

EES-UETP Course title

Impact of Connecting DG on Distribution System Protection

Dr Campbell Booth
University of Strathclyde

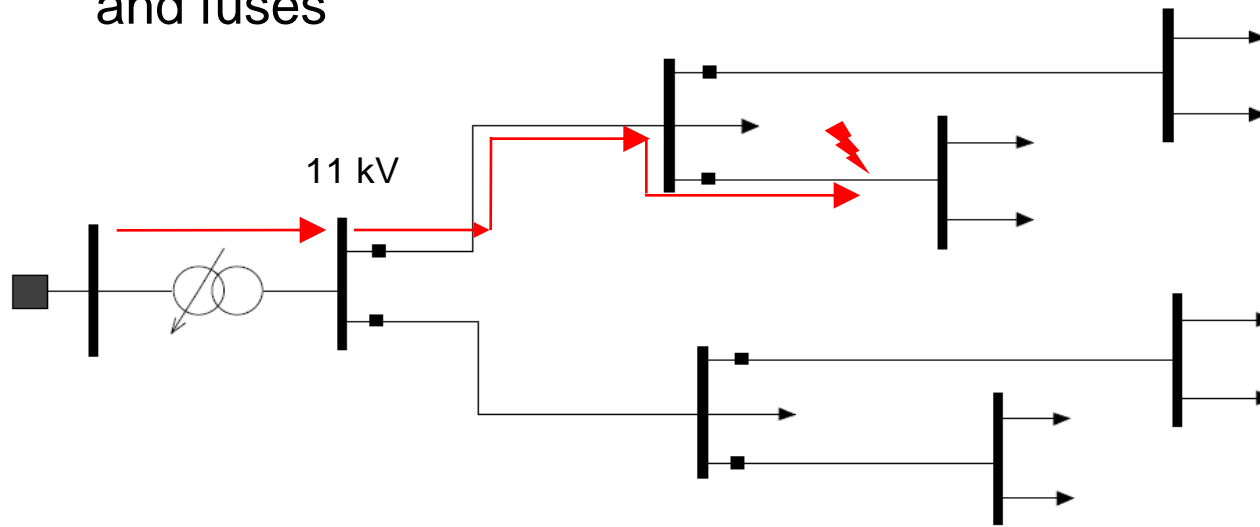
Overview

- ❑ Conventional distribution networks
- ❑ How distribution network are changing (active distribution networks, DG, potential for islanded operation)
- ❑ Potential issues for future networks
 - Protection “blinding”, false tripping/coordination problems (several examples)
 - DG ride-through
 - Converter-interfaced sources
 - Use of DC for distribution?
 - Fault current limitation
- ❑ Protection solutions?



Conventional distribution networks

- ❑ Operated radially
- ❑ Designed for unidirectional power flow
- ❑ Protected with over-current protection relays, reclosers and fuses



How distribution networks are changing

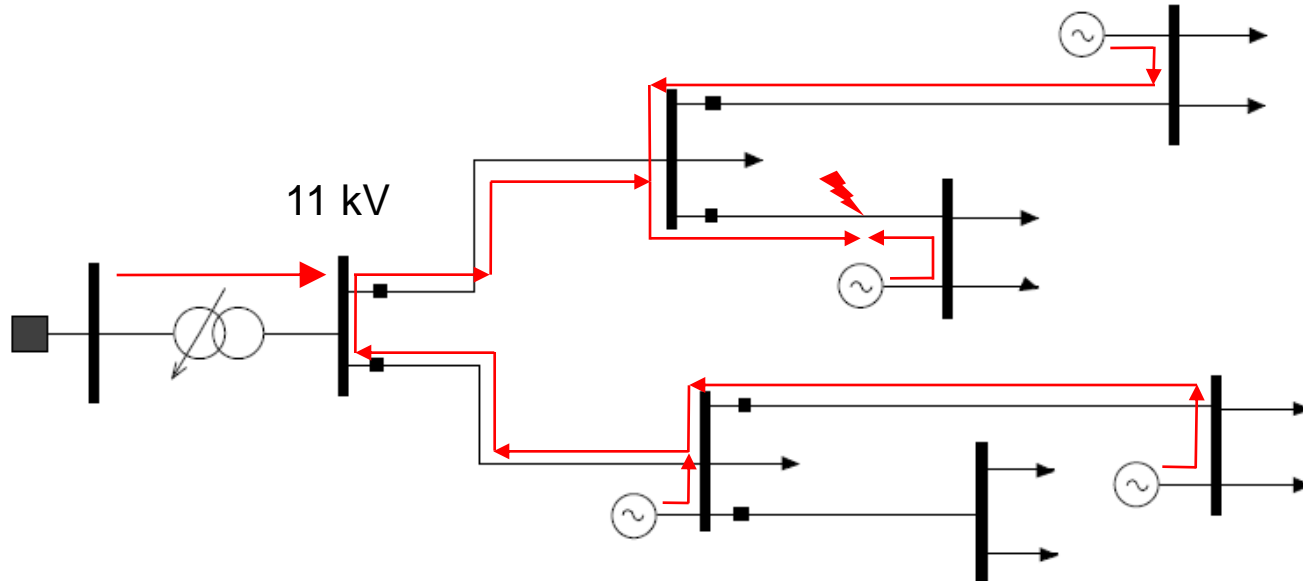
- Increase of distributed generation:
 - Wind
 - Hydro
 - Biomass
 - Photovoltaic
 - Wave/Tidal
 - others
- Connection of energy storage
- Introduction of network automation



Active distribution networks

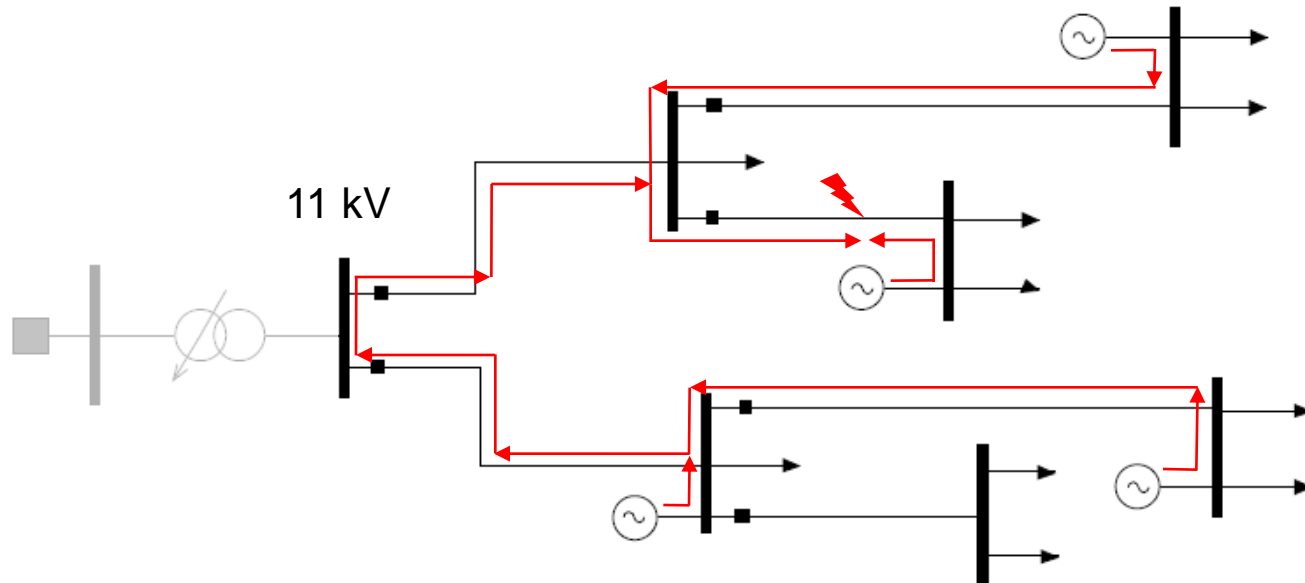
Fault current magnitudes and directions becomes unpredictable, potentially causing problems:

- false tripping of feeders;
- lack of coordination between protection devices;
- other problems.

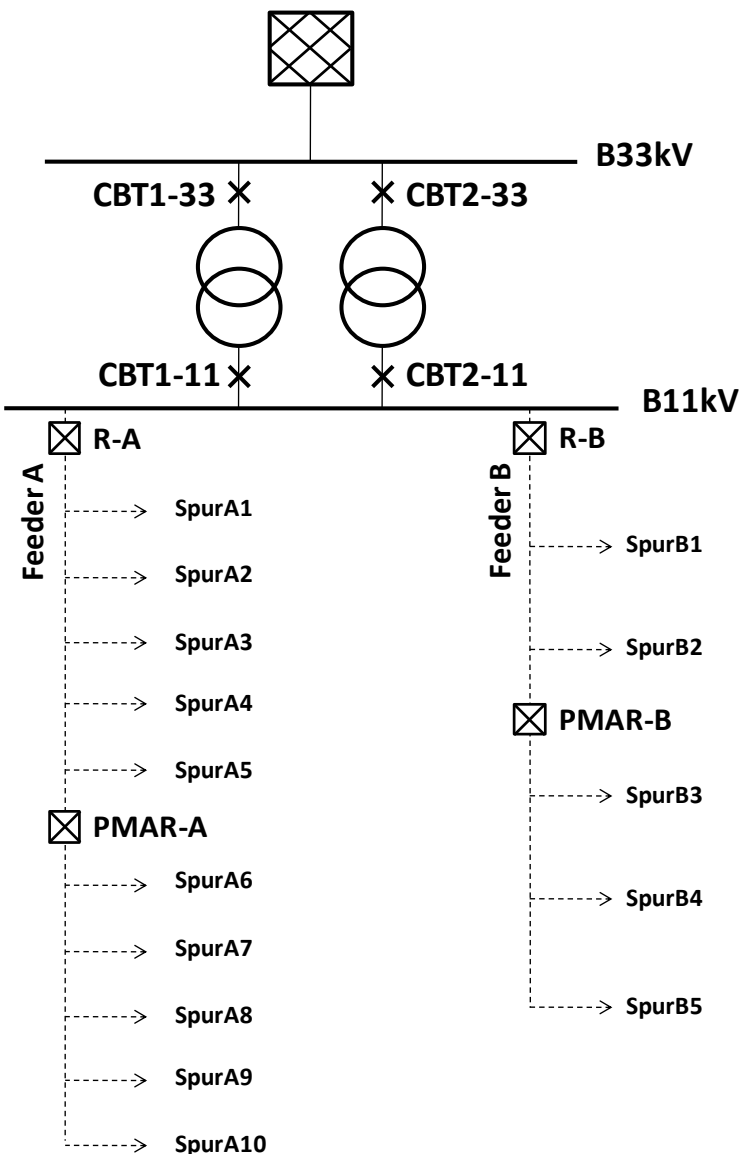


Islanding operation

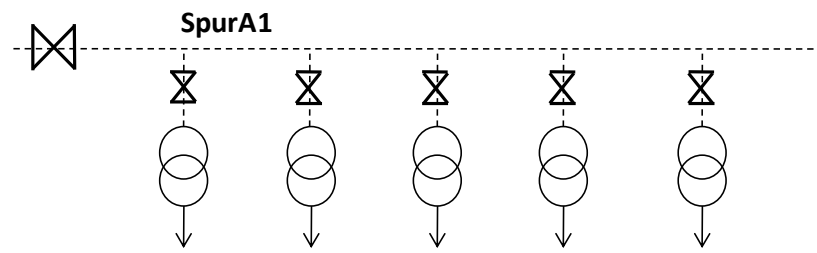
- Reduced fault levels
- Changed fault current direction
- System control?



Protection of distribution networks

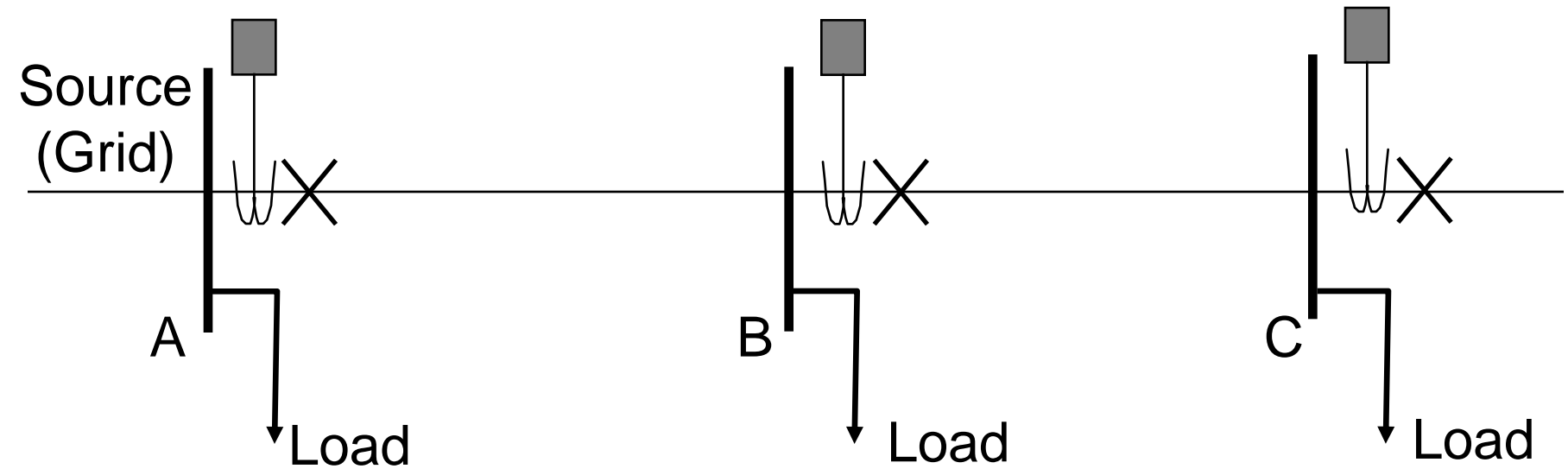


- Distribution network protection is based on overcurrent protection, reclosers and fuses
- In rural distribution networks, 80% of faults are temporary and auto reclosure automation is adopted.

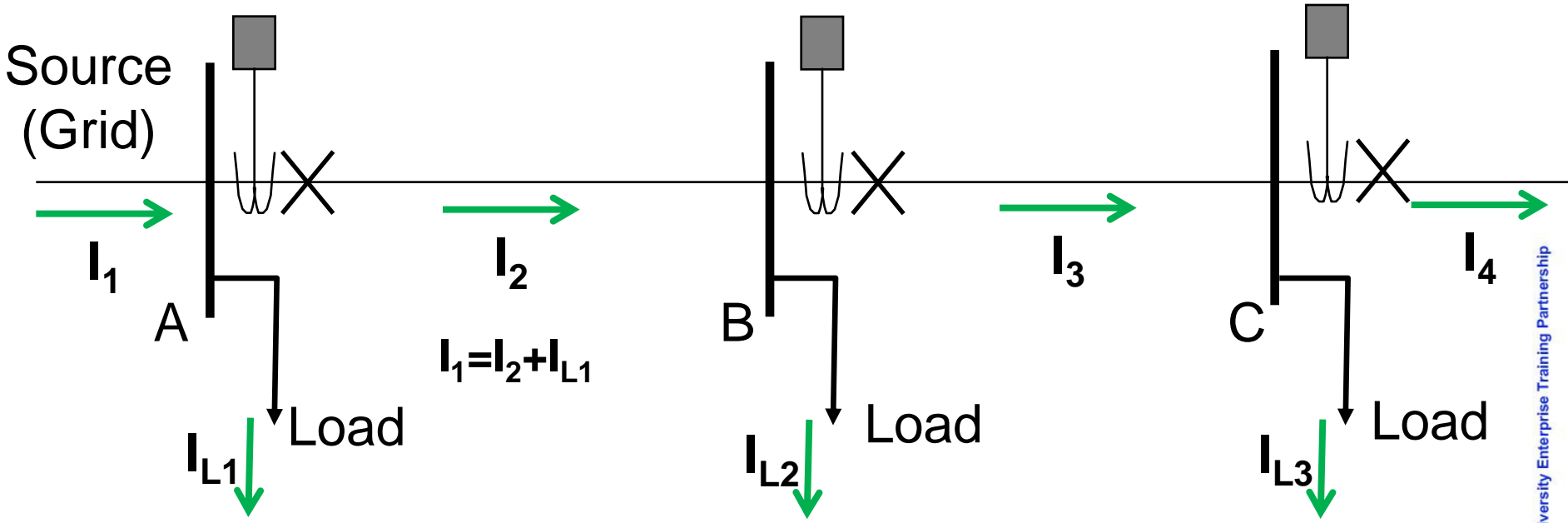


Setting of Overcurrent Relays

Decreasing Fault Current

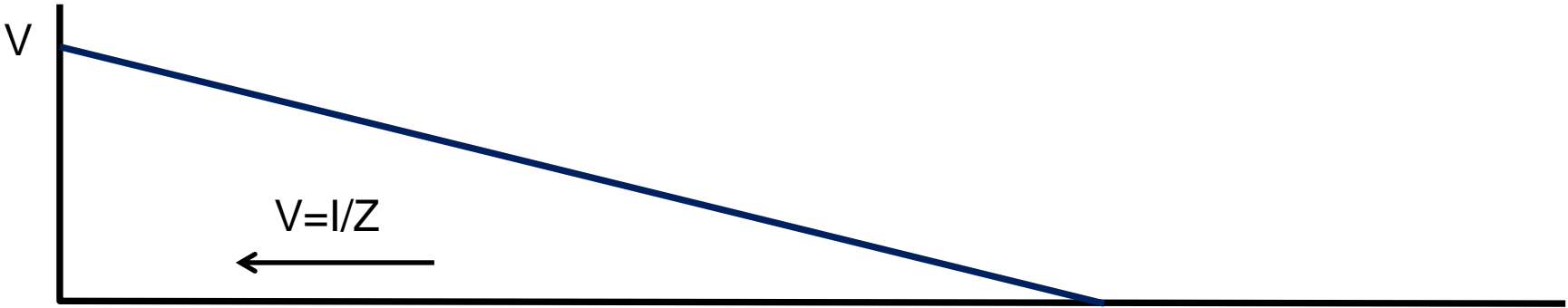
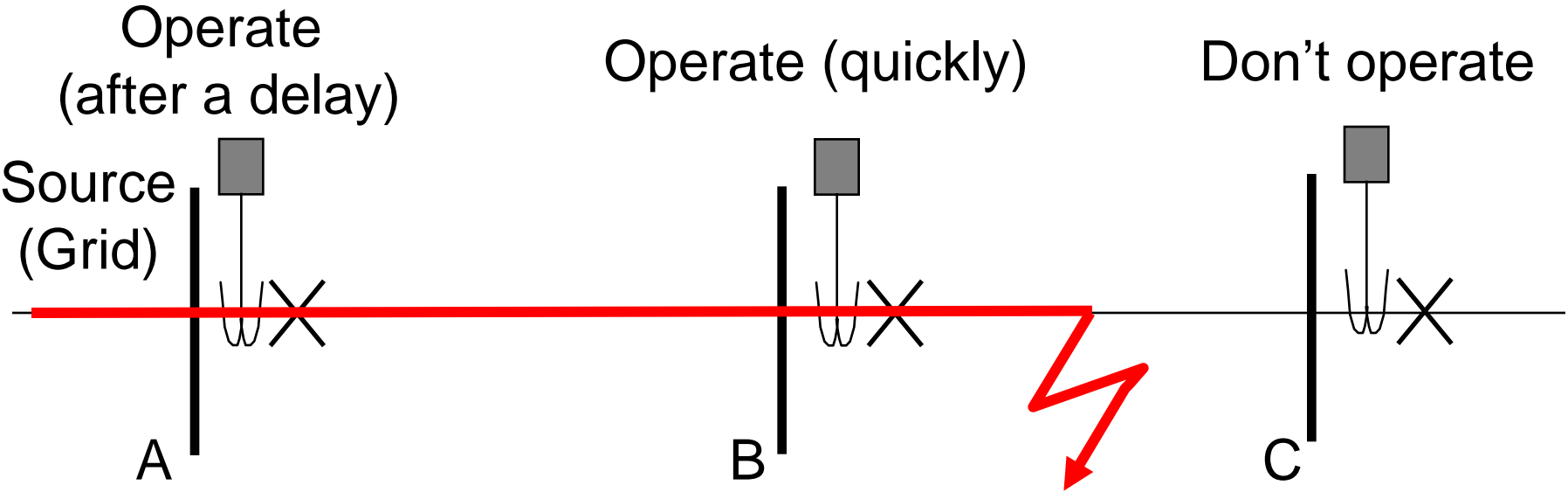


Normal Operation



Fault Behaviour – no DG

11kV 30MVA Source ($Z_{source} = 4.03\Omega$) 1 Ω impedance to fault ($Z_{AB} = 0.2\Omega$)



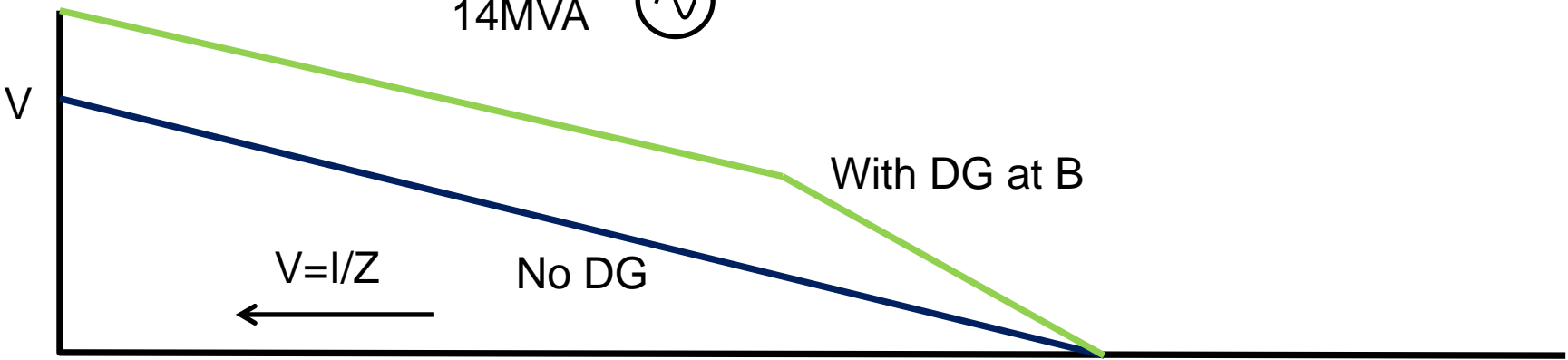
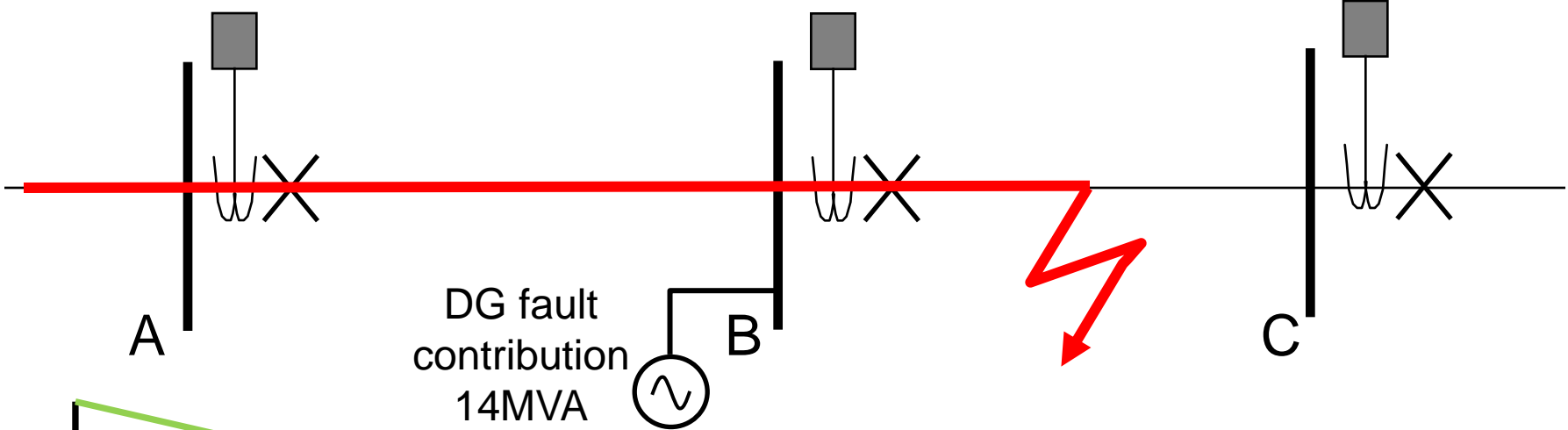
Fault Behaviour – with DG

11kV 30MVA Source ($Z_{source} = 4.03\Omega$) 1 Ω impedance to fault ($Z_{AB} = 0.2\Omega$)

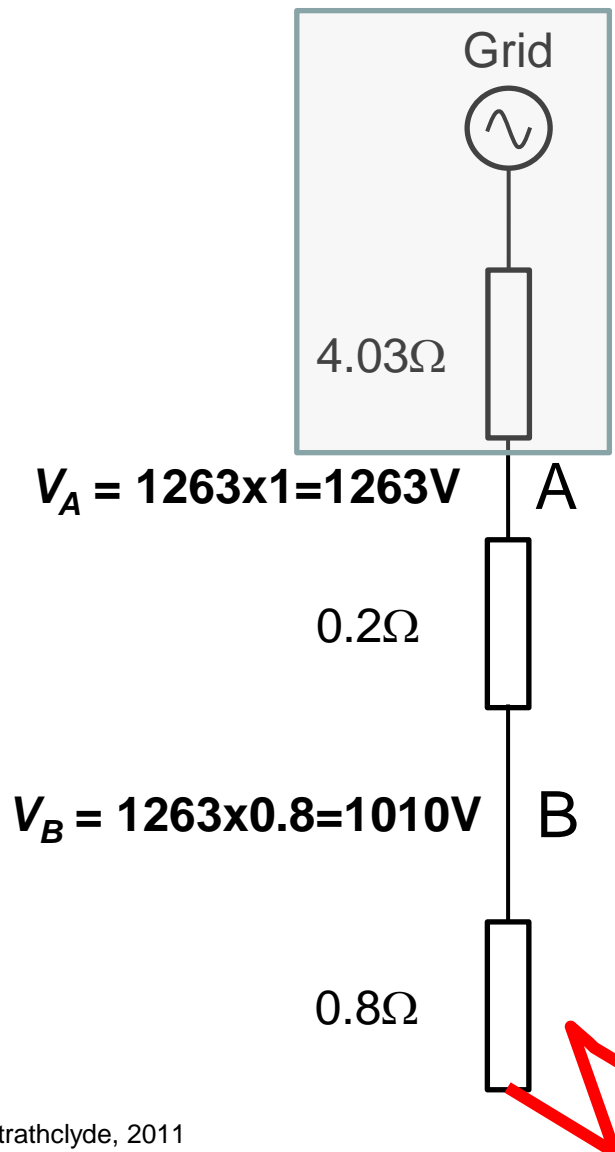
Operate
(after a delay)

Operate (quickly)

Don't operate

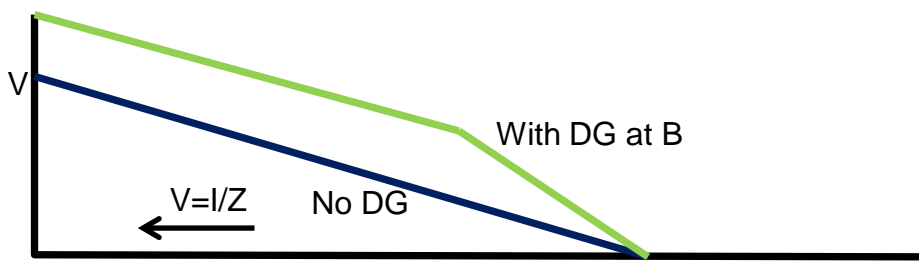


Equivalent circuit – no DG

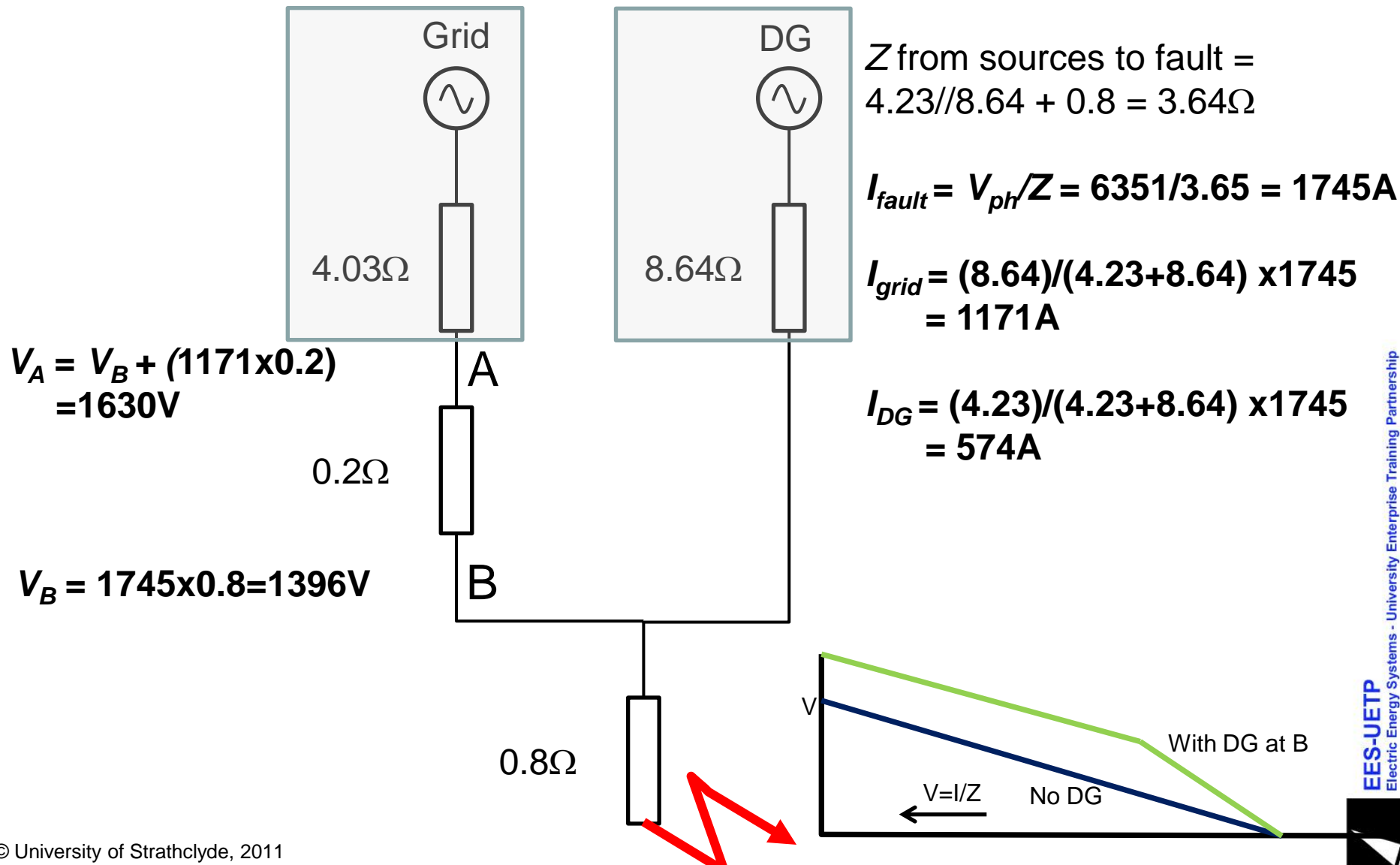


If Z from source to fault = 1Ω
 (0.2Ω for first feeder + 0.8Ω for second feeder):

$$I_{fault} = I_{grid} = V_{ph} / Z = 6351 / 5.03 = 1263A$$



Equivalent circuit – with DG

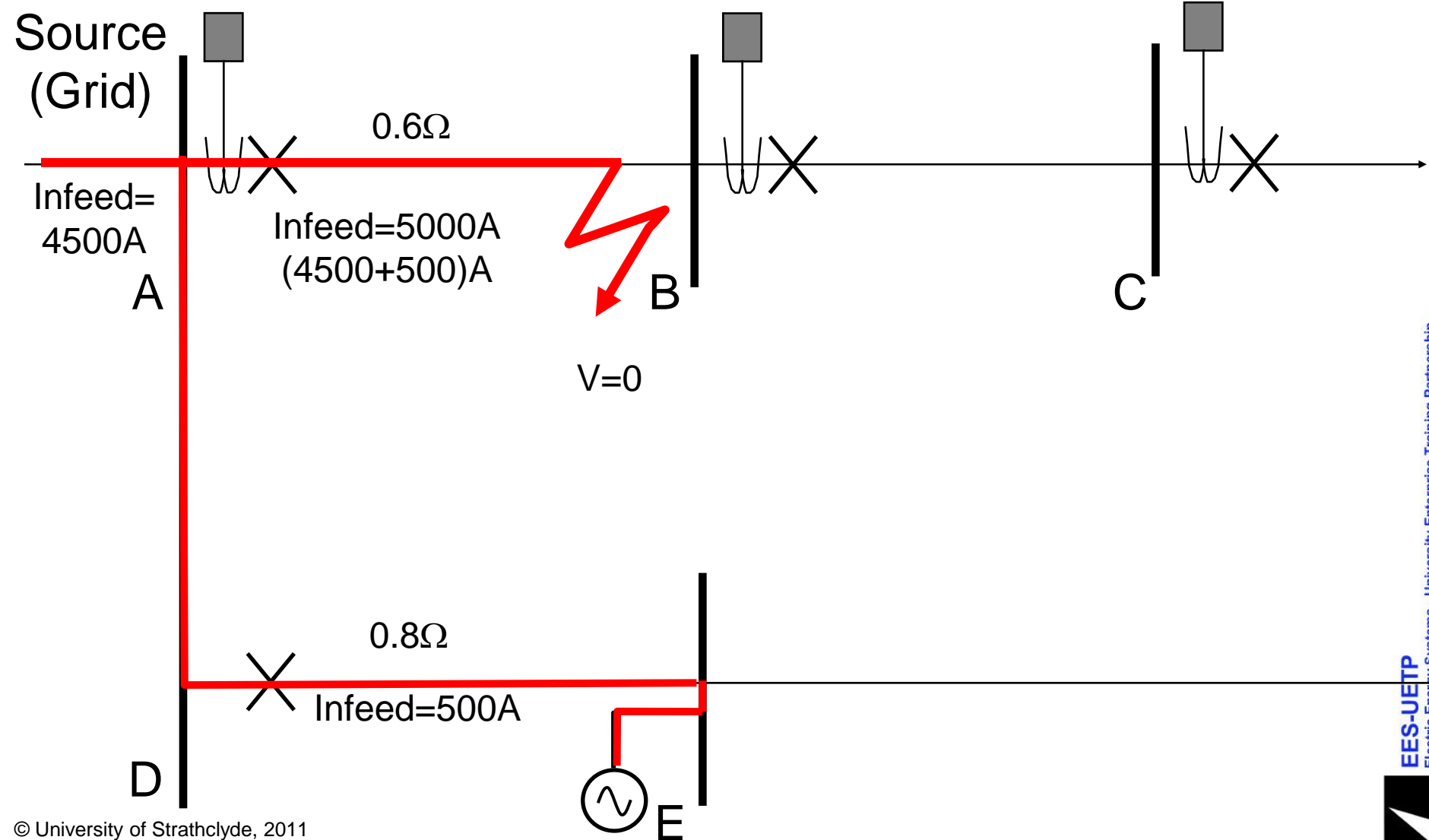


Protection issues - “blinding”

Note under very high DG penetrations and low grid infeed, current infeed from grid could be markedly reduced, therefore increasing risk of feeder protection “blinding” (non-operation of relay at A for backup scenario in this case).



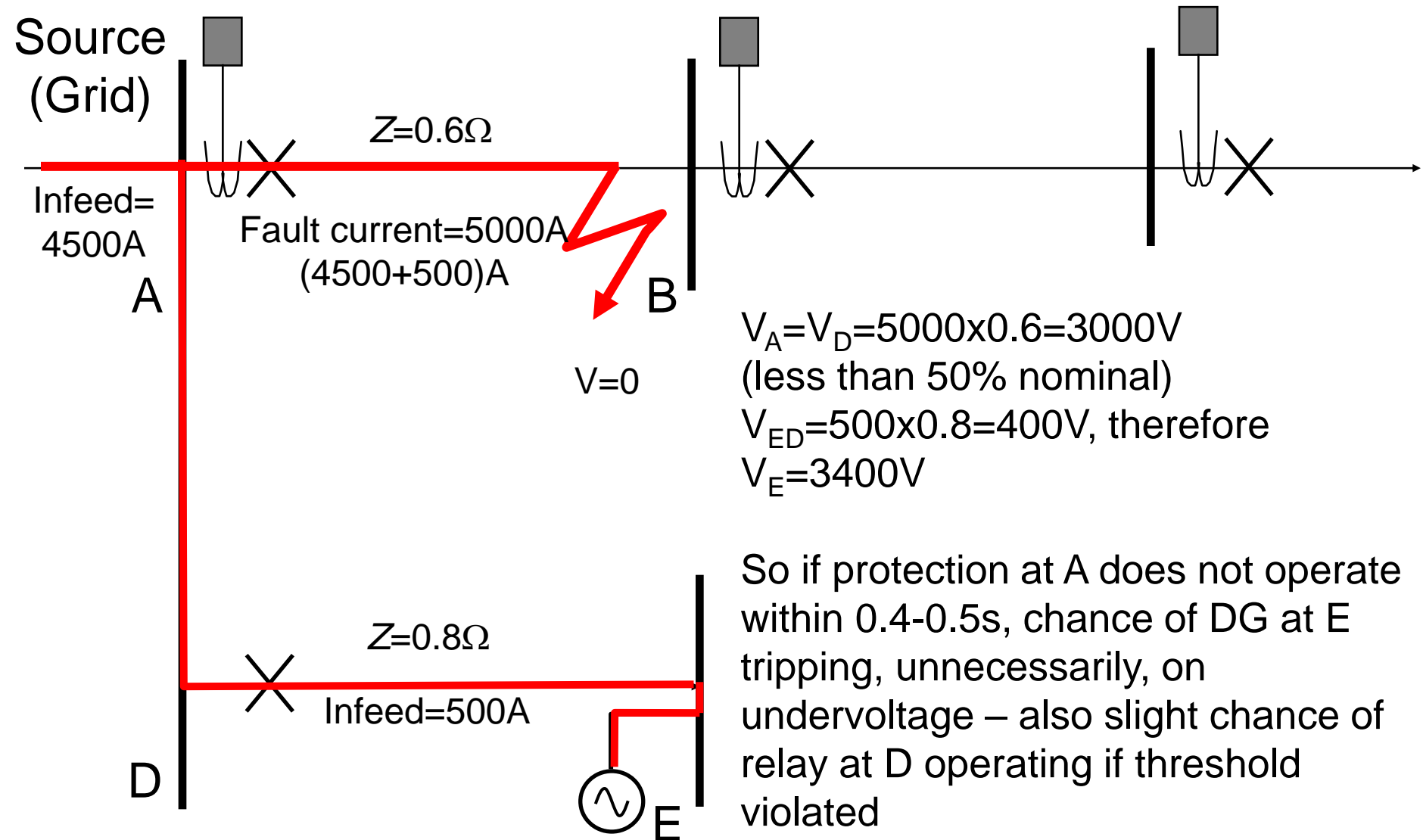
Protection issues – generator tripping on undervoltage



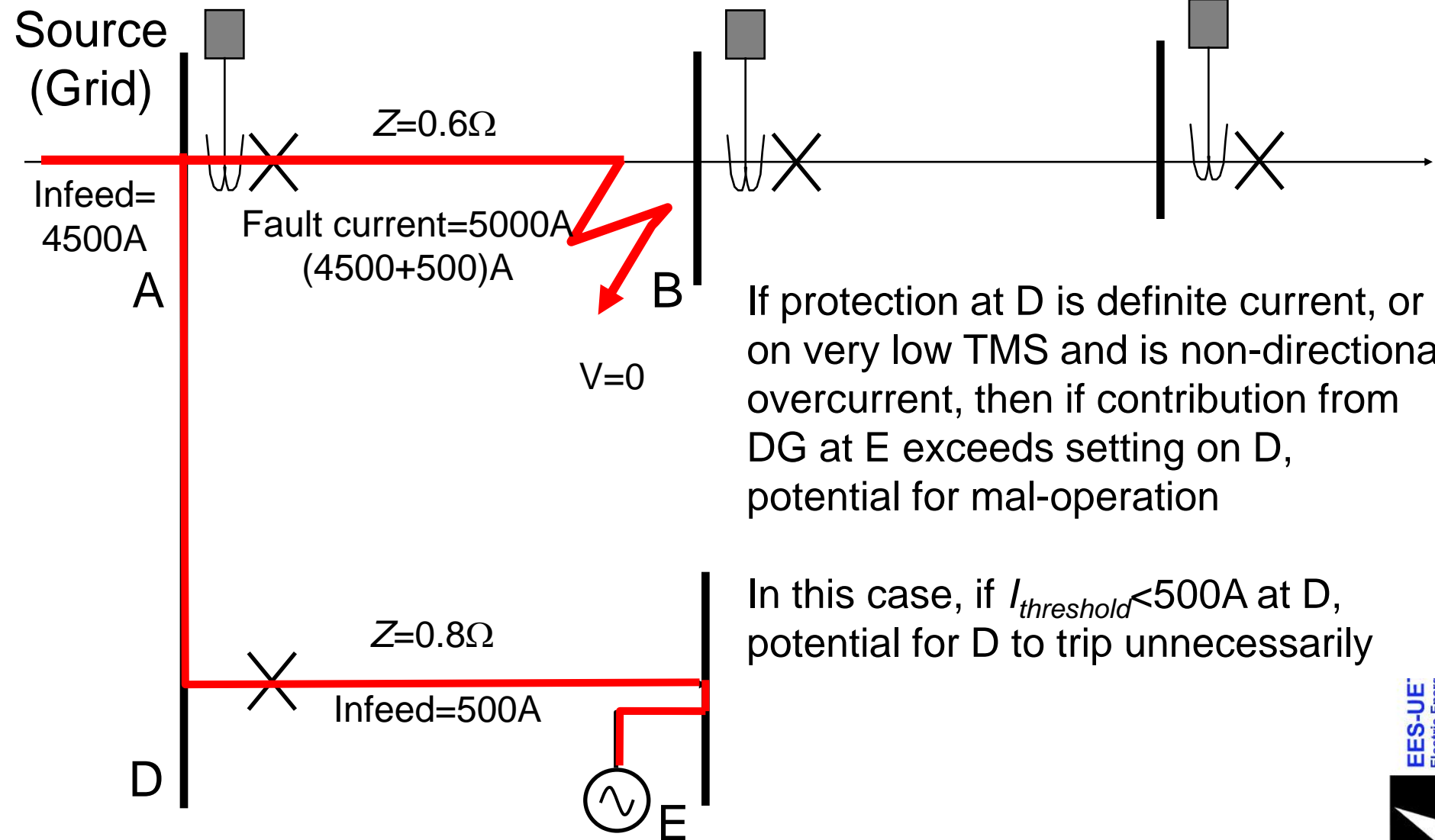
G59 – DG interface protection settings

Prot Function	Small Power Station				Medium Power Station	
	LV Connected		HV Connected			
	Setting	Time	Setting	Time	Setting	Time
U/V st 1	$V_{\phi-n^{\dagger}} - 13\%$	2.5s*	$V_{\phi-\phi^{\ddagger}} - 13\%$	2.5s*	$V_{\phi-\phi^{\ddagger}} - 20\%$	2.5s*
U/V st 2	$V_{\phi-n^{\dagger}} - 20\%$	0.5s	$V_{\phi-\phi^{\ddagger}} - 20\%$	0.5s		
O/V st 1	$V_{\phi-n^{\dagger}} + 10\%$	1.0s	$V_{\phi-\phi^{\ddagger}} + 10\%$	1.0s	$V_{\phi-\phi^{\ddagger}} + 10\%$	1.0s
O/V st 2	$V_{\phi-n^{\dagger}} + 15\%$	0.5s	$V_{\phi-\phi^{\ddagger}} + 13\%$	0.5s		
U/F st 1	47.5Hz	20s	47.5Hz	20s	47.5Hz	20s
U/F st 2	47Hz	0.5s	47Hz	0.5s	47Hz	0.5s
O/F st 1	51.5Hz	90s	51.5Hz	90s	52Hz	0.5s
O/F st 2	52 Hz	0.5s	52Hz	0.5s		
LoM (Vector Shift)	K1 x 6 degrees		K1 x 6 degrees [#]		Intertripping expected	
LoM (RoCoF)	K2 x 0.125 Hz/s		K2 x 0.125 Hz/s [#]		Intertripping expected	

Protection issues – generator tripping on undervoltage



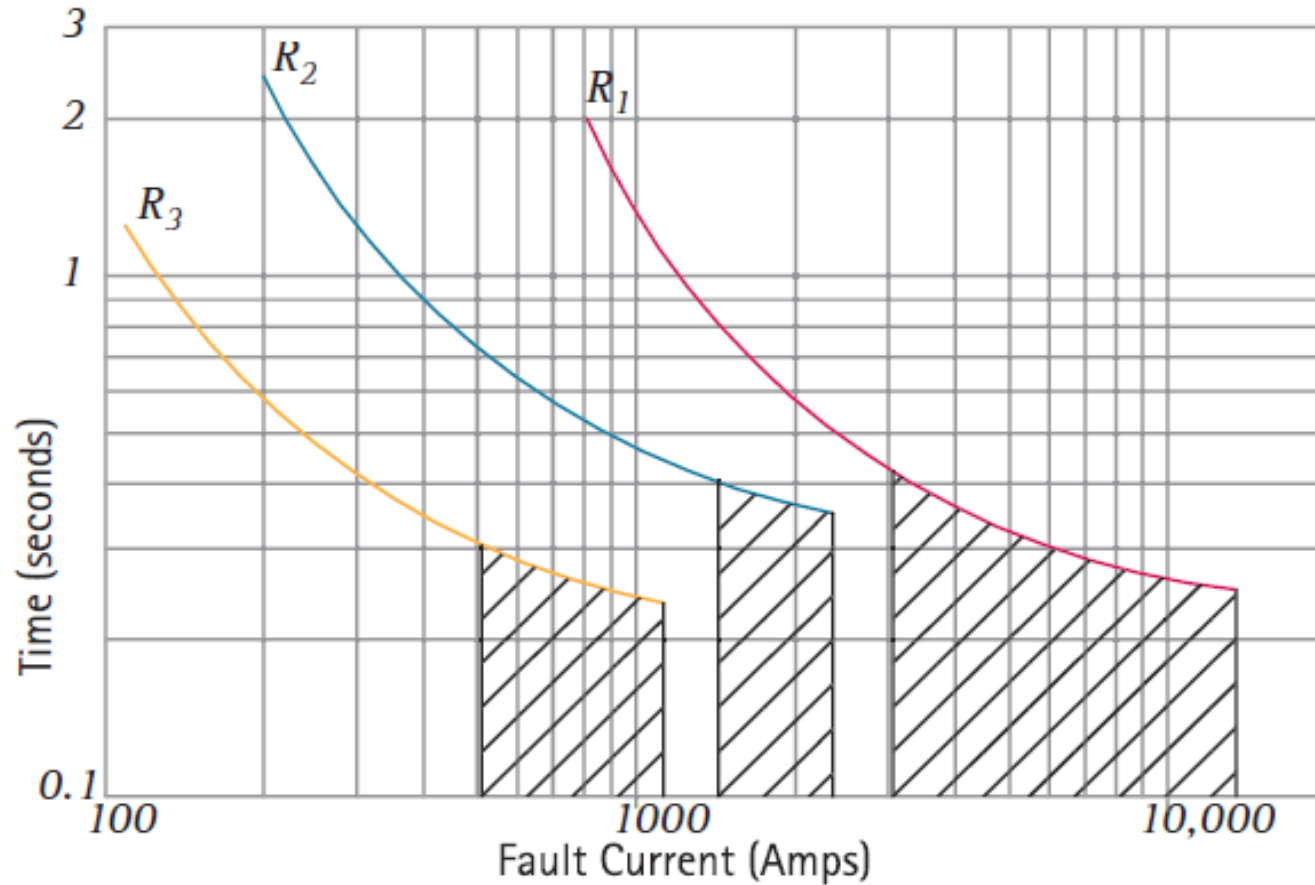
Protection issues – feeder protection maloperation



If protection at D is definite current, or on very low TMS and is non-directional overcurrent, then if contribution from DG at E exceeds setting on D, potential for mal-operation

In this case, if $I_{threshold} < 500A$ at D, potential for D to trip unnecessarily

Protection issues - DG impact on instantaneous (“high set”) protection

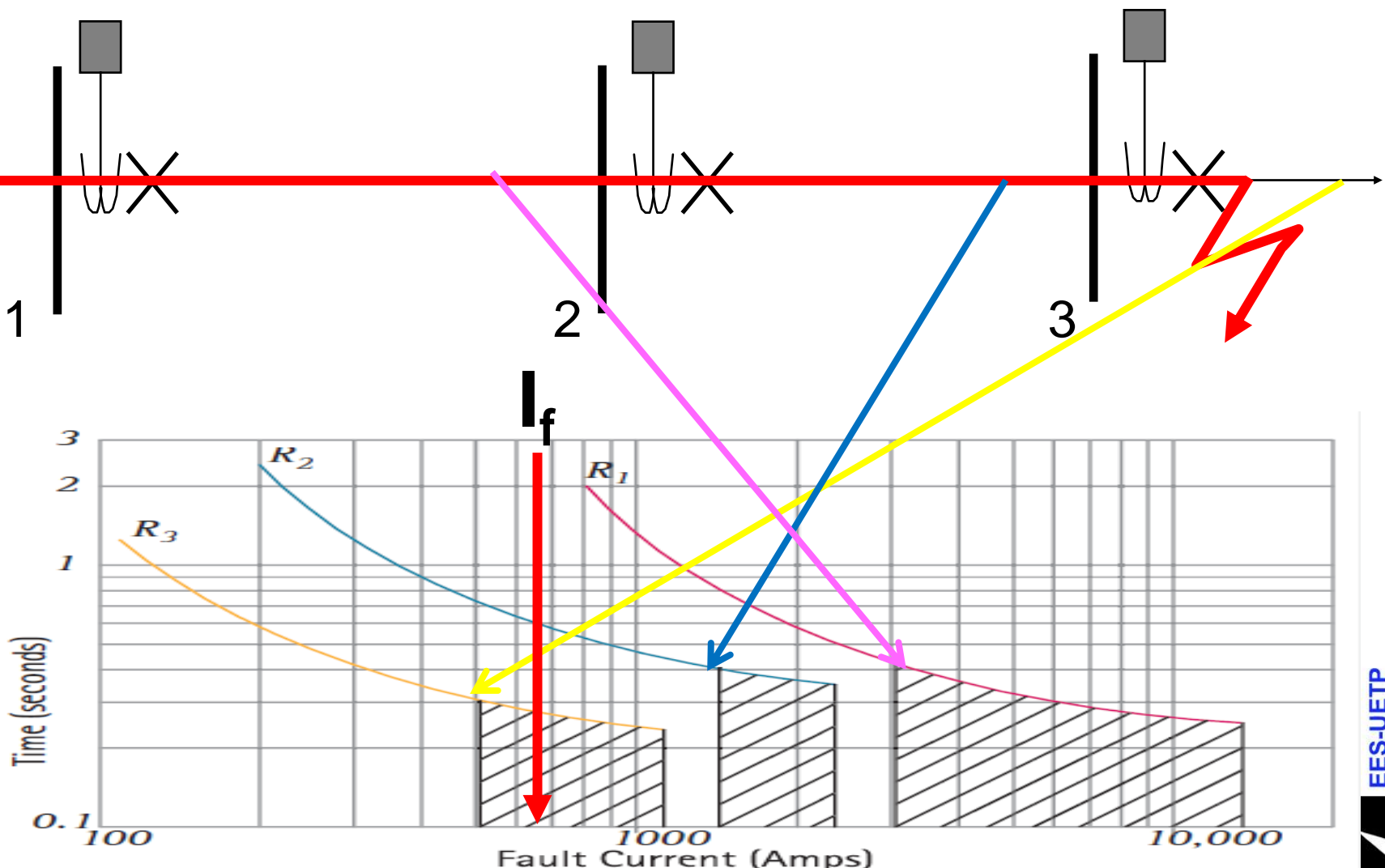


Protection issues - DG impact on instantaneous ("high set") protection

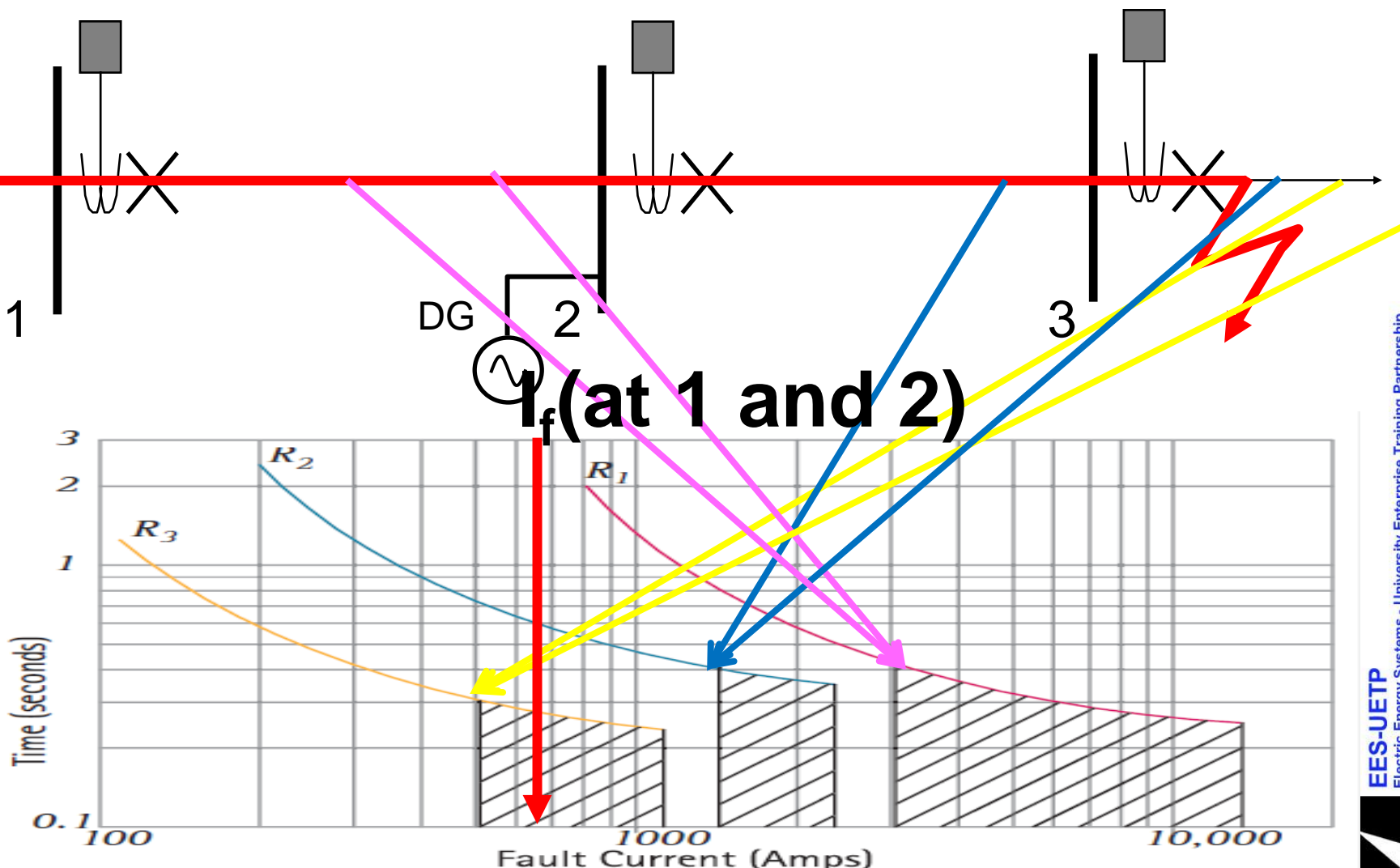
Operate?

Operate (time delay)

Operate (instant)



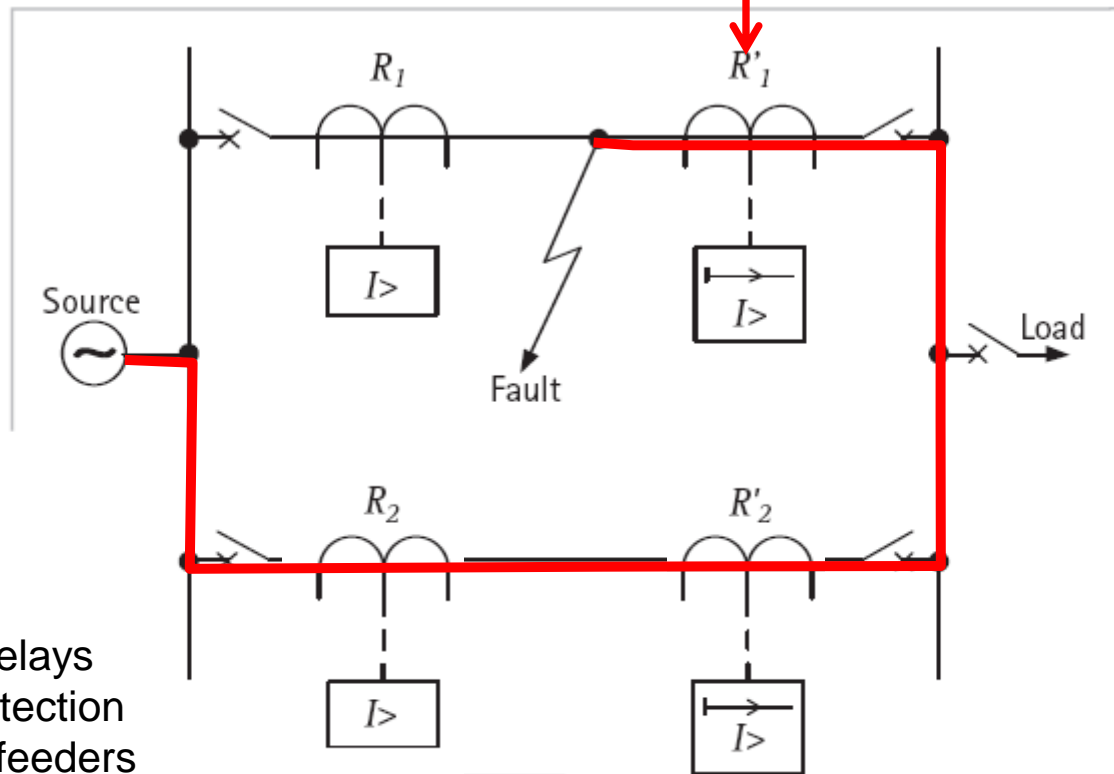
Protection issues - DG impact on instantaneous ("high set") protection



Protection issues - DG impact on directional protection

Sensitive and fast acting directional protection here
($I_{threshold} = 10\%$ of rated line current)

Looks “up” into line
– prevents R_2 operating for this fault



Use of directional relays to provide correct protection operation on parallel feeders
From NPAG: - chapter 9

Figure 9.13: Directional relays applied to parallel feeders



Protection issues - DG impact on directional protection

DG on load side – R'_2 (and possibly R_2) might maloperate?

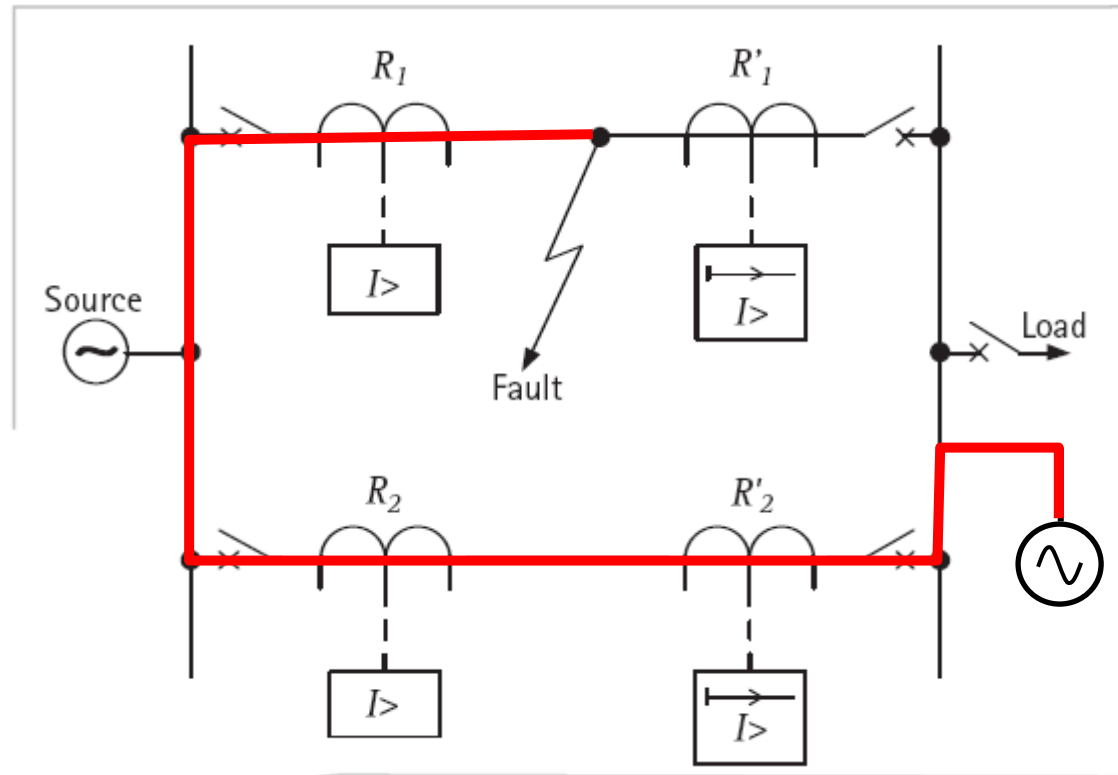


Figure 9.13: Directional relays applied to parallel feeders



Protection issues - DG impact on directional protection

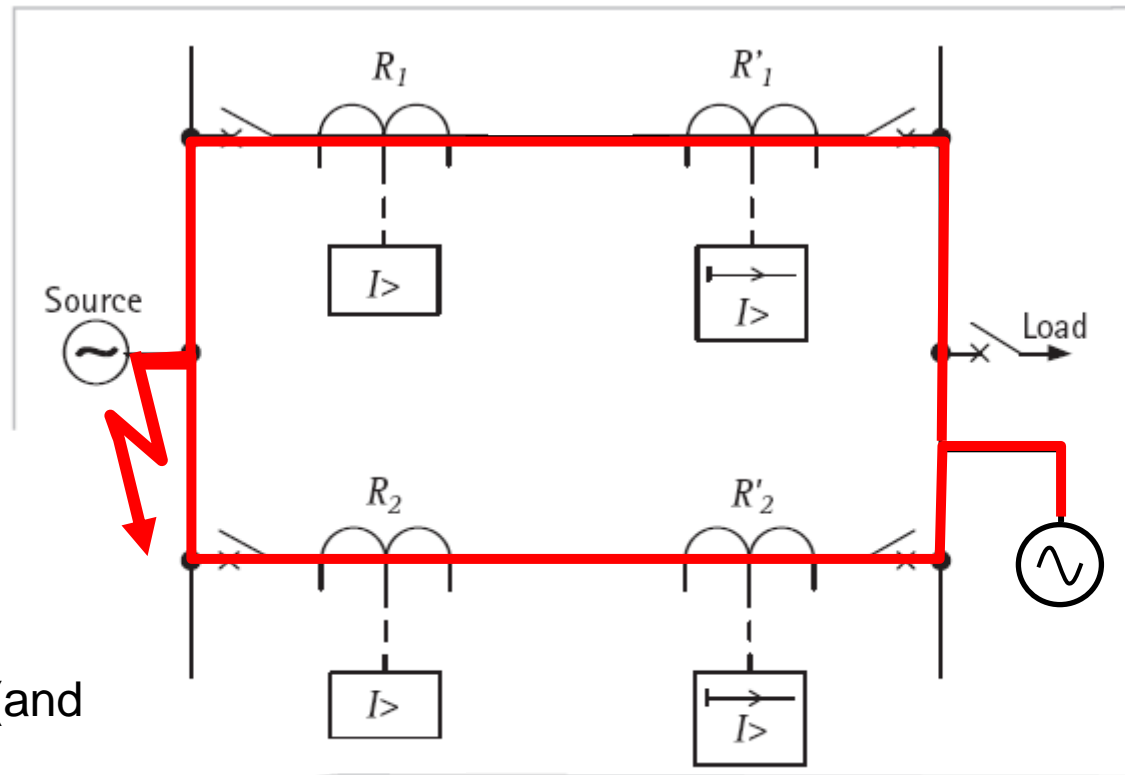


Figure 9.13: Directional relays applied to parallel feeders

DG on load side – R'_1 R'_2 (and possibly R_1 and R_2) might maloperate?

Even under load conditions – back-feed if $DG > \text{local load}$?



Protection issues - DG impact on directional protection

Use of overcurrent relays for protection of ring mains

From NPAG: - chapter 9 www.deadsmall/2VA

Additional DG contribution may result in coordination problems?
R1' will operate for this scenario?

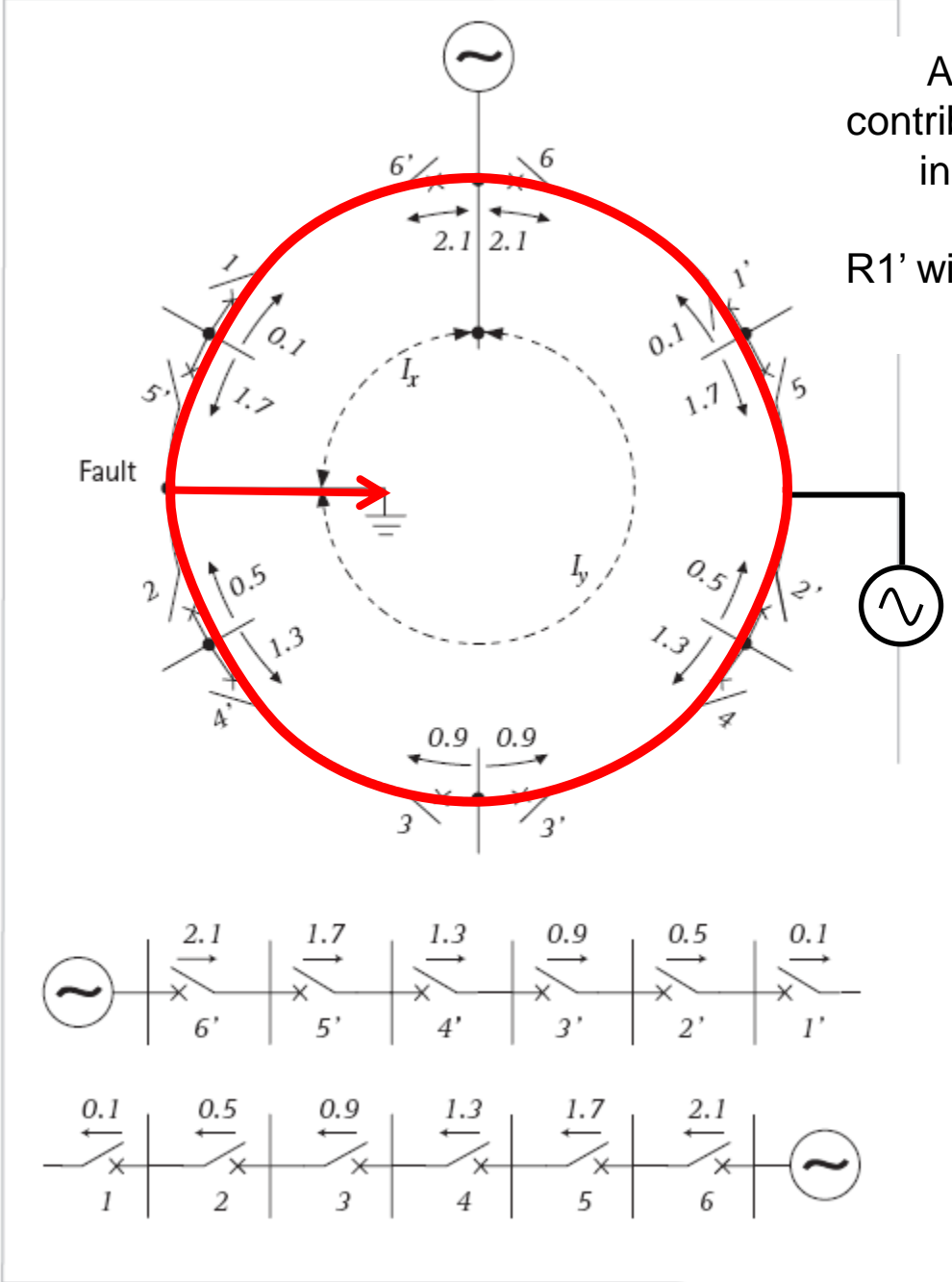


Figure 9.14: Grading of ring mains



Other protection issues

- Future debate over AC/DC – many implications
- Power converters – for interfacing generators and for power conditioning (voltage transformation and control, ac/dc, FACTs)
- DC systems – energy storage issues
- High, variable and restricted fault levels
- Variable inertia in power systems
- Others (harmonics, novel loads, V2G..)



AC/DC?

- DC can transfer approximately 1.41 times the power of an AC system operating at the same AC (peak) voltage.
- Many loads require DC, increasing attractiveness of DC.
- Power converters in DC systems may provide fault current limitation (can also be a disadvantage) - protection coordination problems with converters in DC or hybrid systems
- Use of capacitors to smooth or eliminate voltage ripple on DC systems may lead to a massive increase in initial fault currents on DC systems.



AC/DC?

- The interruption of DC current remains a significant research challenge, particularly in space-limited environments.
- AC - voltage can be easily transformed, currents easier to interrupt.



Converter Interfaces

- Power Electronic Converters (PECs) in power systems are used to:
 - Interface Distributed Generation (DG) to the main power system
 - Interface energy storage devices
 - Enable HVDC transmission
 - Condition power for loads
 - Fault current limiting/interruption applications.
- *“They are already used in most Photovoltaic (PV) and Wind Turbine (WT) systems and are expected to be used in nearly all emerging wave and tidal power technologies¹.”*
- *“We strongly believe that high voltage direct current (HVDC) will play an increasing role in the future of electric power transmission².”*



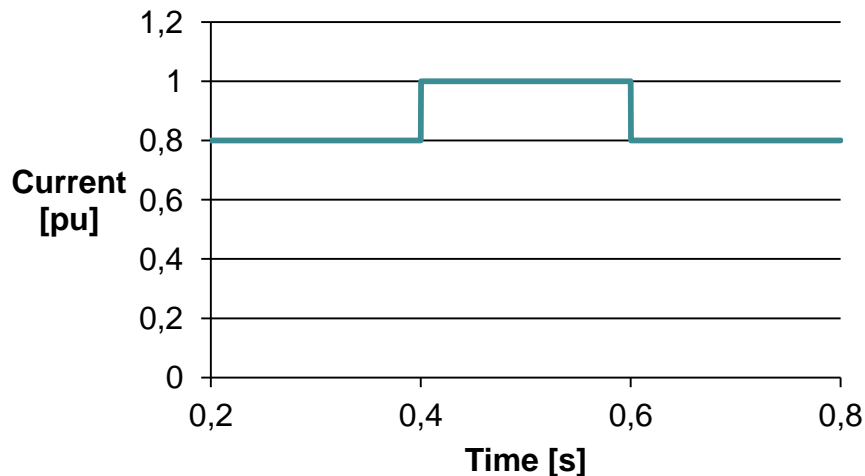
1. L. Freeris and D. Infield, "Renewable Energy in Power Systems," 1st ed Chichester: John Wiley & Sons Ltd, 2008, pp. 122, 128, 133, 192, 144-145.
2. [Abhay_Kumar_lead_engineer_and_project_manager_HVDC_with_ABB_in_Sweden.](http://commons.wikimedia.org/wiki/File:Giant_photovoltaic_array.jpg)
3. http://commons.wikimedia.org/wiki/File:Giant_photovoltaic_array.jpg
4. http://commons.wikimedia.org/wiki/File:HVDC_Europe.svg



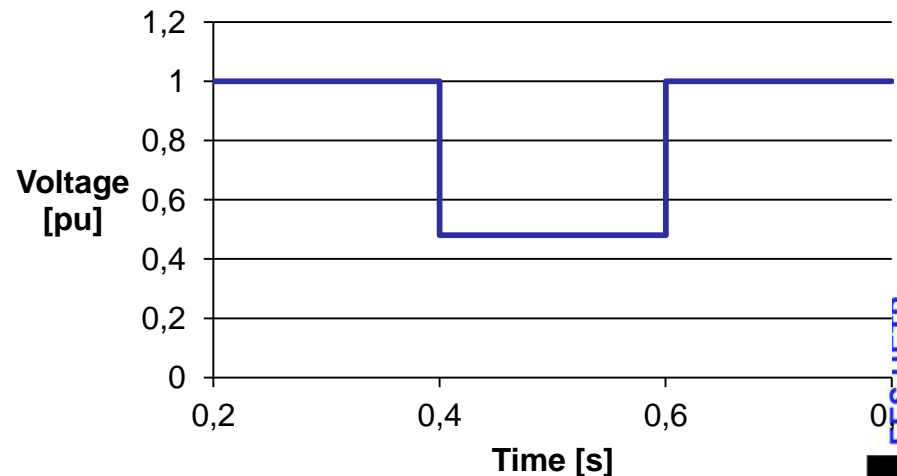
Converter Interfaces: Research

- Close up faults have the potential to damage PEC semiconductors.
- Fault current output of PECs must be limited to avoid damage.
- Reducing fault current could lead to network protection non-operation and PEC protection operating in an uncoordinated fashion with the network protection.
- **How should a network with relatively low fault current levels and uncoordinated PEC/protection system operation be protected?**

RMS Converter Response

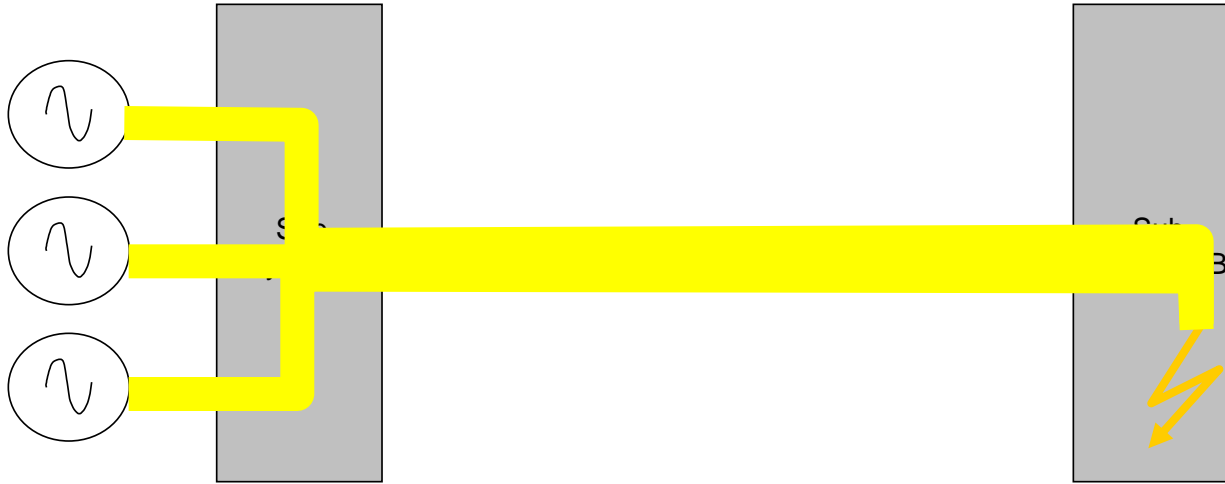


RMS Converter Response



Converter Interfaces (1)

System with no converter in fault current path

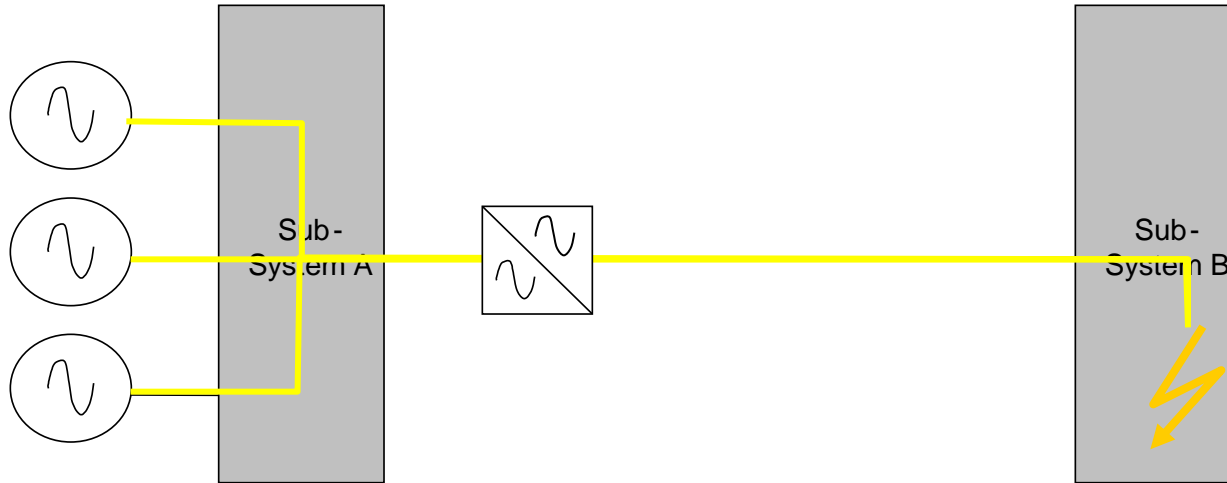


- System fault levels are only restricted by the capacity of generators and the equipment in the path of the fault
- Network protection coordination is relatively straightforward - local protection operates first, then backup...
- Ultimately generator protection may trip if there is a massive failure of network protection



Converter Interfaces (2)

System with converter in fault current path



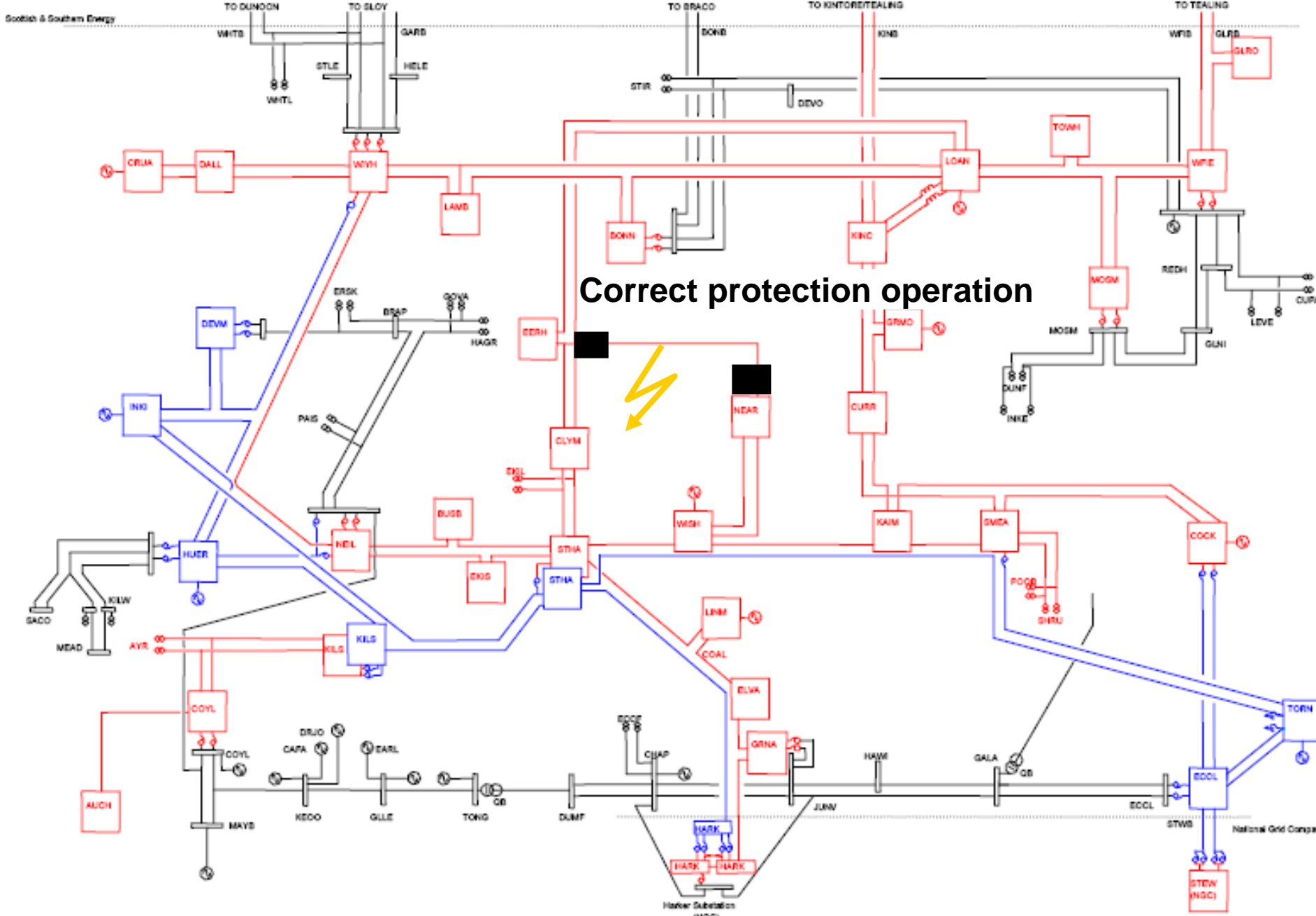
- ❑ Converters normally act to limit fault current
- ❑ Converters' inbuilt protection may stop conduction very quickly before "correct" downstream protection operates
- ❑ May lead to protection coordination problems...



Converter Interfaces (3)

What might happen if ScottishPower's transmission network had converter-interfaced generators with sensitive, fast acting protection?



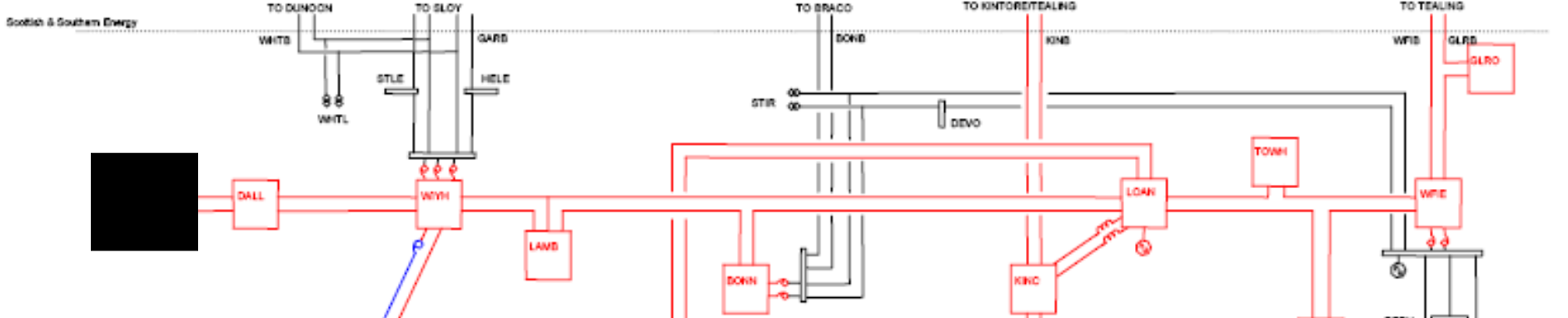


Correct protection operation

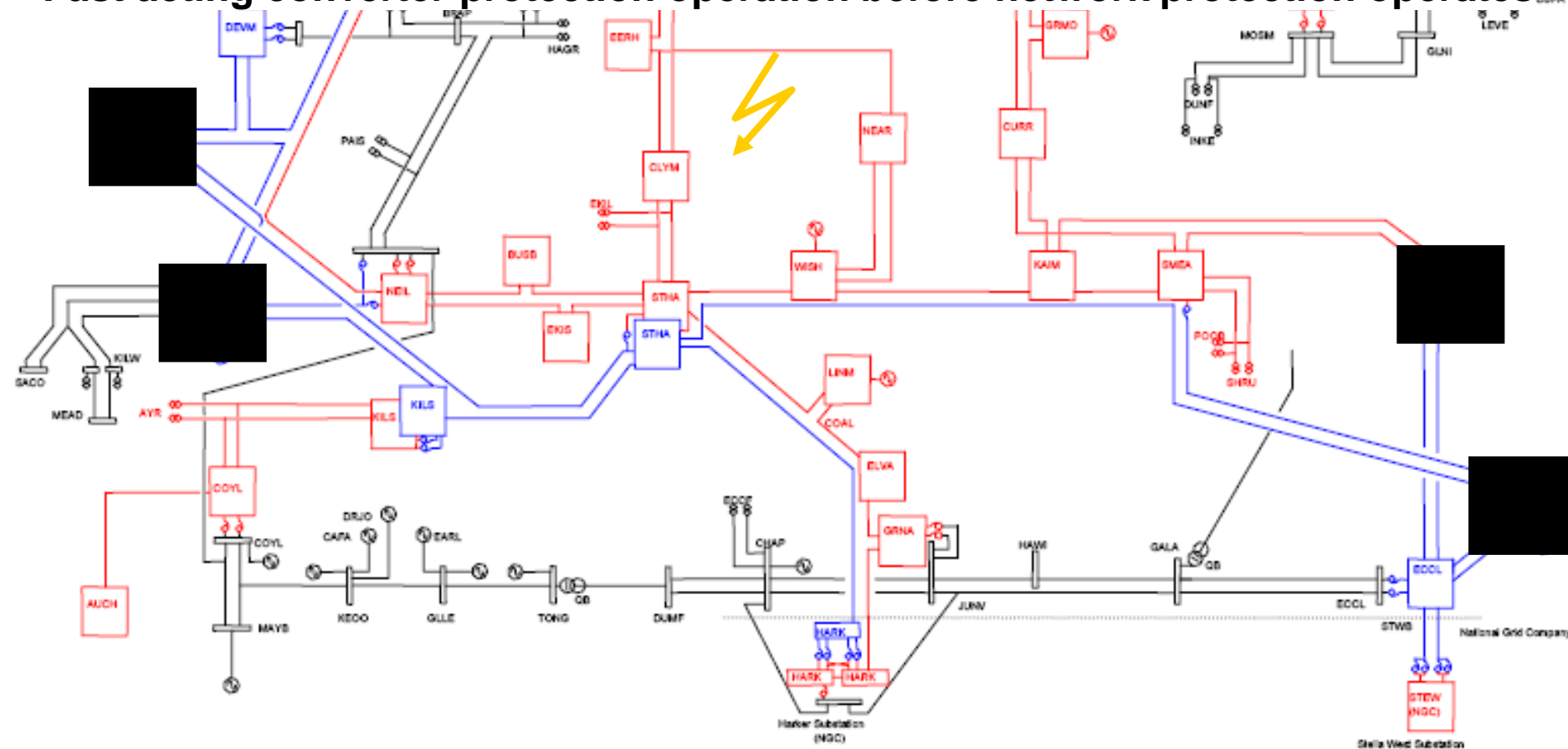
400kV BLUE
275kV RED
132kV BLACK

INTERCONNECTED TRANSMISSION SYSTEM
SPT Existing Transmission System, April 2006

Figure A



Fast acting converter protection operation before network protection operates



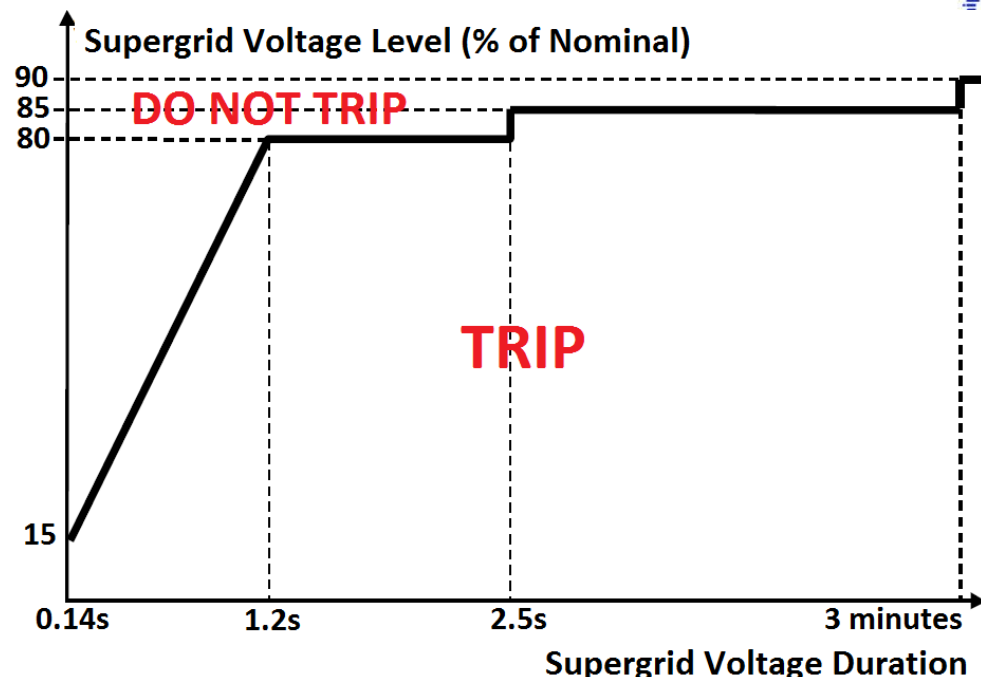
400KV BLUE
275KV RED
132KV BLACK

INTERCONNECTED TRANSMISSION SYSTEM
SPT Existing Transmission System, April 2006

Figure A

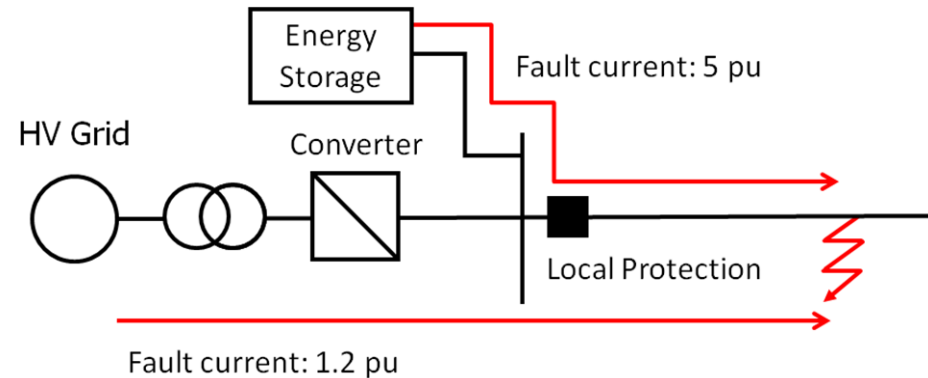
Converter Interfaces: Research

- “During the period of the fault the PEC should provide **maximum** reactive current without exceeding its transient rating limit.”
- “Duration and fault clearance times should be specified in a bilateral agreement between the PEC installer and the Distribution Network Operator (DNO).”
- Fault current is not specified other than “to provide **maximum reactive current**.”
Behaviour for different fault types (e.g. earth, phase-phase, resistive) is also not specified.



Converter Interfaces: Research

- **Incorporation of energy storage devices to meet the deficit in fault current from PECs.**
 - “UK-micro-grids project” used a flywheel unit to provide sufficient fault current for fault detection.
 - System may not readily scale to larger fault levels.

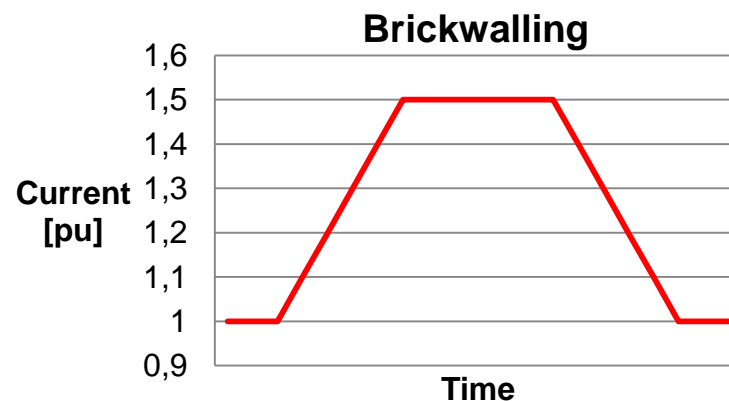
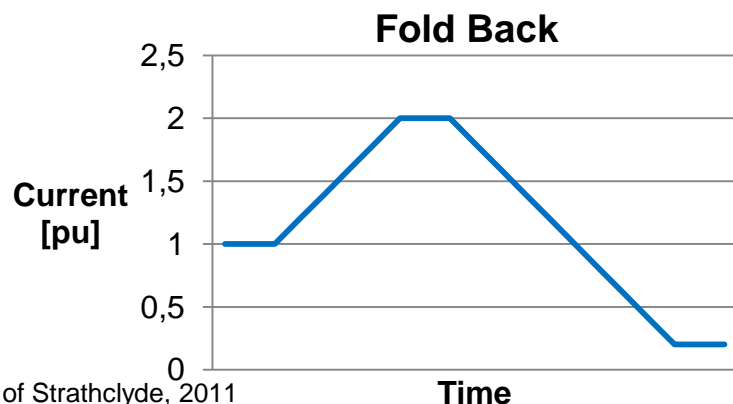


- **Advanced fault detection algorithms.**
 - Voltage based fault detection – Uses the voltage drop associated with a fault for detection. May not operate correctly for specific grounding configurations or low impedance micro-grid systems.
 - Travelling wave protection techniques – Uses the waves propagating from the fault point to pinpoint the fault location. Problems may arise when the fault occurs at a zero-crossing point or from harmonics on the power system.



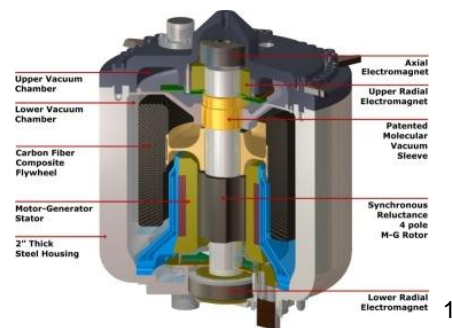
Converter Interfaces: Research

- **Adaptive protection coordination** – After tripping of adjacent circuits and/or resulting changes in fault levels the protection relay settings adapt to ensure correct operation. Has not been widely deployed and requires a secure and reliable communication system.
- **Control of fault behaviour of PECs** – Fold back and brickwalling are methods of controlling the fault current provided by the PEC. Fault current output of the converter is increased for a short duration to increase the likelihood of fault detection while reducing the risk of damage to the PECs' electronics. Fault current may still be insufficient for protection scheme fault detection.



Future Research

- International grid code evaluation to compare the requirements of Power Electronic Converters (PECs) under fault conditions.
- Simulate PEC-dense power system to study the protection system and PEC interaction/control under fault conditions.
- Evaluate PEC-dense power system protection under different conditions.
- Apply protection solutions and evaluate their effectiveness.
- Laboratory demonstration of PEC-dense power system.
- Laboratory verification of PEC penetration related solutions.



Possible future protection solutions

■ Network fault detection?

- Using current? Voltage?
- Stability against transients?

■ Protection grading?

- Current? Short cables? Problematic?
- Time? Impact on sensitive loads?
- Energy storage? Capacitive discharge?

■ Need for communication?

- Unit protection?
- Backup?



Increased fault levels

- Significant penetration of DG may lead to increase in system fault levels
 - May be close to or exceed commercially-available breaker capacities
 - Plant thermal limits – worst case scenarios
 - Withstand and containment considerations
 - System design – cable clamping



Fault level reduction

- Fault level reduction may be achieved using
 - Network “splitting” to reduce parallel paths – increase impedance to fault
 - Use series-connected reactors – increase impedance
 - Increased transformer reactance
 - Dedicated fault current limiters - superconductors
- Fault level reduction often impacts on network performance – typically through voltage depression



Fault level reduction

- Superconducting fault current limiter
- When the current passing through the superconducting material increases above a threshold, the material rapidly becomes resistive, acting to “clamp” the current



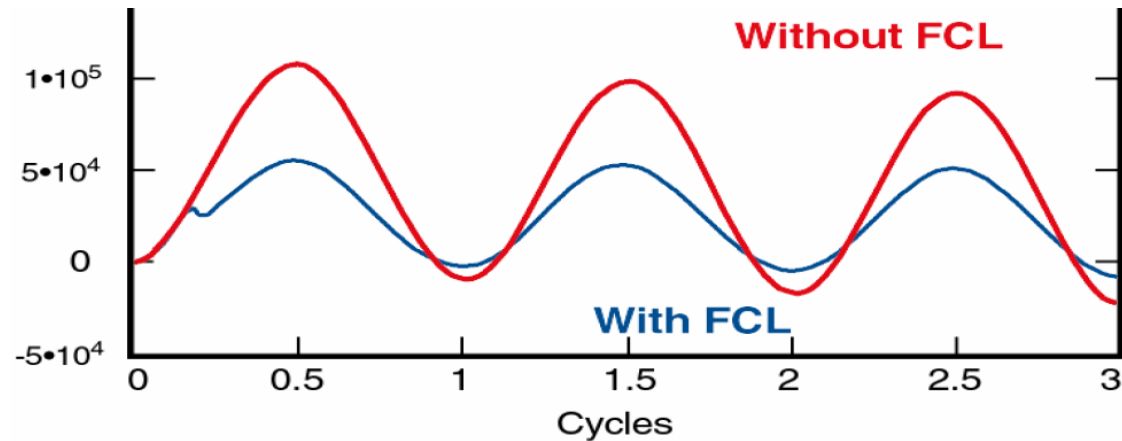
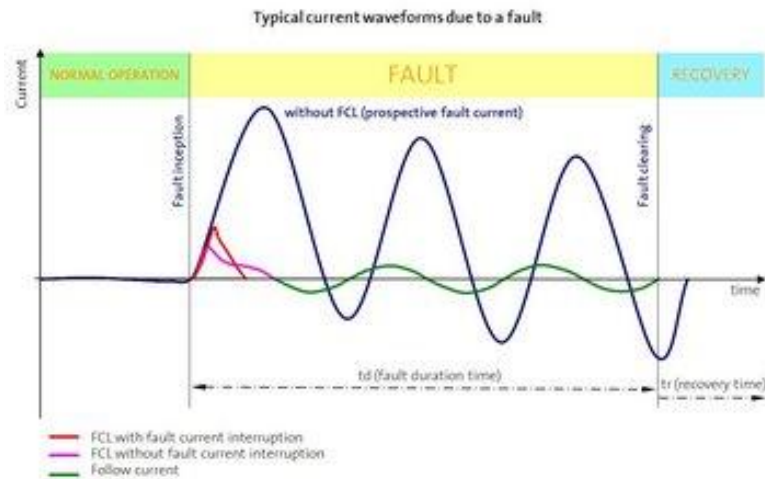
<http://www.scientificmagnetics.co.uk/cryogenic-systems.html>

<http://www.epriweb.com/public/000000000001009035.pdf>

http://en.wikipedia.org/wiki/Fault_current_limiter



Fault level reduction



<http://mydocs.epri.com/docs/public/000000000001009035.pdf>



Fault Current Limitation: Issues and Research Challenges

- Protection system implications
 - Fault detection in severely current-limited environments?
 - May be addressed using communications, unit protection, centralised protection
 - Research still required
- Other issues
 - Impact on network performance
 - Operation during normal transients
 - ...



Summary

- Conventional distribution networks
- How distribution network are changing (active distribution networks, DG, potential for islanded operation)
- Potential issues for future networks
 - Protection “blinding”
 - False tripping/coordination problems (several examples)
 - DG “ride-through”
 - Converter-interfaced sources
 - Use of DC for distribution?
 - Fault current limitation
- Protection solutions?

