

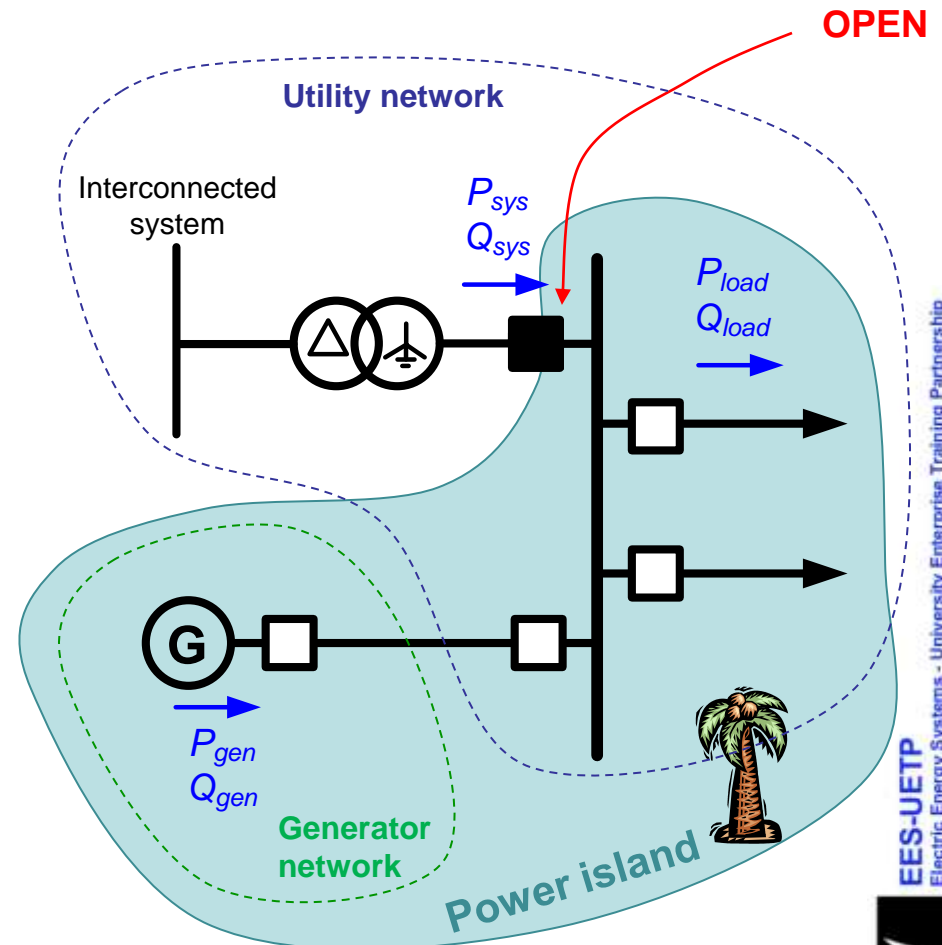
**Protection of Future Networks with Distributed
Generation**

Loss of Mains Protection

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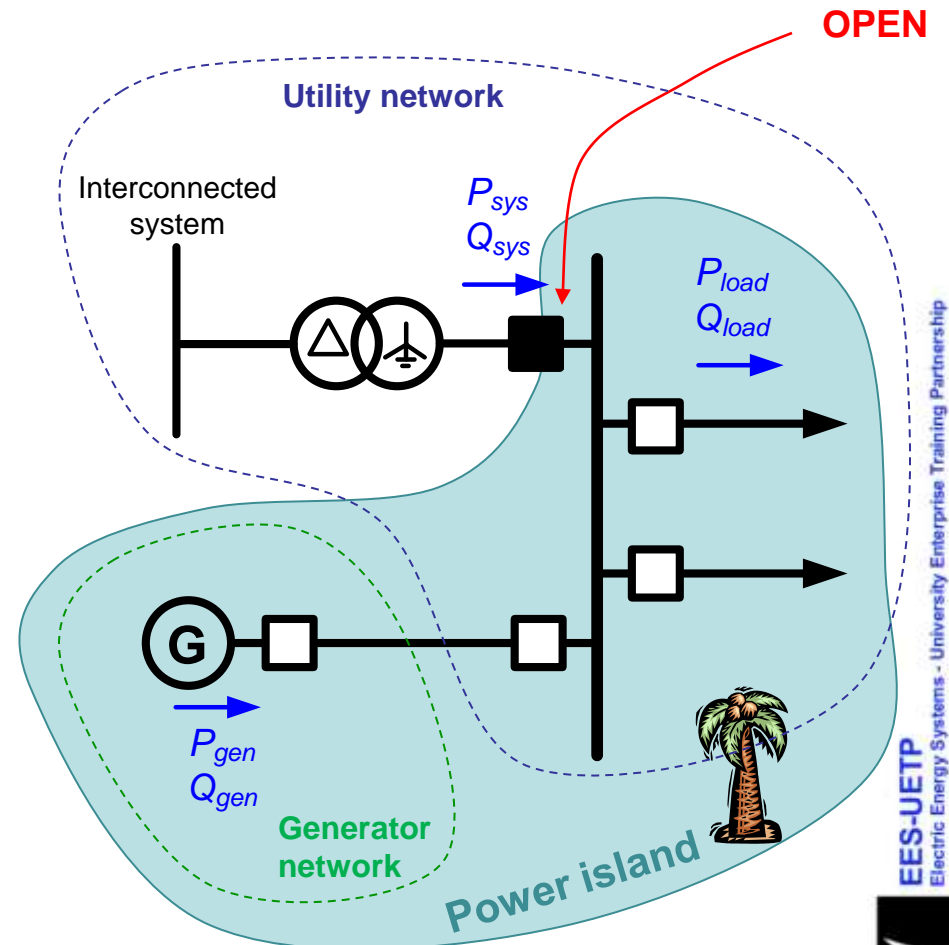
Loss-Of-Mains – LOM

- 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, then the generator could remain connected, causing a safety hazard within the network.
- Automatic reconnection of the generator to the network may occur causing damage to the generator and the network.
- **Islanding is not permitted in most countries.**



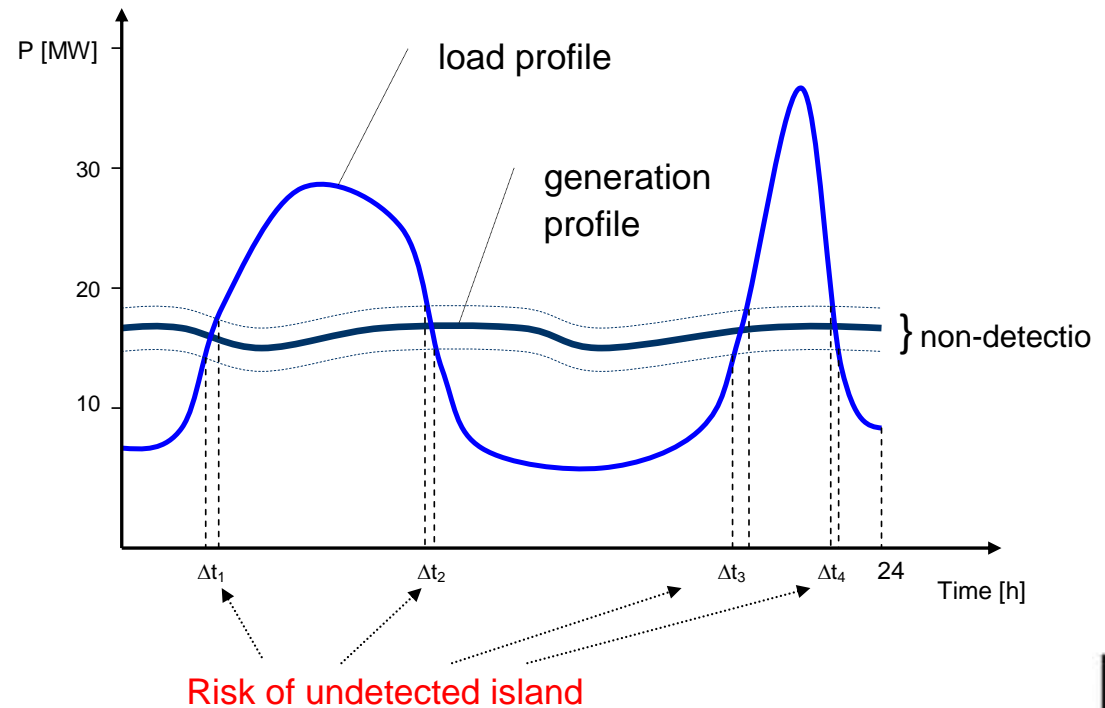
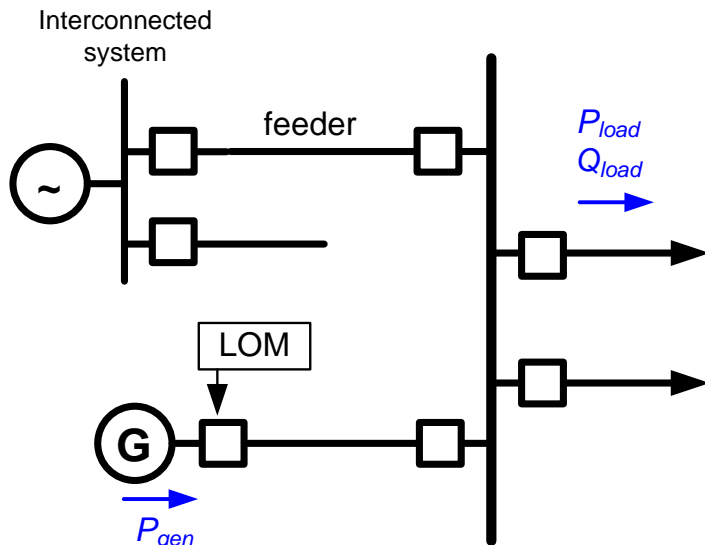
Loss-Of-Mains – LOM

- Operating in islanded mode:
 - **Unearthed?**
 - **Unsynchronised reclose?**
 - **Live when utility personnel believe not energised?**
 - **Faults in islanded mode may remain undetected**



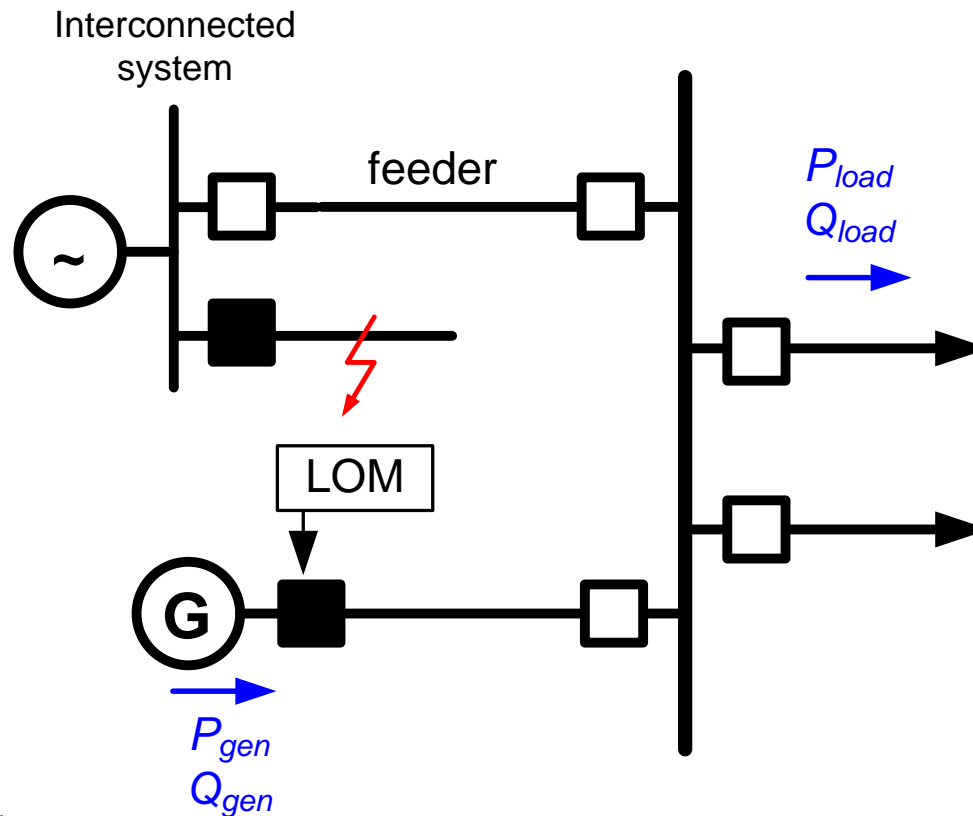
LOM performance requirements - sensitivity

- 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

- LOM should be stable under remote faults cleared by the utility system.
- It is undesirable to issue a false trip as it leads to the unnecessary disconnection of the generator.



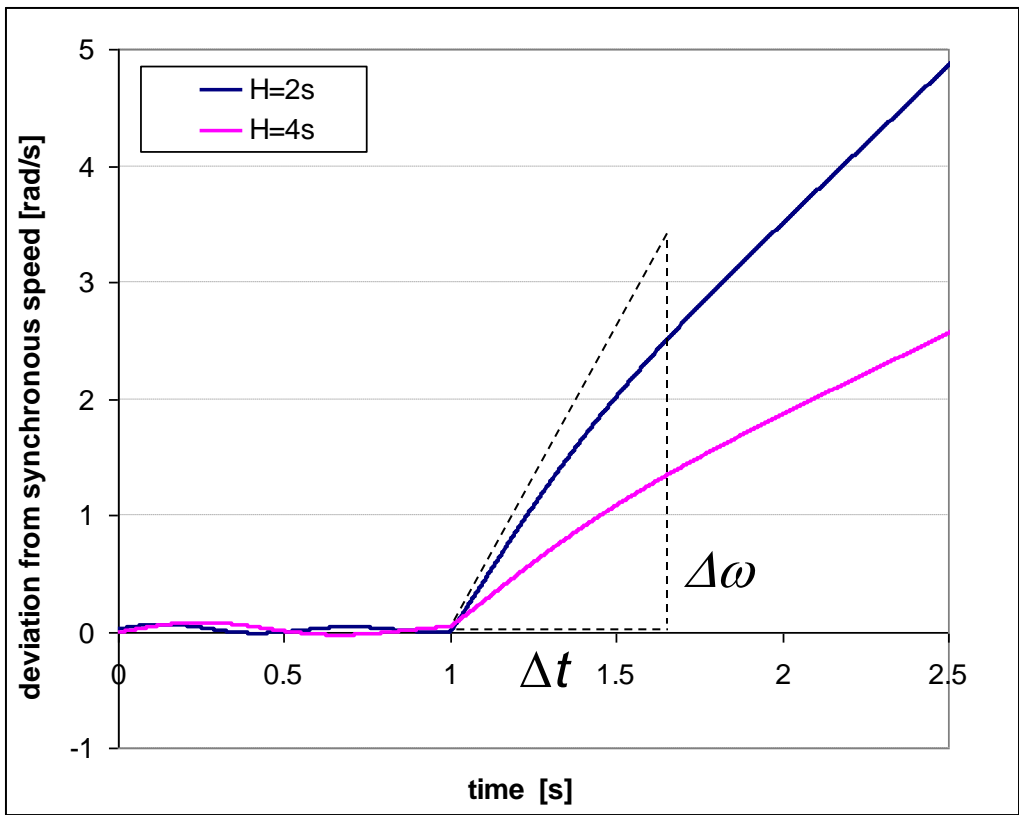
Generator performance during islanding

- Simplified rotor swing equation in SI units:

$$J \frac{d\omega_r}{dt} = T_m - T_e$$

where:

- J – inertia constant [kg m²]
- ω_r – rotor speed [rad/s]
- T_m – mechanical torque [N m]
- T_e – electromagnetic torque [N]



$$H = \frac{\text{kinetic energy at synchronous speed}}{\text{machine nominal power}} = \frac{\frac{1}{2} J \omega_{r0}^2}{S_n}$$

H – inertia constant [s]

Generator performance during islanding

- Taking into account that $\omega_r = 2\pi f_r$ and $f_r = \frac{f}{p}$ initial rate of change of frequency during islanding can be calculated as follows:

$$(1) \quad J \frac{d\omega_r}{dt} = \Delta T \qquad (2) \quad H = \frac{\frac{1}{2} J \omega_{r0}^2}{S_n} \Rightarrow J = \frac{2 \cdot H \cdot S_n}{\omega_{r0}^2}$$

$$(3) \quad \frac{2 \cdot H \cdot S_n}{\omega_{r0}^2} \frac{d\omega_r}{dt} = \frac{2 \cdot H \cdot S_n}{\omega_{r0}^2} 2\pi \frac{df_r}{dt} = \frac{2 \cdot H \cdot S_n}{\cancel{2\pi} \frac{f}{\cancel{p}} \omega_{r0}} \frac{\cancel{2\pi} df}{\cancel{p} dt} = \Delta T$$

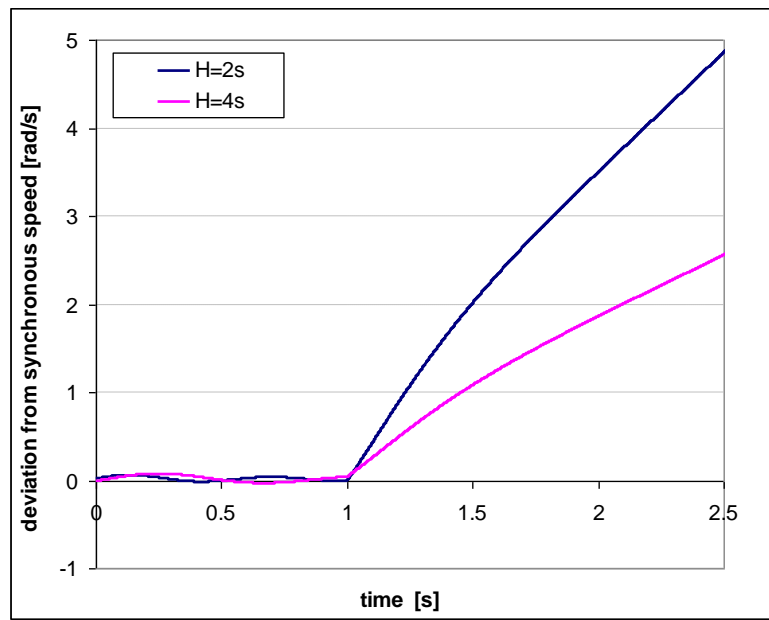
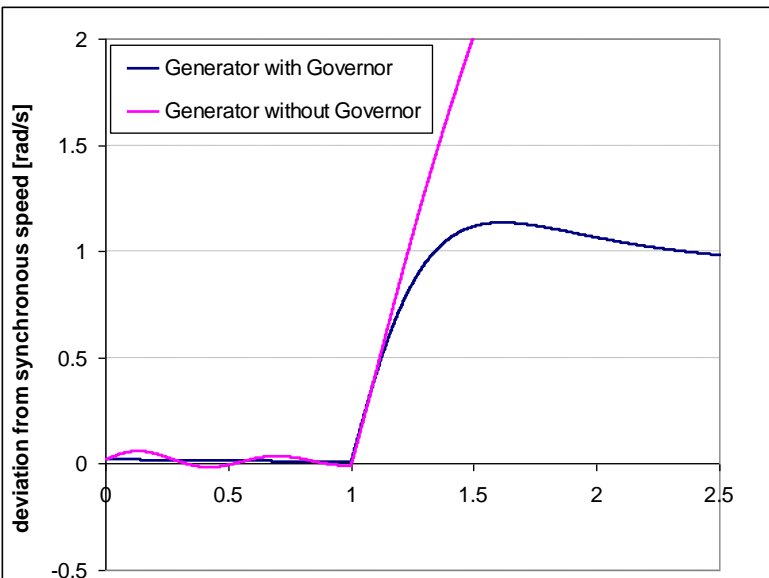
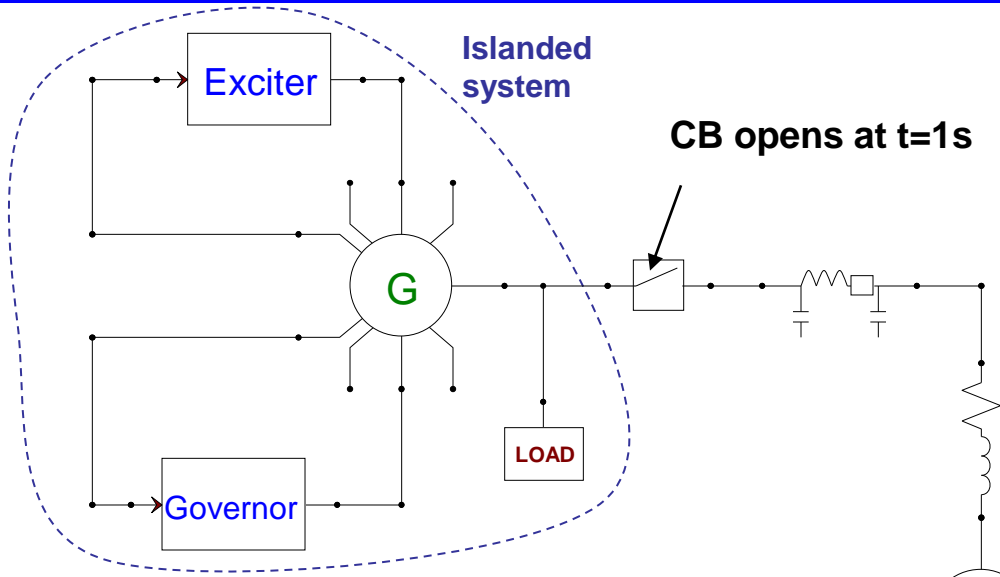
$$(4) \quad \frac{2 \cdot H \cdot S_n}{f} \frac{df}{dt} = \Delta T \omega_{r0} \Rightarrow \frac{2 \cdot H \cdot S_n}{f} \frac{df}{dt} = \Delta P$$

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



Generator performance during islanding

- Governor influences the dynamic performance during the islanding event
- In the first 100-200ms the impact can normally be neglected.



LOM detection methods

- Rate-Of-Change-Of-Frequency (ROCOF)
- Voltage Vector Shift (VS)
- Reverse VAR method
- Direct Intertrip
- Rate of Change of Power
- Active methods



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]

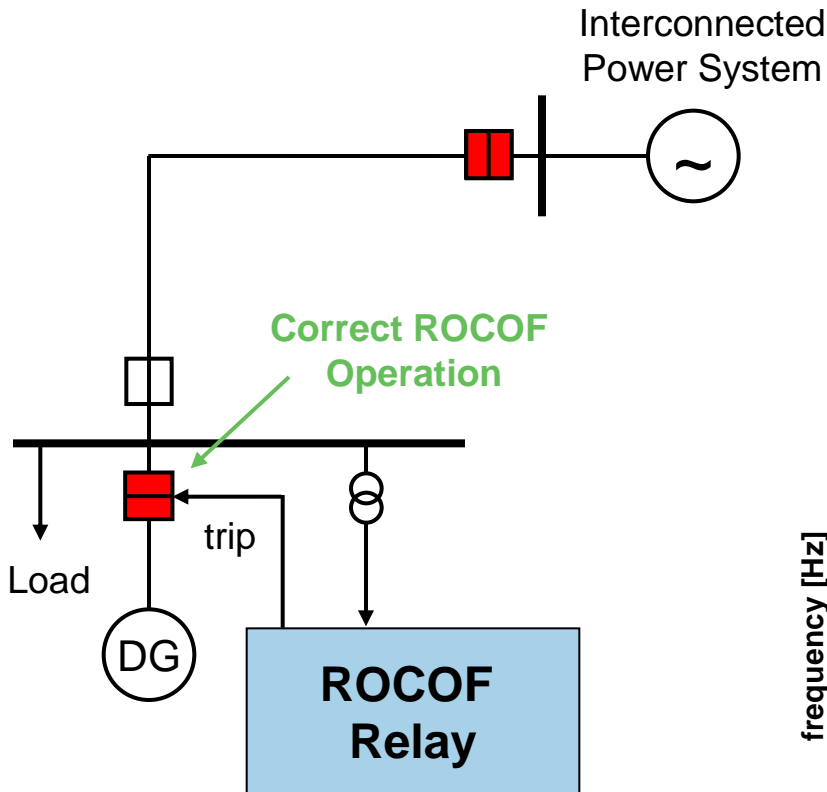
S_n – nominal generator rating [MVA]

f – generator rated frequency [Hz]

H – inertia constant of the generator [s]

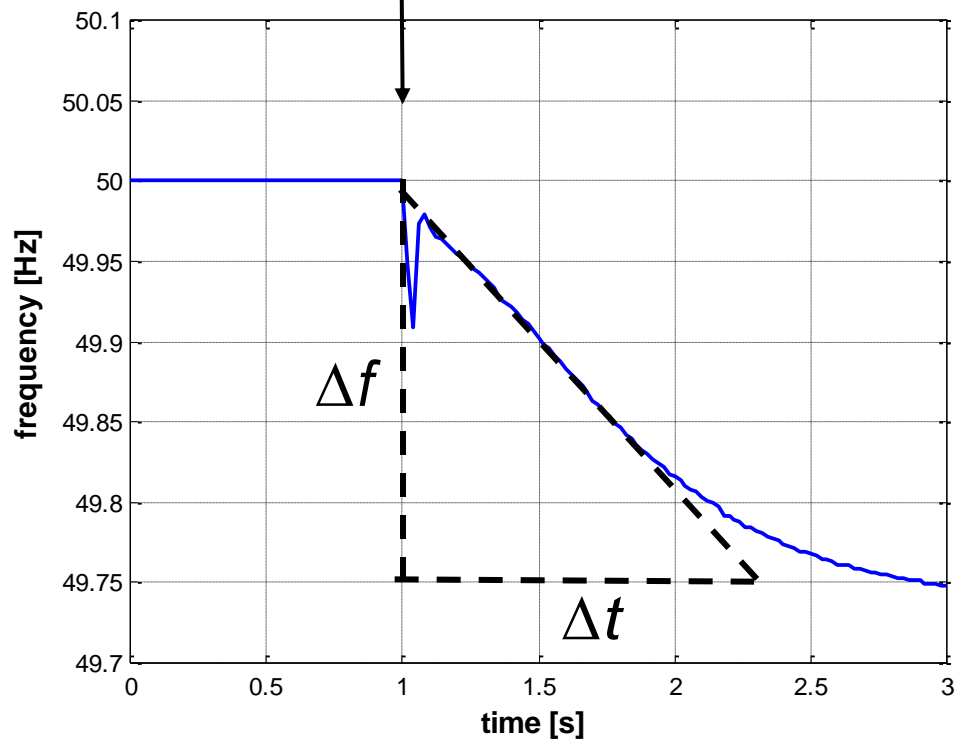


ROCOF sensitivity

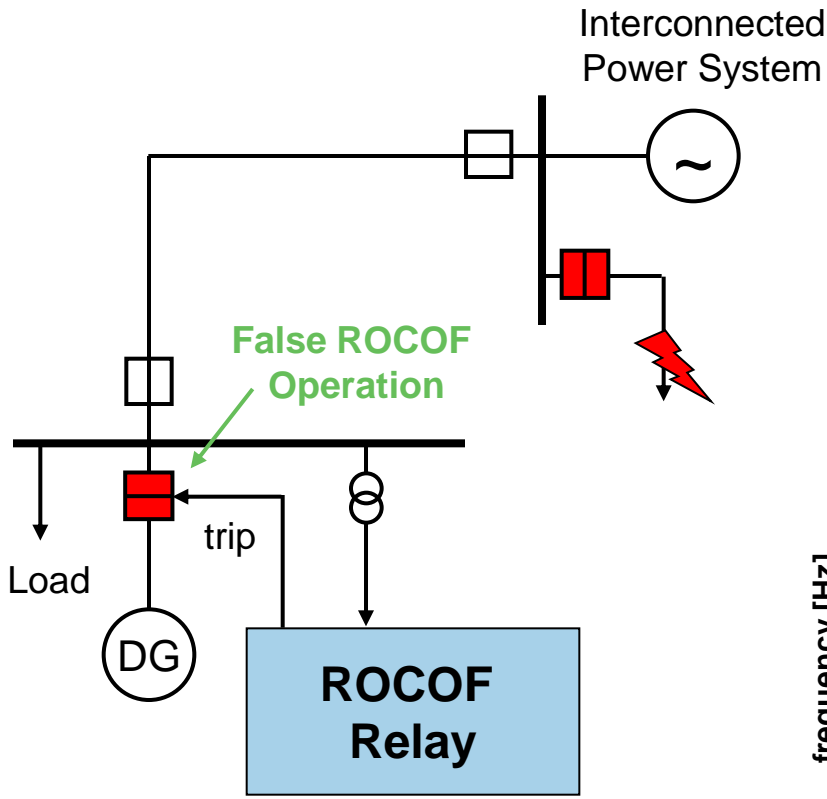


$$ROCOF = \frac{\Delta f}{\Delta t}$$

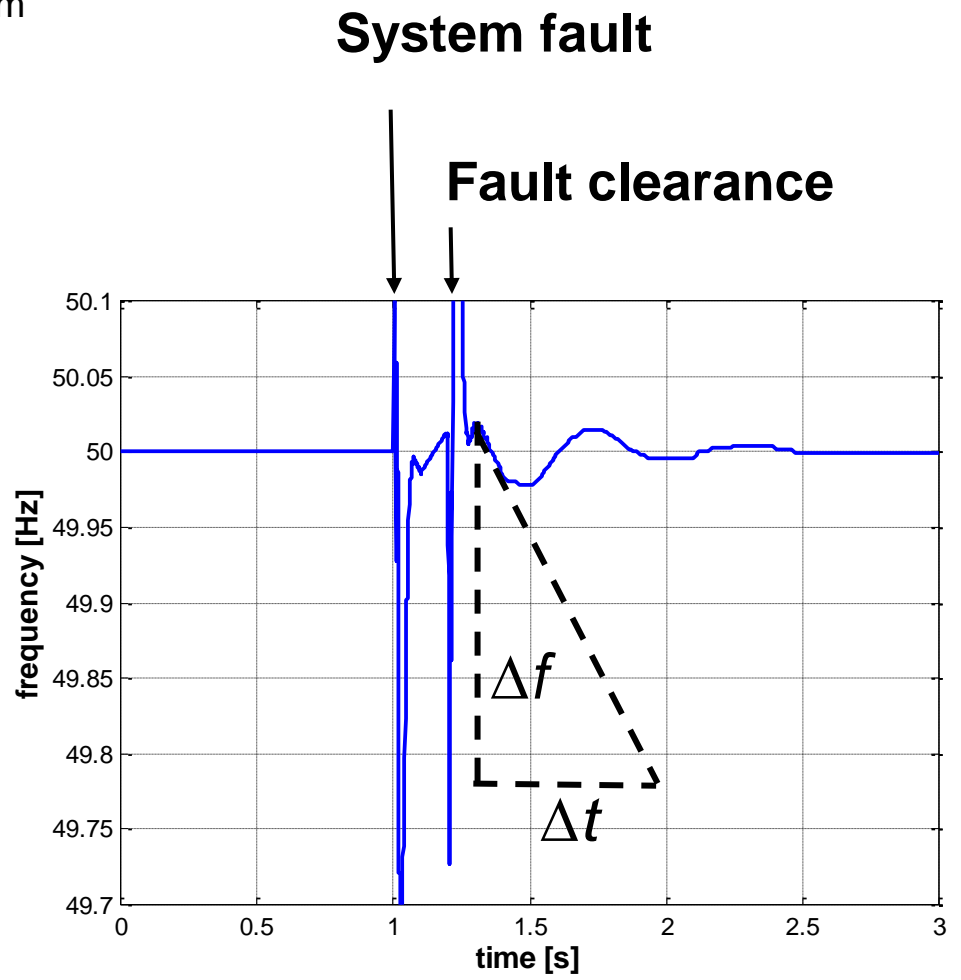
Loss of grid connection



ROCOF stability



$$ROCOF = \frac{\Delta f}{\Delta t}$$



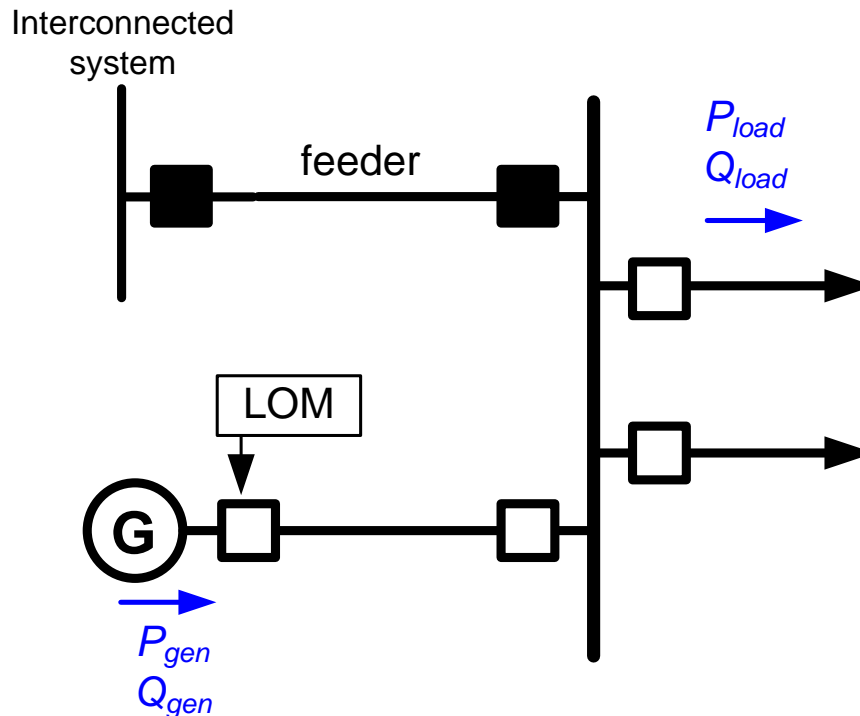
ROCOF – summary

- ROCOF method is based on the local measurement of the system frequency at the generator terminals.
- ROCOF does not require communication
- It generally provides a good sensitivity to genuine islanding events but has a small non-detection zone
- ROCOF can suffer from unwanted (spurious) operations during remote system faults.



Example

30MVA Distributed Generator with a rotor inertia of $J = 1285 \text{ kg m}^2$ is protected by ROCOF LOM protection set to 0.4 Hz/s . Due to tripping of the feeder protection the generator has become islanded. Will the ROCOF relay operate if the local load prior to islanding was $P_{load} = 20 \text{ MW}$ and the generator output was $P_{gen} = 22 \text{ MW}$? Assume the generator has one pole pair.



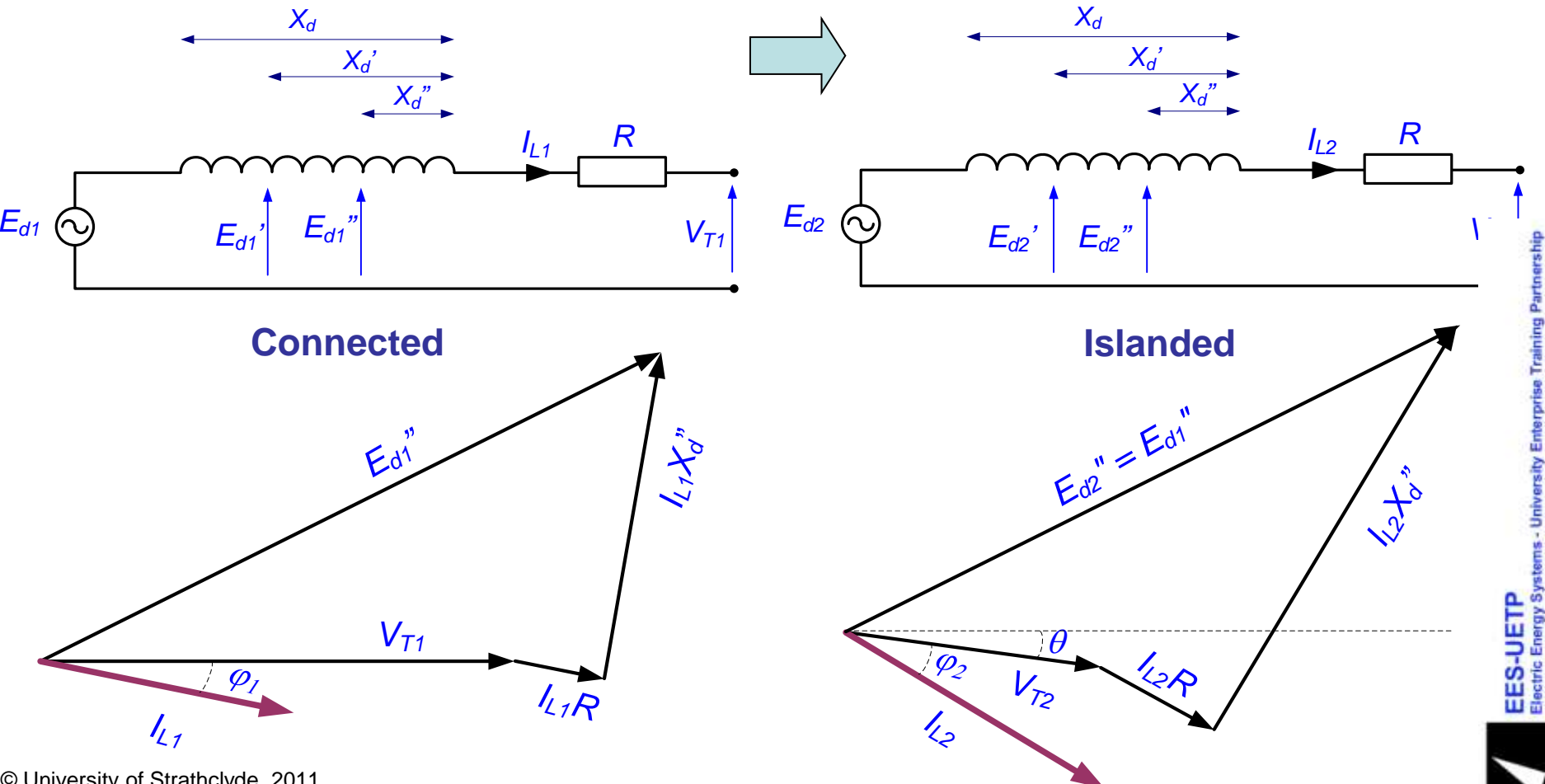
Voltage Vector Shift (VS) LOM Method

- 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 (recommended setting of 6° - 10° requires imbalance of more than $30\%S_n$ to cause operation)



Voltage Vector Shift (VS) LOM Method

- Generator terminal voltage angle changes by θ due to step change in load current and the generator reactance.

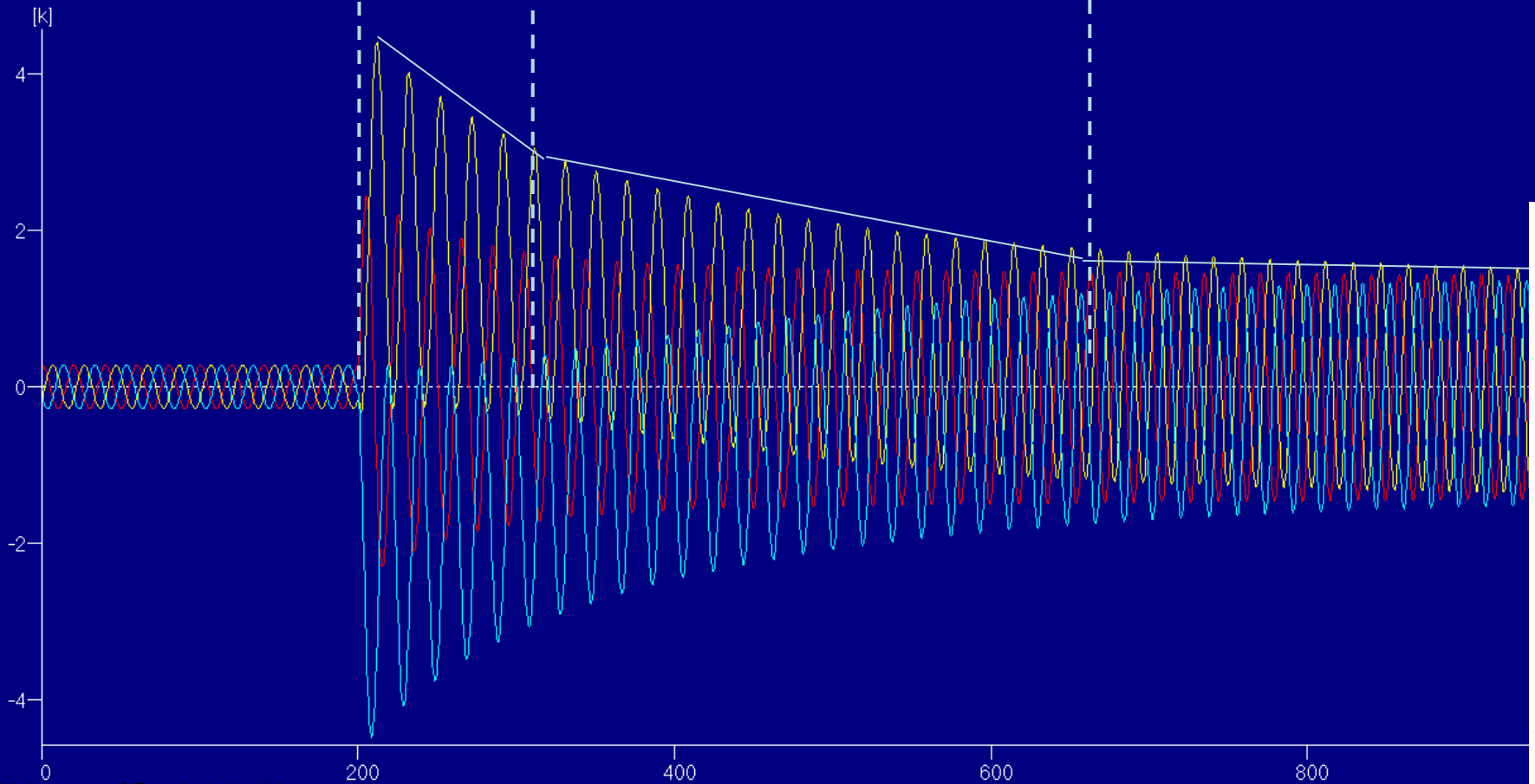


Typical fault current on a synchronous generator

Subtransient period

Transient period

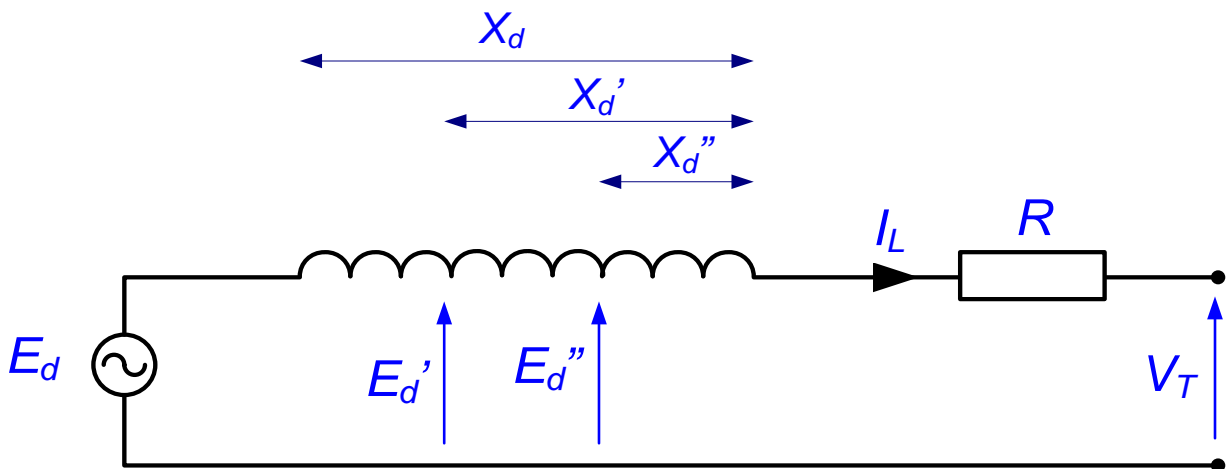
Steady-state period



Example

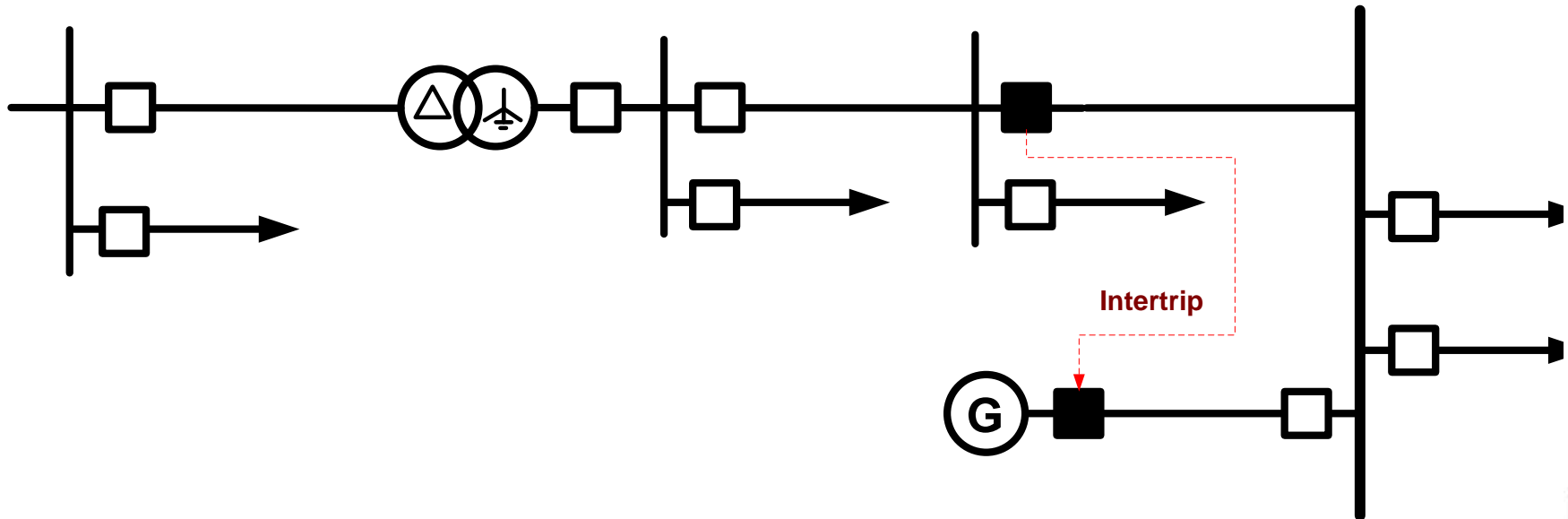
Vector Shift is used to protect a Distributed Generator. Calculate the voltage angle change if the generator output increased from 15MW to 25MW as a result of an LOM event. Before islanding, the generator operates at unity power factor $pf_1=1$ and after LOM the power factor changes to $pf_2=0.85$ (lagging) measured with respect to the original terminal voltage position. Assume that at the time of islanding the generator terminal voltage was $V_{T1} = 1\angle 0^\circ$ pu.

Generator: $S_n = 30 \text{ MVA}$ $V_n = 33 \text{ kV}$
 $X_d'' = 0.23 \text{ pu}$ $R_a = 0.05 \text{ pu}$



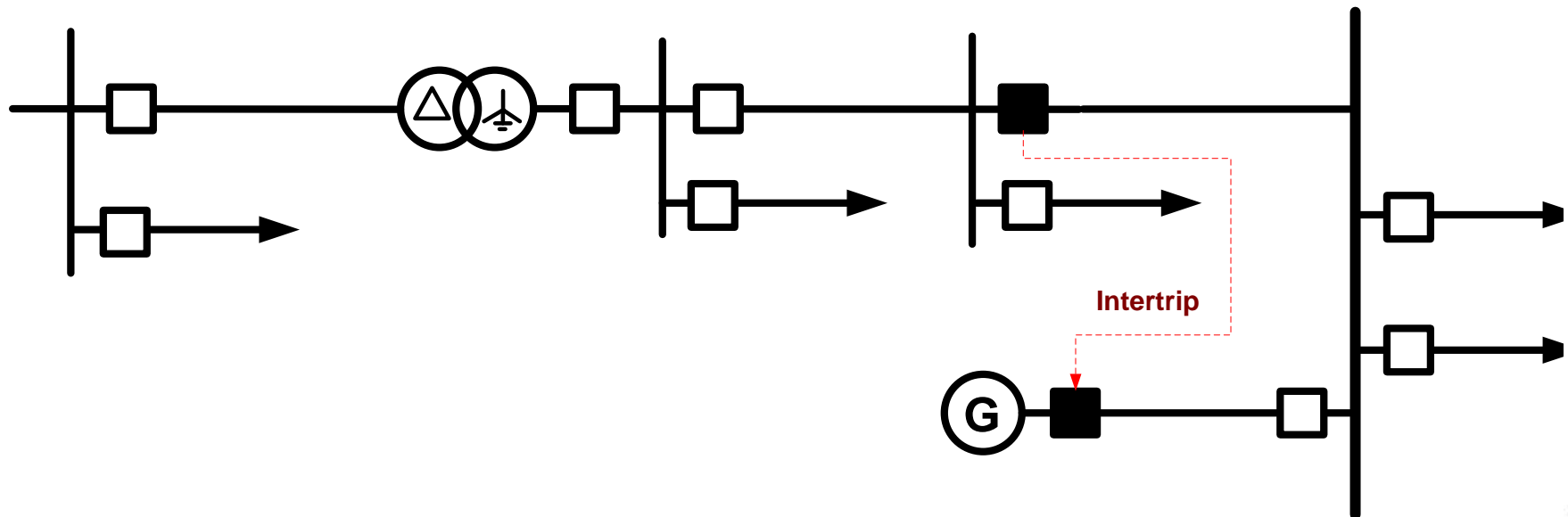
Direct Intertripping

- Intertripping scheme detects the opening of contacts at the point of disconnection and transmits the signal to all the generators that could potentially support the island.
- Intertripping scheme does not depend on any measurements.
- The operation is almost instantaneous.



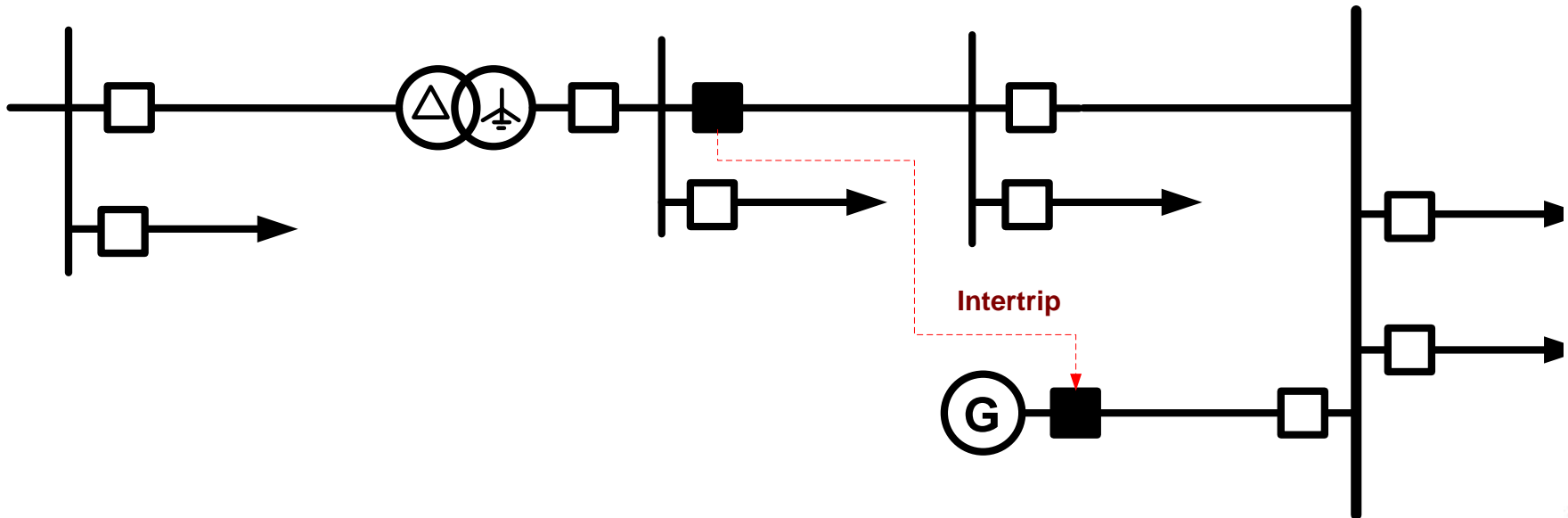
Direct Intertripping

- Intertripping must be transmitted from every point of disconnection where the viable island could be formed.
- Cost of intertripping is comparatively high (£15k-£100k).
- Communication media has to be reliable. Commonly used techniques include: leased land line, radio (10km), microwave (20km), PLC (100km), fibre optic cable (20-50km), copper cable (10km).



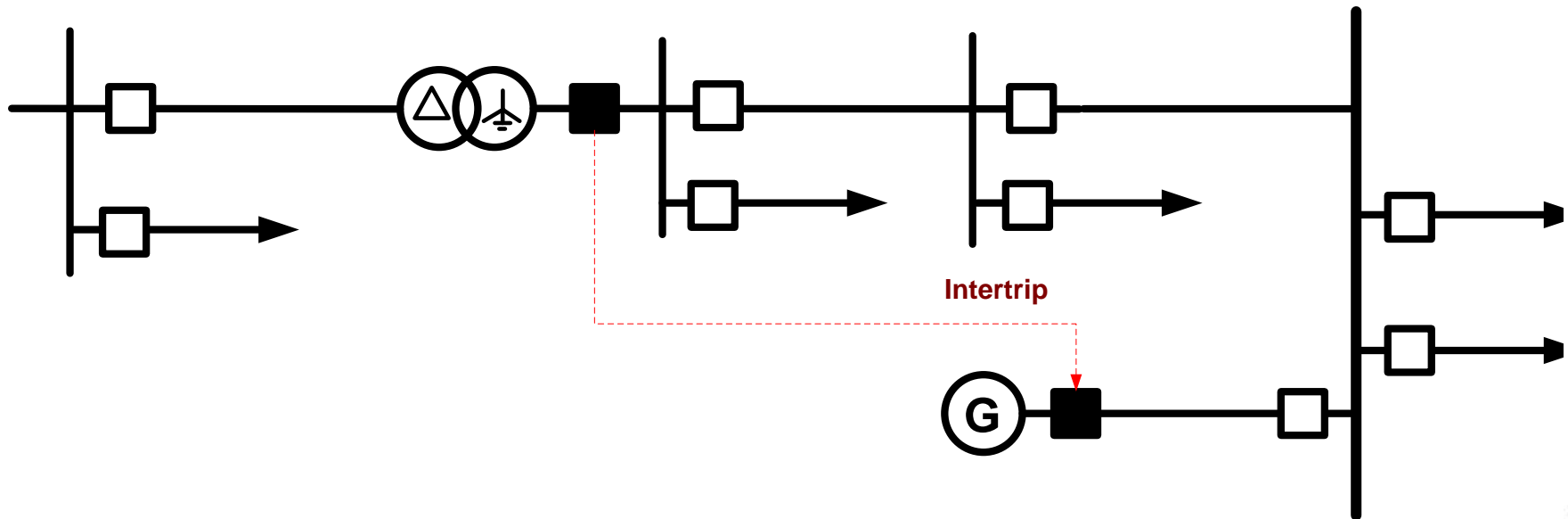
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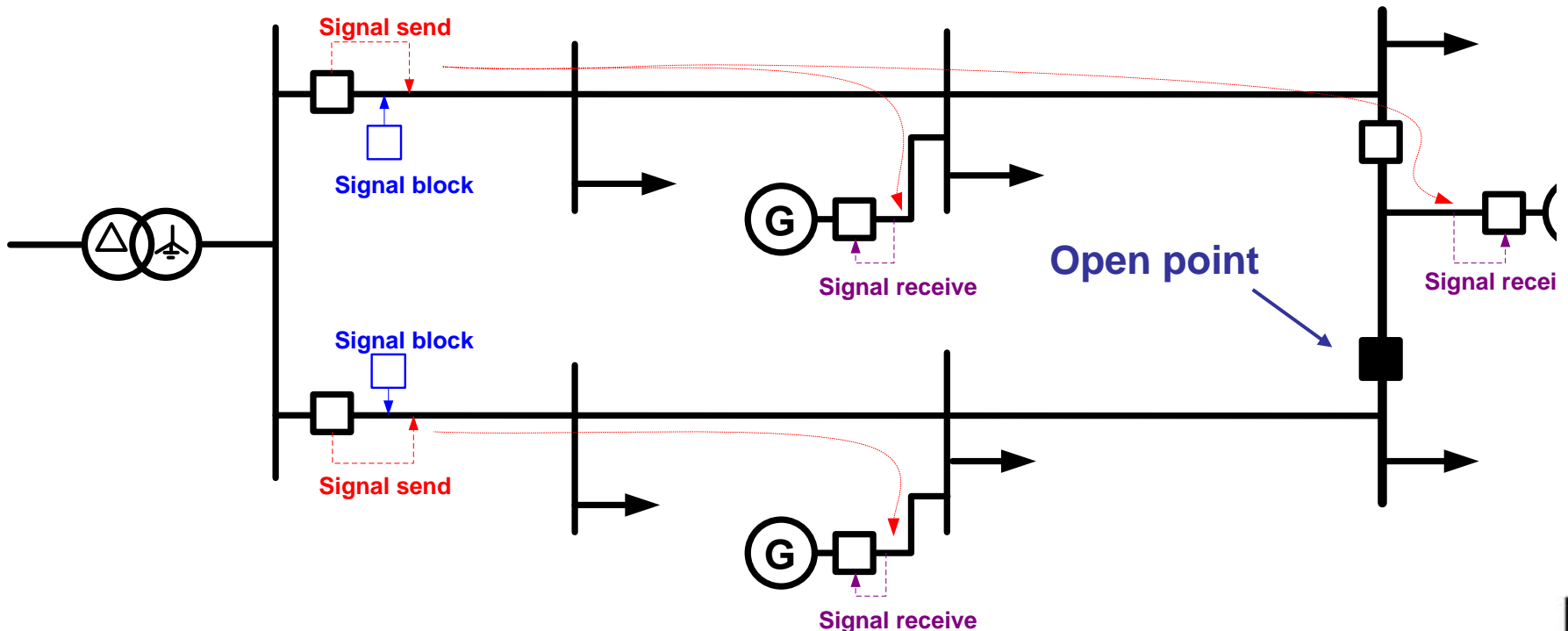
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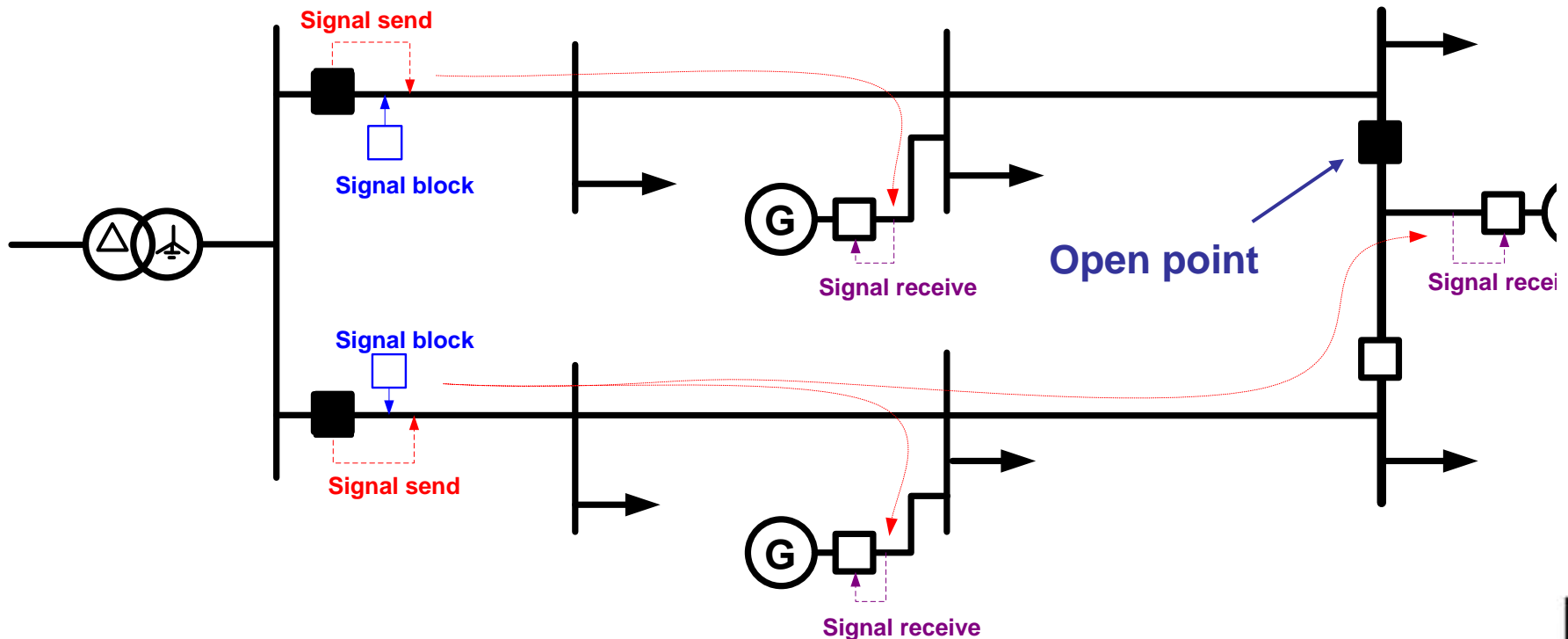
Intertripping of Open Ring Feeders

- 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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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:

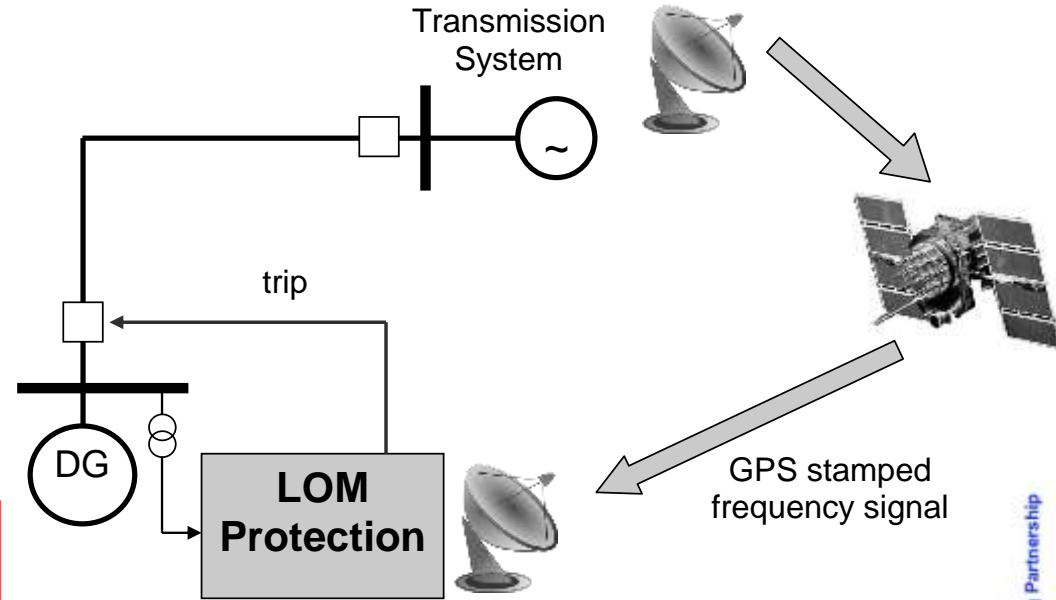
$$\alpha_n = \alpha_{n-1} + 2\pi(f_n - f_n^{est})\Delta t$$

α_n – calculated angle;

f_n – frequency measured locally;

f_n^{est} – estimated frequency received from the satellite;

Δt – angle calculation time step.

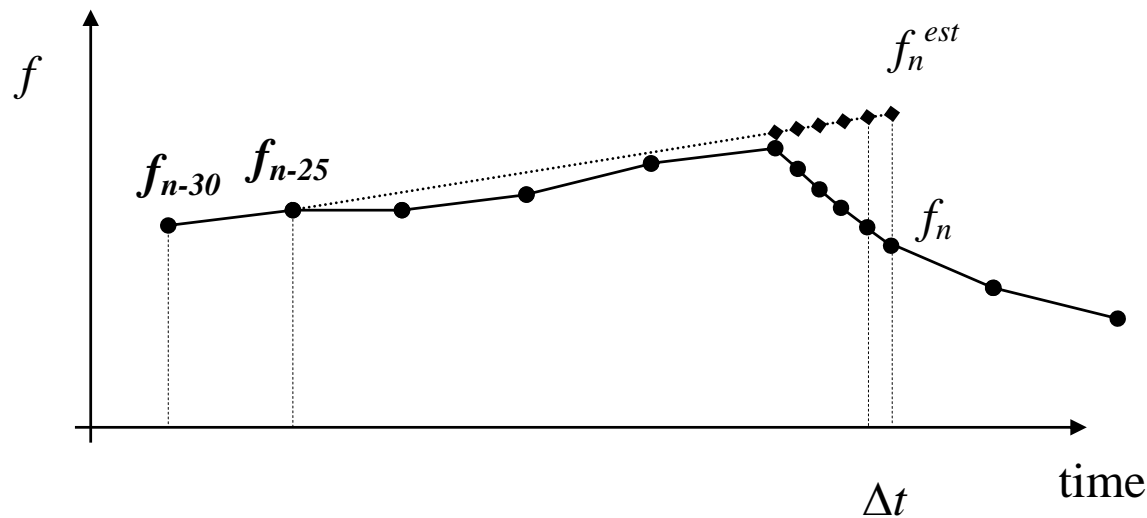


- A tripping signal is sent when α_n exceeds the preset threshold.



Satellite based LOM protection

- The algorithm uses voltage angle rather than rate of change of frequency as a decisive quantity.
- Satellite channel latency is compensated in software



- The method is less sensitive to system faults while preserving good sensitivity to genuine LOM events

