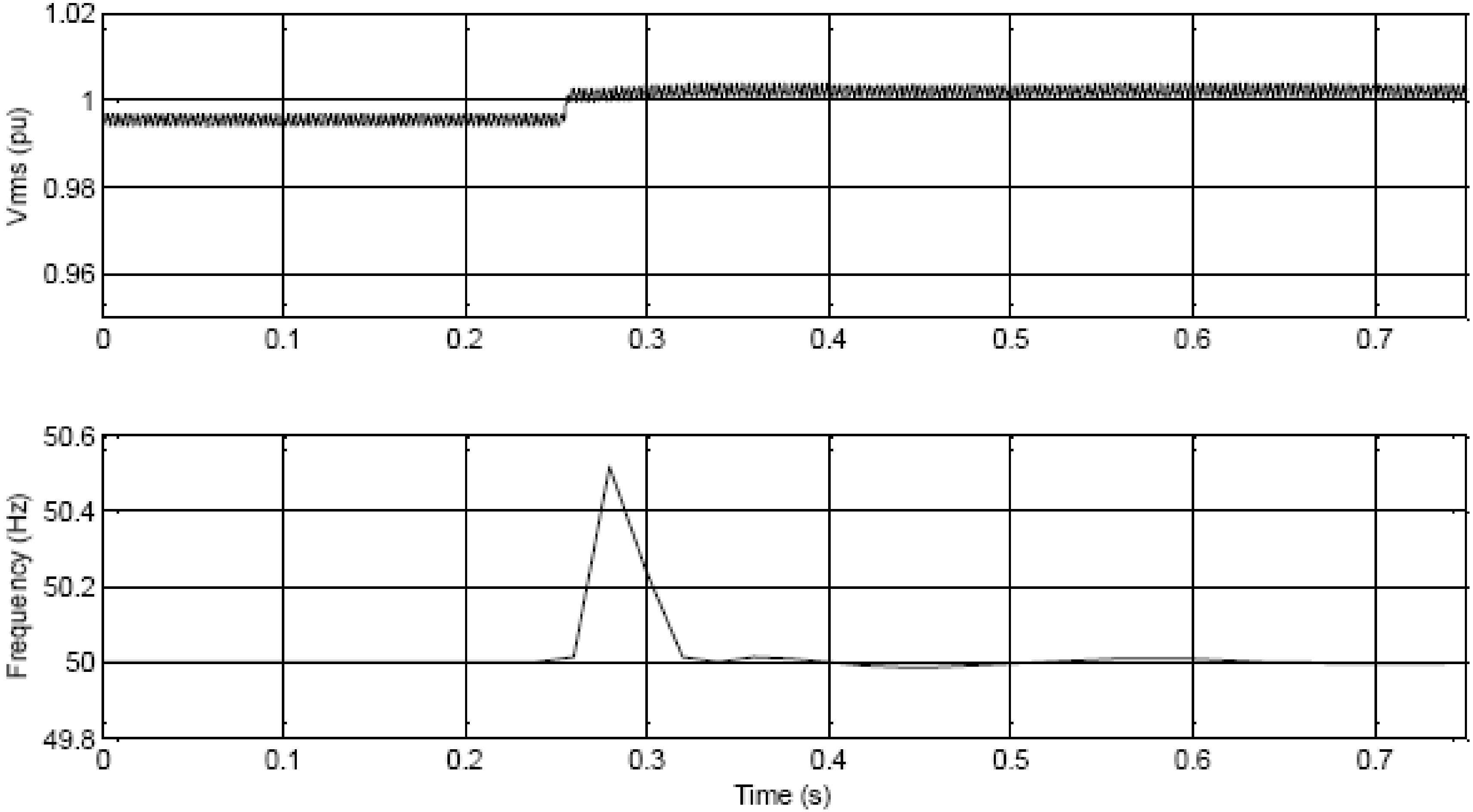
ROCOF relay with setting of 1Hz/s incorrectly operated.
Relay failed to distinguish between islanding event and adjacent feeder fault

Case 5: Switching on a 10MW/phase load at DG terminals



ROCOF relay incorrectly operates if setting < 0.9Hz/s

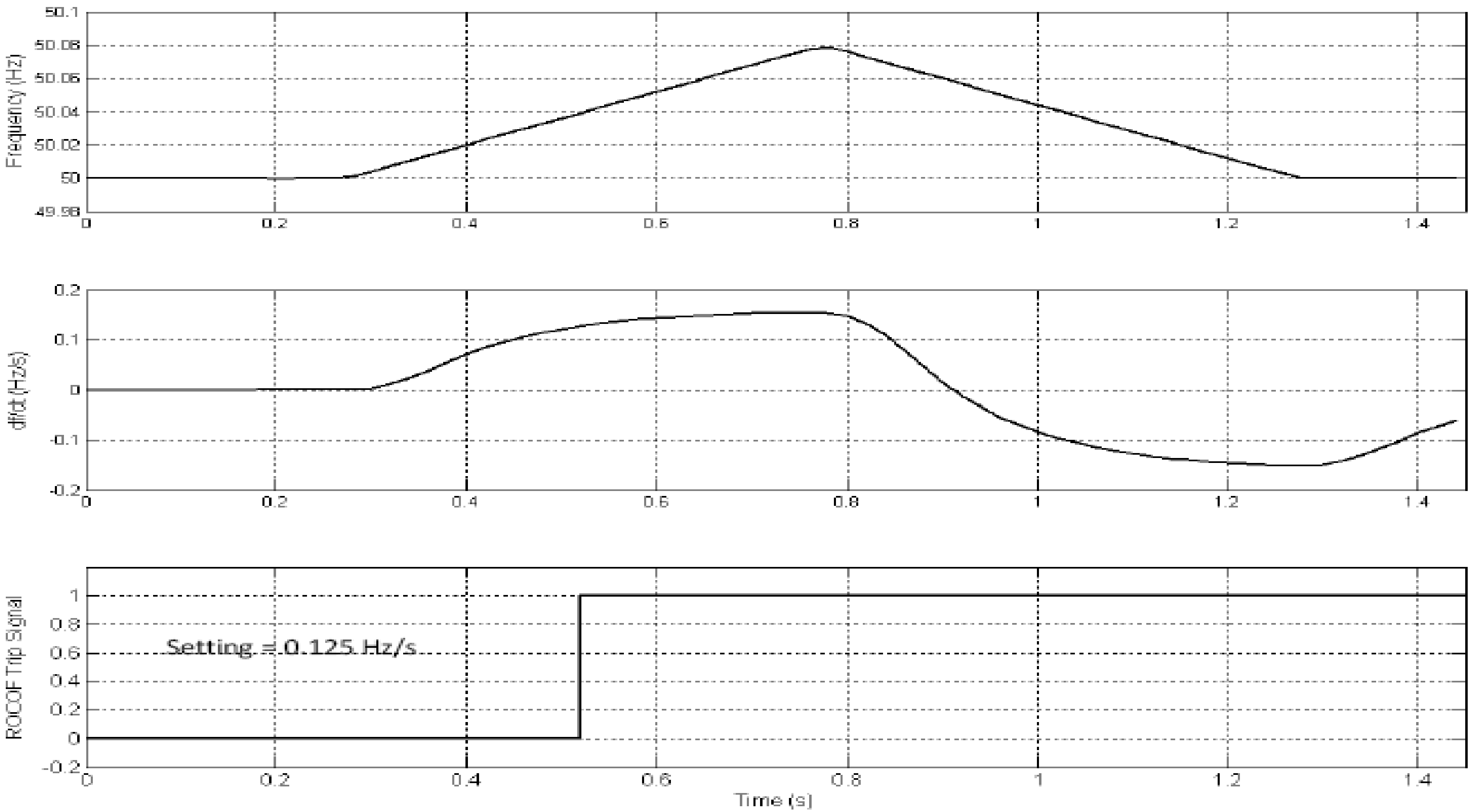
Case 5: Switching off a 10MW/phase load at DG terminals



ROCOF relay incorrectly operates if setting < 0.9Hz/s

Case 6: Impact of sudden loss of major generation infeed

to test ROCOF stability, test signal used with freq increase of 0.16 Hz/s for 0.5s and then decreases at 0.16Hz/s for 0.5s.



Summary:- Operating performance of ROCOF relays

- Relay not capable of detecting LOM when load and generation in island are approximately matched
- Relay very susceptible to nuisance tripping; to increase stability higher Hz/s setting value required
- High setting value compromises relay dependability and increases non-detection zone

- To increase security of ROCOF relays, whilst attempting to preserve dependability, various solutions are proposed:
  - time delays of 50 – 500ms used to reduce number of nuisance trips
  - time delays = monitoring of rate of change of frequency over few cycles
  - increasing duration of measuring window over which ROCOF calculated
  - measuring windows = 40ms (2 cycles) to 2s (100cycles at 50Hz)
  - Under-voltage interlock; block ROCOF if DG terminal voltage <0.8pu
- Difficult to completely prevent mal-operation of ROCOF during disturbance or non-islanding event
- Setting value must balance security and dependability

Future challenges

- Existing status
  - *very low levels of distributed generation*
  - *not considered in existing "passive" distribution network design*
  - *assumed to be of no importance in stability and reliability of overall system*
- Short term projections
  - *increased levels of distributed generation (20% by 2010 ?)*
  - *needs "active" distribution networks*
  - *power electronics for generator interfaces & power quality enhancement*
  - *requires safe, effective and economic protection and control*
- Long term projections
  - *UK:- 60% reduction in CO2 emissions by 2050*
  - *micro-grids:- independent cells of dispersed generation*
  - *power grid interconnects pseudo-autonomous micro-grids*
  - *how to ensure stability and reliability of "loose" network ?*