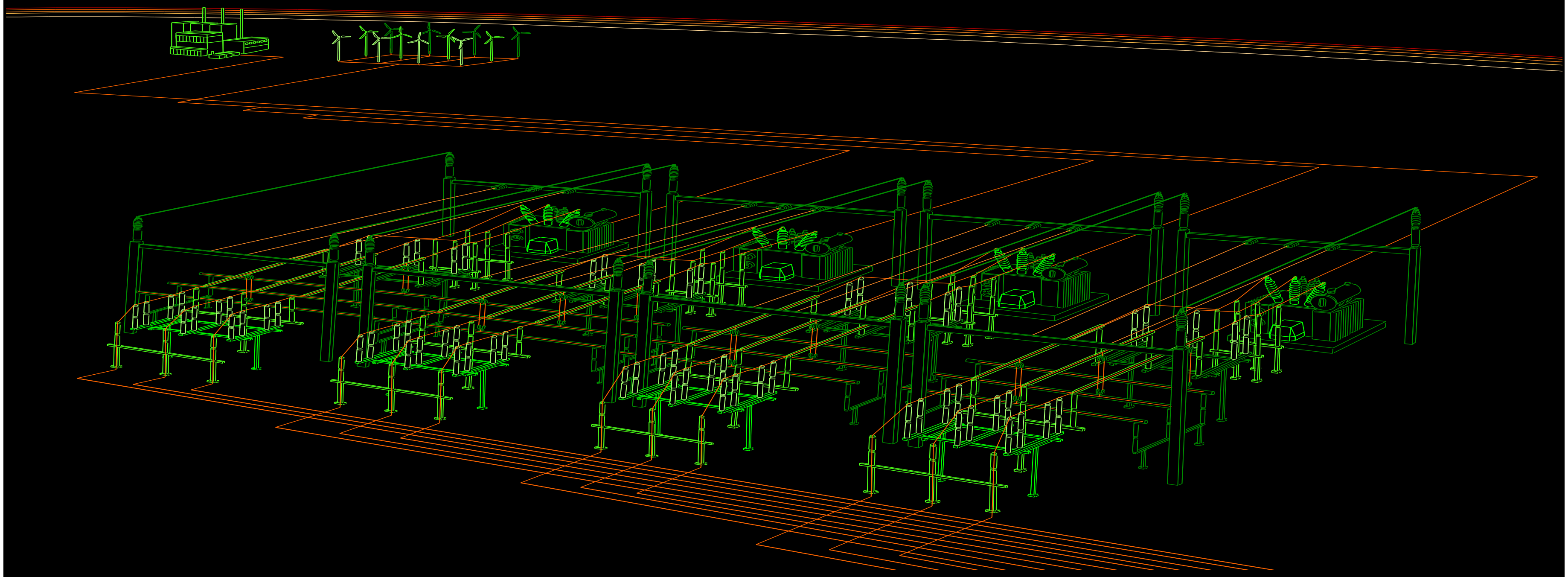


Alexandre Oudalov, ABB Switzerland Ltd., 2010.01.29

Microgrids – Novel Architectures for Future Power Systems

Protection Systems for Microgrids

Protection Systems for Microgrids
Outline

- Introduction
- Key protection issues
- Adaptive over-current protection based on:
  - Pre-calculated settings
  - Real time setting calculation
- Use of fault current source
- Conclusions

ABB

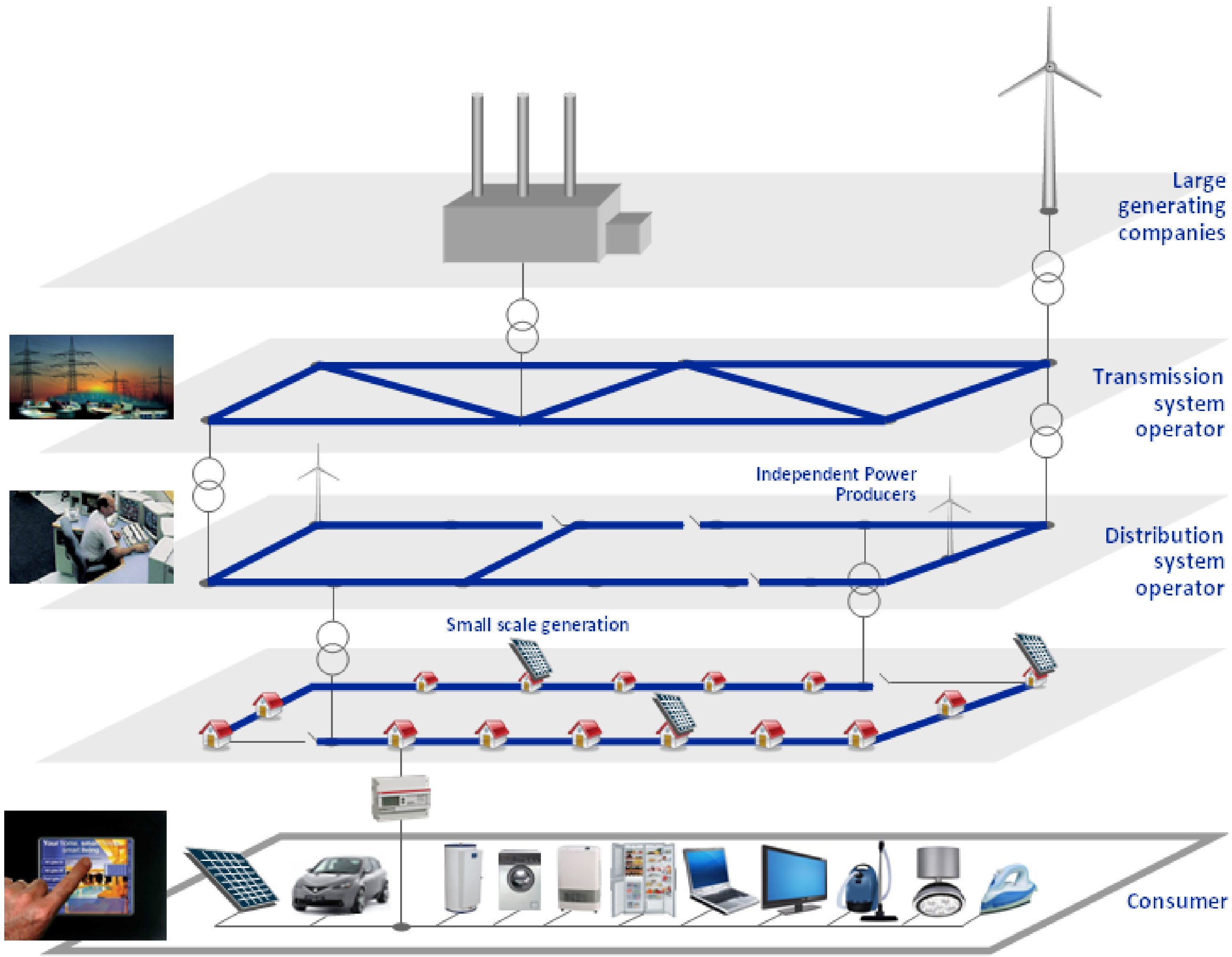
Hierarchy of Electric Power System
The way from Megawatts to Watts

1 High voltage transmission level, >110 kV, meshed grid

2 Medium voltage distribution level, 6-69 kV, radial grid

3 Low voltage distribution level, <1000 V, radial grid

4 Low voltage household level



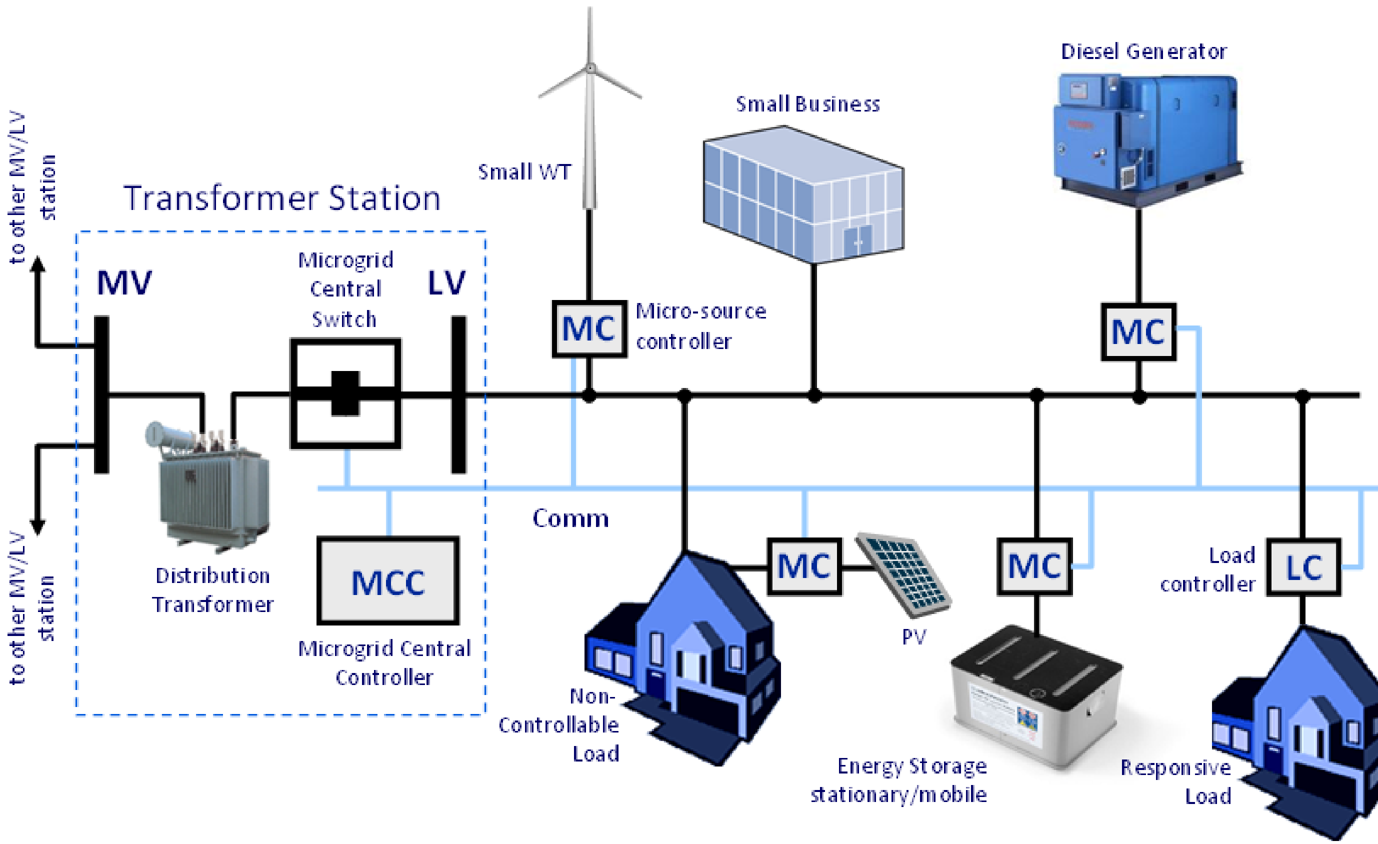
1 HV/MV substation 10 -100 MW (up to 10000 households)

2 MV/LV substation 100 kW – 10 MW (up to 1000 households)

3 Household connection point (up to 10 kW)

4 LV appliances (up to 5 kW)

Protection Systems for Microgrids
Grid connected and islanded modes

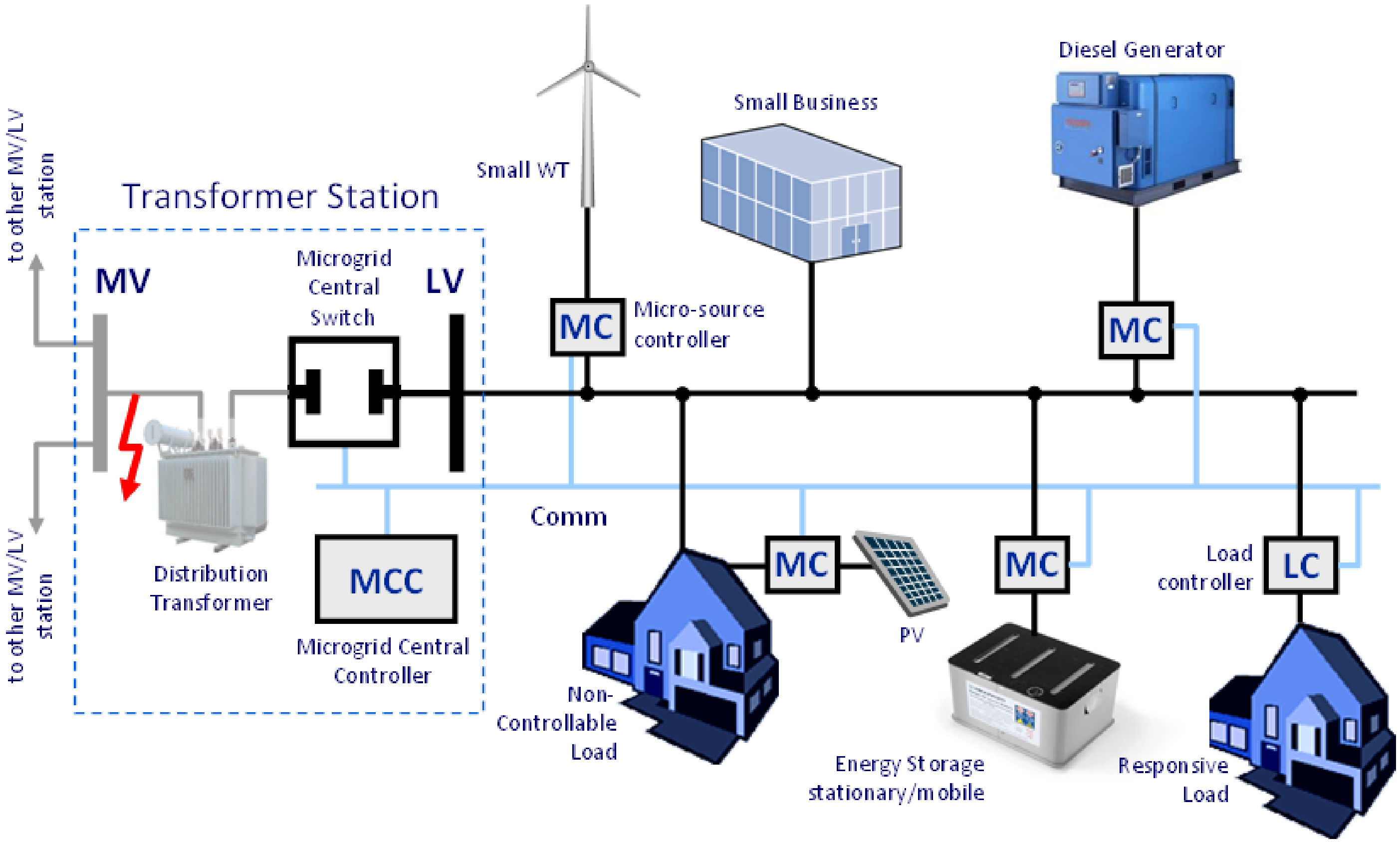


Protection must respond to both utility grid and microgrid faults

utility grid faults: protection isolates the microgrid from the utility grid as rapidly as necessary to protect the microgrid loads.

microgrid faults: protection isolates the smallest possible section of the radial feeder to eliminate the fault.

Protection Systems for Microgrids
Grid connected and islanded modes



Protection must respond to both utility grid and microgrid faults

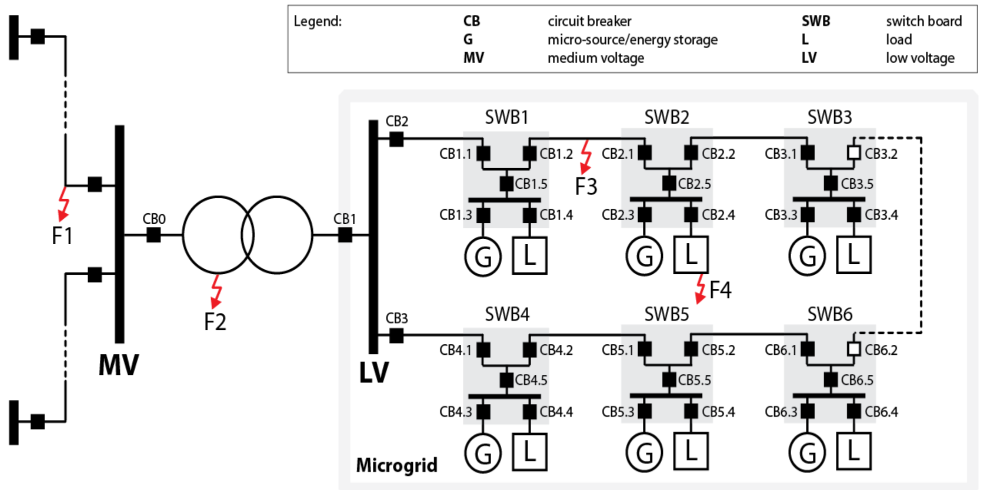
utility grid faults: protection isolates the microgrid from the utility grid as rapidly as necessary to protect the microgrid loads.

microgrid faults: protection isolates the smallest possible section of the radial feeder to eliminate the fault.

Protection Systems for Microgrids
Challenges

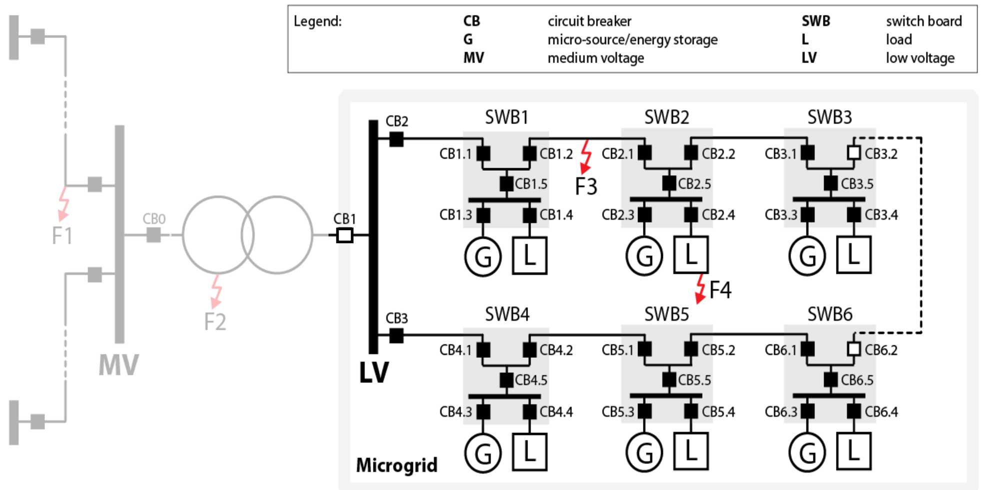
- Operating conditions of microgrids are constantly changing:
  - intermittent DERs
  - network topology change including islanding
- Short-circuit currents vary (both amplitude and direction) depending on microgrid operating conditions
- Availability of a sufficient short-circuit current level in the islanded operating mode of microgrid.
- A generic over-current protection with a single setting group may become inadequate. It will not guarantee a fault sensitivity or a selective operation for all possible faults

Protection Issues in Microgrids
Grid connected operation



Operating mode	Fault location			
	External faults (main grid)		Internal faults (microgrid)	
	MV feeder, bus-bar (F1)	Distribution transformer (F2)	LV feeder (F3)	LV consumer (F4)
Grid connected (CB1 is closed)	Fault is normally managed by MV system. Microgrid isolation by CB1 in case of no MV protection tripping. Possible fault sensitivity problems for CB1.	Fault is normally managed by MV system (CB0). CB1 is opened by “follow-me” function of CB0. In case if communication fails then possible fault sensitivity problem for CB1.	Disconnect a smallest portion of microgrid (CB1.2 and CB2.1). CB1.2 is opened by fault current from the grid (high level). Low level of a reversed fault current from feeder’s end may cause sensitivity problems for CB2.1. In this case a “follow-me” function of CB1.2 can open CB2.1. In case if communication fails then possible fault sensitivity problems for CB2.1.	Faulty load is isolated by CB2.4 or fuse. In case of no tripping the SWB is isolated by CB2.5 and local DER is cut-off. No sensitivity or selectivity problems.

Protection Issues in Microgrids
Islanded operation



Operating mode	Fault location			
	External faults (main grid)		Internal faults (microgrid)	
	MV feeder, bus-bar (F1)	Distribution transformer (F2)	LV feeder (F3)	LV consumer (F4)
Islanded (CB1 is open)	---	---	Disconnect the smallest portion of microgrid (CB1.2 and CB2.1). Low level of fault currents from both directions may cause sensitivity problems for CB1.2 and CB2.1.	Faulty load is isolated by CB2.4 or fuse. In case of no tripping the SWB is isolated by CB2.5 and local DER is cut-off. Low level of fault current may cause sensitivity problems for CB2.4 and CB2.5

Protection Issues in Microgrids
Needs for adaptive protection

- Simplest idea with two pre-computed setting groups (for grid and islanded modes) is not suitable
- It is essential to ensure that settings chosen for over-current relays take into account a microgrid state (topology and type and amount of connected DER)
- Relay settings must be checked/adapted periodically with regard to a current microgrid state to ensure a fault sensitivity and a selective tripping in case of the fault

Protection Systems for Microgrids
Novel protection systems

- Two main research directions:
  - Automatic adaptive protection, i.e. change of protection settings depending on the microgrid configuration:
    - Based on pre-calculated settings
    - Based on real-time calculated settings
  - Increase the amount of fault current level by help of a dedicated device

Adaptive Protection System for Microgrids
Requirements

- Use of digital (microprocessor based) OC relays (fuses or electro-mechanical and standard solid state relays are especially for selectivity holding inapplicable, because they don’t provide flexibility for setting of tripping characteristics).
- Digital OC relays must dispose of possibility for using different tripping characteristics (several setting groups, i.e. modern digital over-current relays for low voltage applications have up to 6 settings groups) that can be automatically parameterized locally or remotely.
- Use of new/existing communication infrastructure (e.g. twisted pair, power line, optic fibre, radio, etc.) and standard communication protocols (Modbus, Profibus, DeviceNet, IEC61850, etc.) such that individual relays can communicate and exchange information with a central unit or between different individual relays fast and reliably to guarantee a required application performance.

Adaptive Protection System for Microgrids
Based on pre-calculated values

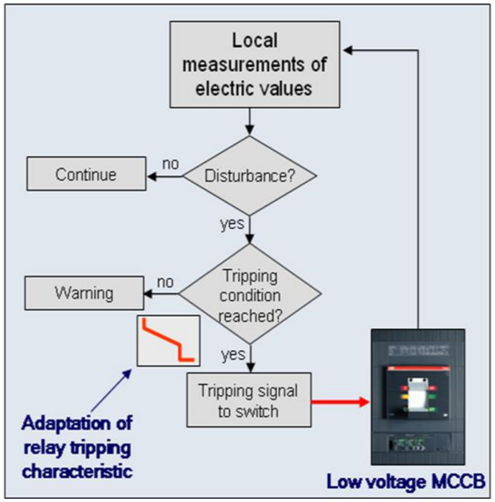
Use of existing ABB hardware:

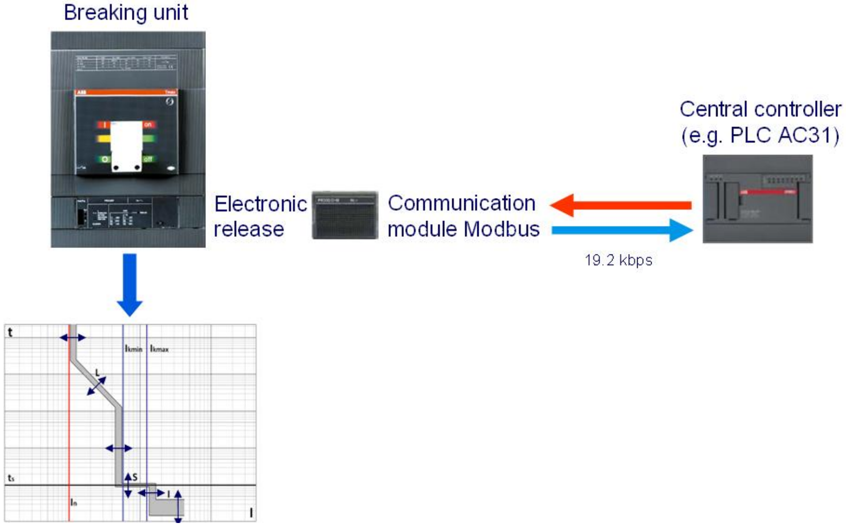
Moulded case circuit breakers

Electronic trip units with communication modules (Modbus).

Programmable Logic Controllers

- The main goal of the adaptive protection system is to adapt protection settings with regard to a current microgrid state
- The concept is based on real-time measurements (status of circuit breakers and DER output) and communication system
- By polling individual CBs the Microgrid Central Controller (MCC) can read data (electrical values, status) from CBs and if necessary modify protection settings (tripping characteristics)





Adaptive Protection System for Microgrids
Off-line analysis

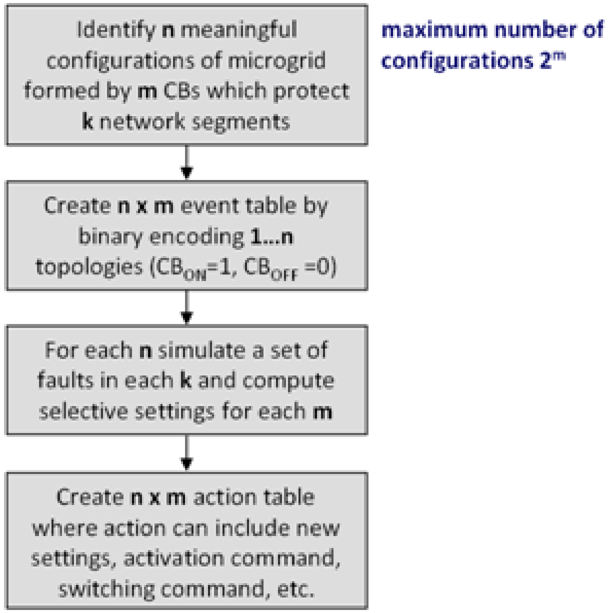
- A set of meaningful microgrid configurations (network and feeding-in states of DERs) is created for off-line fault analysis and is called an event table
- Each record in the event table has a number of elements equal to a number of monitored CBs in the microgrid and is binary encoded, i.e. element=1 if a corresponding CB is closed and 0 if it is open

	CB 0	CB 1	CB 2	CB 3	CB 1.1	CB 1.2	CB 1.3	CB 1.4	CB 1.5	CB 2.1	CB 2.2	CB 2.3	CB 2.4	CB 2.5	CB 3.1	CB 3.2	CB 3.3	CB 3.4	CB 3.5		CB6.4	CB6.5
Base case	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	....	1	1
Case 1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	0	1	1	....	0	1
⋮																						
Case n	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	....	1	1

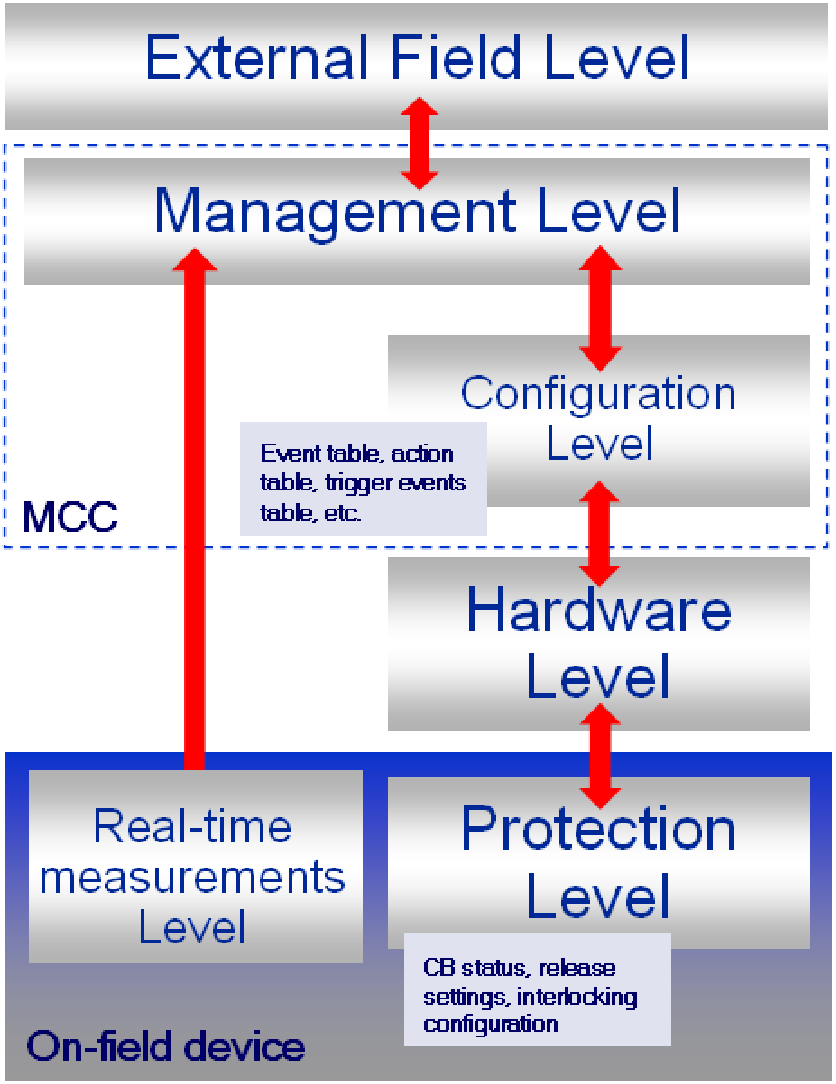
- Fault currents passing through all monitored CBs are calculated for various faults in different locations of the protected microgrid at a time
- During repetitive short-circuit calculations a topology or a status of a single DER is modified between iterations

Adaptive Protection System for Microgrids
Off-line analysis

- Based on these results suitable settings for each directional over-current relay and for each particular system state are calculated in a way that guarantees relay sensitivity and selectivity
- These settings are grouped into an action table which has the same dimension as the event table. In addition to a regulation of protection settings other actions such as activation of protection function can be done, e.g. a directional interlock can be activated in the islanding mode
- The event and action tables are part of the configuration level of the microgrid protection and control system



Adaptive Protection System for Microgrids
Based on pre-calculated values



Utility information (DMS and EMS), energy market price, weather forecast, etc.

Historic measurements, DMS and energy management software

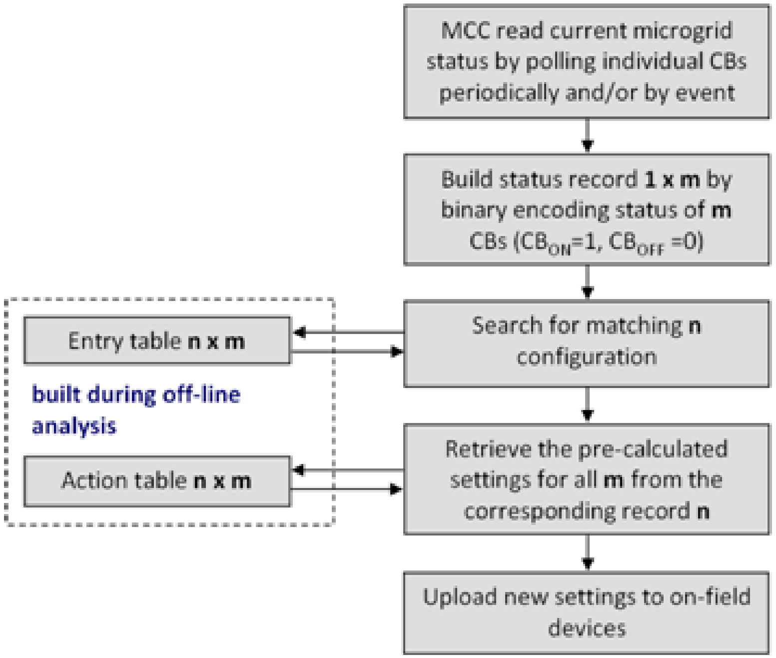
Station computer or PLC is able to detect a system status change and to send the required action to change a configuration to hardware level

Communication network between devices and central unit. In the case of a large distribution network, this function can be divided between several local controllers which communicate only selected information to the central unit. Hardware level transmits a required action from the configuration level to on-field devices

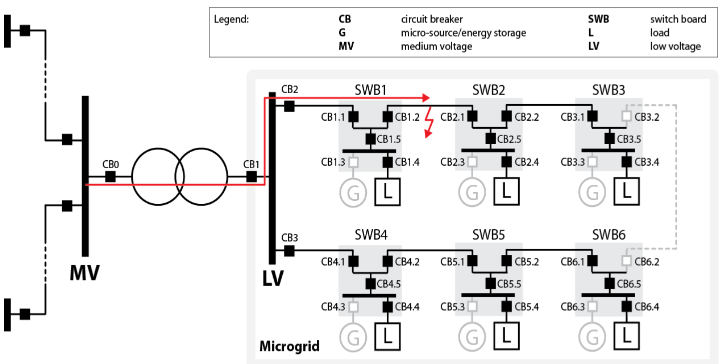
On-field devices

Adaptive Protection System for Microgrids
Based on pre-calculated values

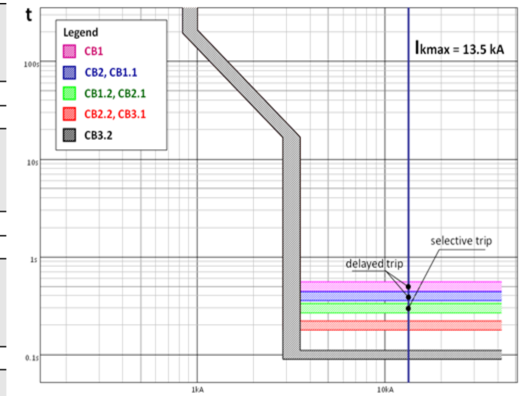
- MCC monitors the microgrid state by polling CBs (periodically or triggered by an event, e.g. tripping of CB, protection alarm, etc.)
- The microgrid state information is used to construct a status record which has a similar dimension as records in the event table.
- The status record is used to identify a corresponding entry in the event table.
- Finally, the algorithm retrieves the pre-calculated relay settings from the corresponding record in the action table and uploads the settings to on-field devices

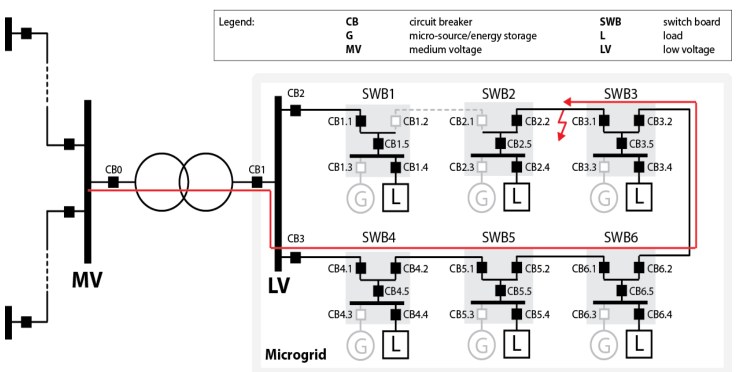


Adaptive Protection System for Microgrids
Based on pre-calculated values

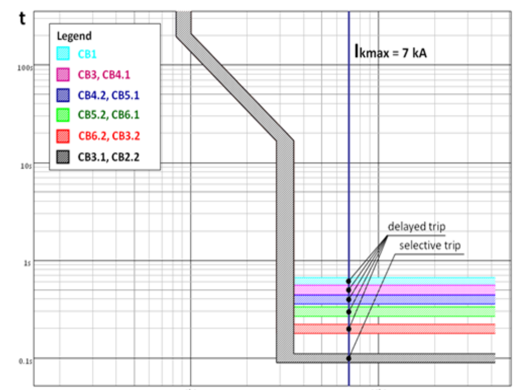


Upper feeder	CB1	CB2	CB1.1	CB1.2	CB2.1	CB2.2	CB3.1	CB3.2	
	1	1	1	1	1	1	1	0	
	0.5	0.4	0.4	0.3	0.3	0.2	0.2	0.1	
Lower feeder		CB3	CB4.1	CB4.2	CB5.1	CB5.2	CB6.1	CB6.2	
		1	1	1	1	1	1	0	
		0.4	0.4	0.3	0.3	0.2	0.2	0.1	
DER + load	CB1.3	CB1.4	CB1.5	CB2.3	CB2.4	CB2.5	CB3.3	CB3.4	CB3.5
	0	1	1	0	1	1	0	1	1
DER + load	CB4.3	CB4.4	CB4.5	CB5.3	CB5.4	CB5.5	CB6.3	CB6.4	CB6.5
	0	1	1	0	1	1	0	1	1



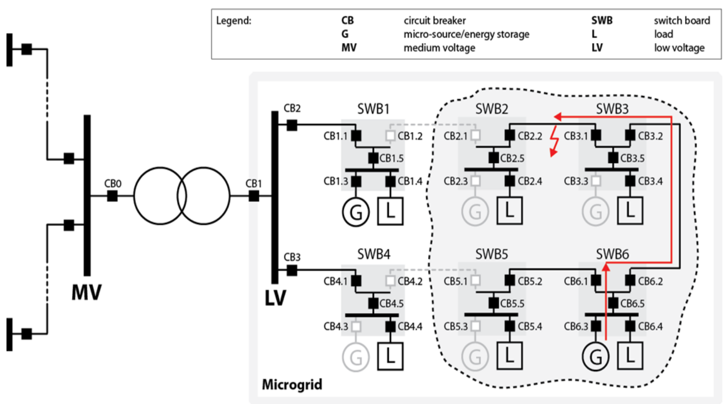


Upper feeder	CB1	CB2	CB1.1	CB1.2	CB2.1	CB2.2	CB3.1	CB3.2	
	1	1	1	0	0	1	1	1	
	0.6	0.3	0.3	0.2	0.2	0.1	0.1	0.2	
Lower feeder		CB3	CB4.1	CB4.2	CB5.1	CB5.2	CB6.1	CB6.2	
		1	1	1	1	0	1	1	
		0.5	0.5	0.4	0.4	0.3	0.3	0.2	
DER + load	CB1.3	CB1.4	CB1.5	CB2.3	CB2.4	CB2.5	CB3.3	CB3.4	CB3.5
	0	1	1	0	1	1	0	1	1
DER + load	CB4.3	CB4.4	CB4.5	CB5.3	CB5.4	CB5.5	CB6.3	CB6.4	CB6.5
	0	1	1	0	1	1	0	1	1

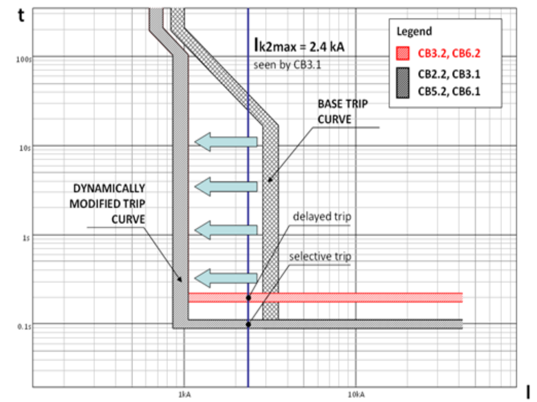


Position of CBs (1=close and 0=open) from event table and tripping time delays from action table for two possible network topologies (no DER)

Adaptive Protection System for Microgrids
Based on pre-calculated values



Upper feeder		CB1	CB2	CB1.1	CB1.2	CB2.1	CB2.2	CB3.1	CB3.2
		1	1	1	0	0	1	1	1
	I_{kmin}	3.2	3,2	3.2	3.2	3.2	1.2	1.2	1.2
	t_s	0.5	0.4	0.4	0.3	0.3	0.1	0.1	0.2
Lower feeder			CB3	CB4.1	CB4.2	CB5.1	CB5.2	CB6.1	CB6.2
			1	1	0	0	1	1	0
	I_{kmin}		3.2	3.2	3.2	3.2	1.2	1.2	1.2
	t_s		0.4	0.4	0.3	0.3	0.1	0.1	0.2
DER + load	CB1.3	CB1.4	CB1.5	CB2.3	CB2.4	CB2.5	CB3.3	CB3.4	CB3.5
	1	1	1	0	1	1	0	1	1
DER + load	CB4.3	CB4.4	CB4.5	CB5.3	CB5.4	CB5.5	CB6.3	CB6.4	CB6.5
	0	1	1	0	1	1	1	1	1



Position of CBs (1=close and 0=open) from event table and tripping time delays and minimum fault current levels in kA from action table for the islanded microgrid case (with DER)

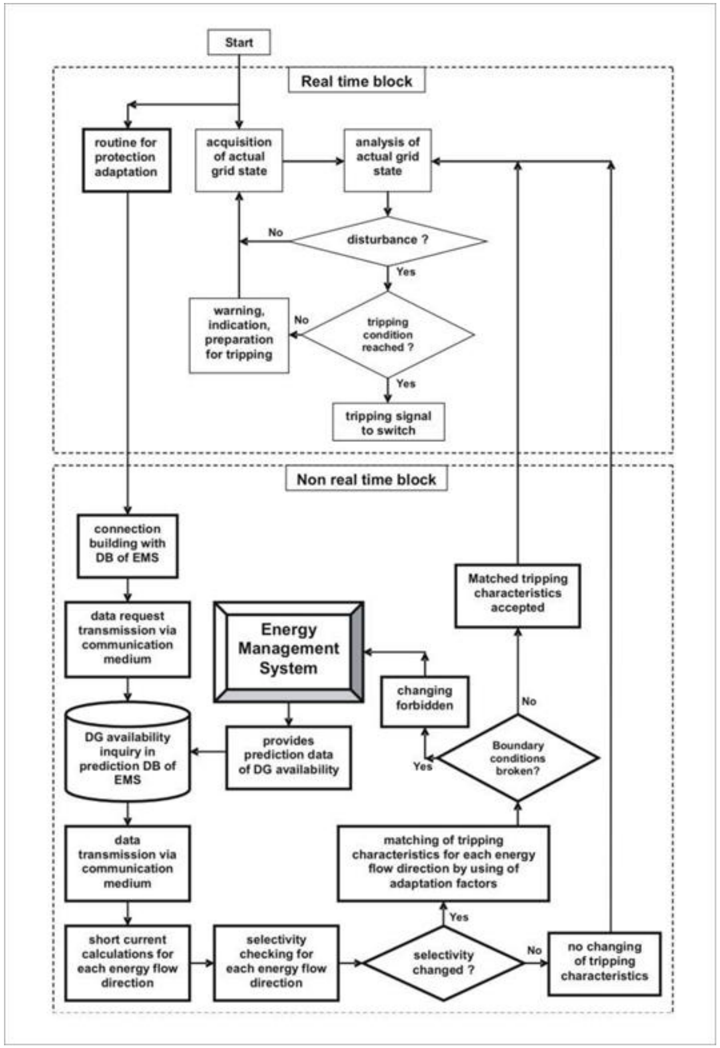
In case all CBs in the island have the same fault current settings we anticipate a use of adaptive directional interlock

Adaptive Protection System for Microgrids
Based on pre-calculated values

- Utility unwillingness to modify protection parameters
- Pre-calculated settings:
  - Can be tested and double-checked beforehand
  - Low infrastructure requirements: reading switch positions, (uploading new settings), switching setting groups.
  - The approach is limited by the number of possible topology configurations
- Alternatively, an on-line calculation of settings is possible:
  - It is not instantaneous
  - Calculation is subject to protection philosophy (e.g. margins)
  - In lieu of testing the settings, the algorithm must be thoroughly verified

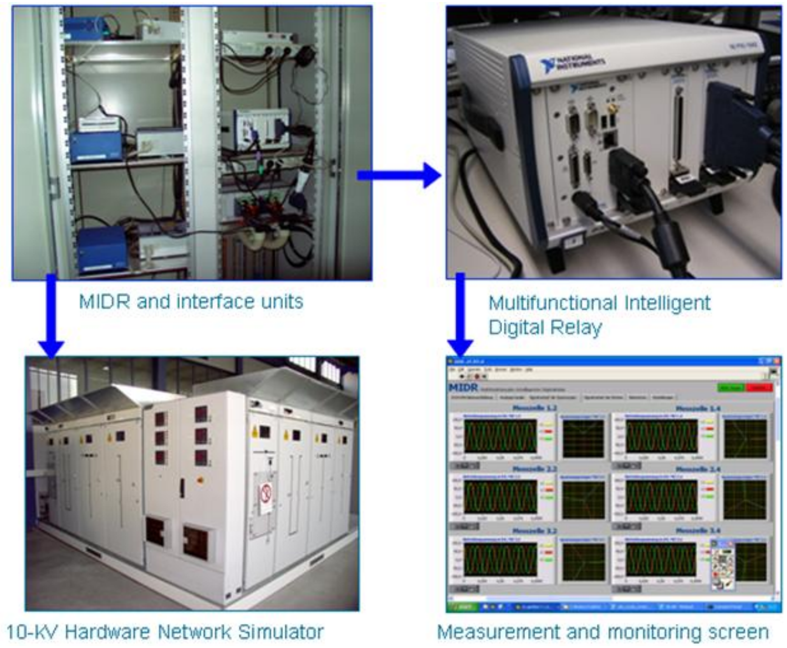
Adaptive Protection System for Microgrids
Based on real time calculations

- A new protection concept consists of:
  - A non-real time block which saves in a data base the detailed information about characteristics of all microgrid units: lines, transformers and DER (provided short circuit power).
  - A real time block analyses the grid operation continuously and calculates the actual short-circuit current supplied by all available DER connected to the appropriate feeder and adapts if necessary settings for protection units.



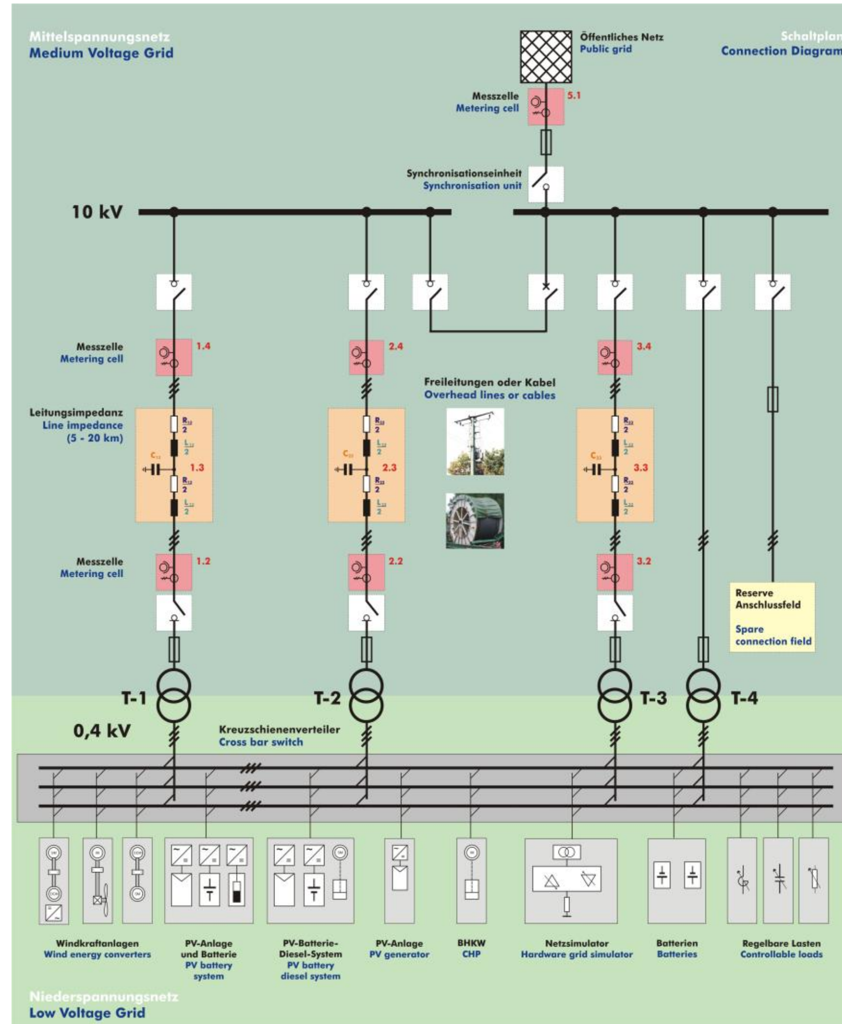
Adaptive Protection System for Microgrids
Based on real time calculations

- Developed hard- and software platform Multifunctional Intelligent Digital Relay (MIDR) permits automatic adaptation of protection settings, according to the actual grid structure and operation of DER.
- The MIDR allows continuous monitoring of the analogue and digital signals originating from equipment and network.
- In case of a grid fault the MIDR generates selective tripping signals which are sent to respective circuit breaker/s.



Adaptive Protection System for Microgrids
Based on real time calculations

- The MIDR was validated by performing experiments in a laboratory.
- For the tests the MIDR was connected to a 10-kV hardware network simulator.
- Current and voltage measurements have been processed by the MIDR in real-time.
- Data from the EMS were received periodically

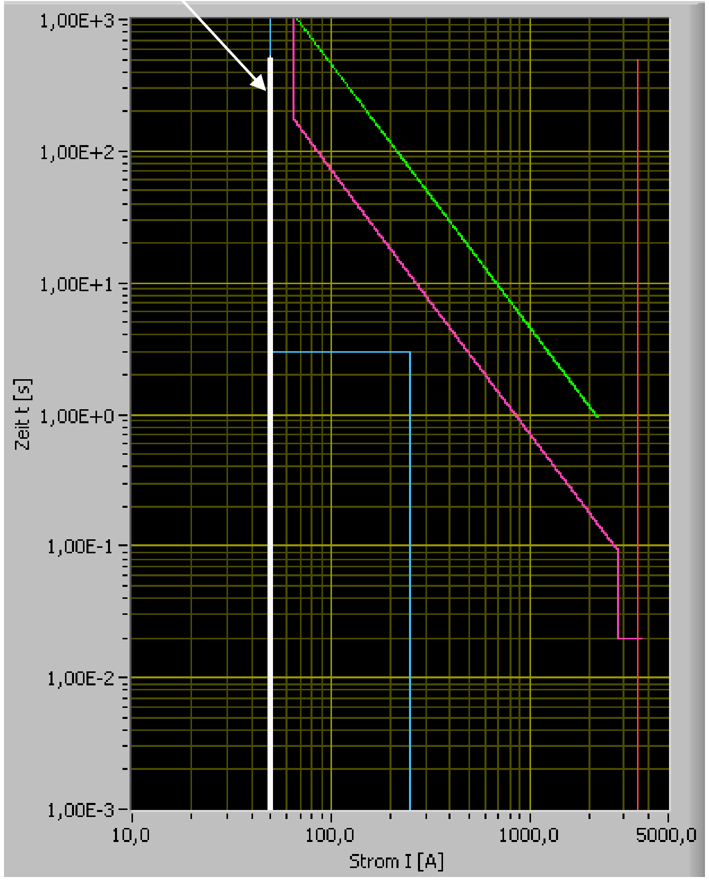


ISET Fraunhofer IWES ABB

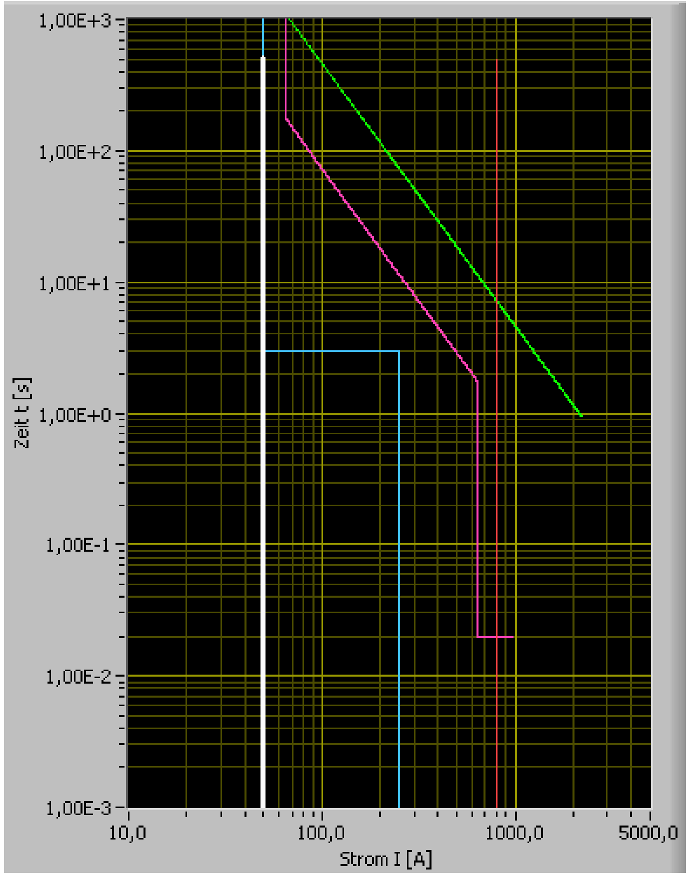
Adaptive Protection System for Microgrids
Based on real time calculations

Available short circuit power
Tripping characteristic of CB
Damage curve of LV cable

Nominal load (motor) current   Motor start-up characteristic



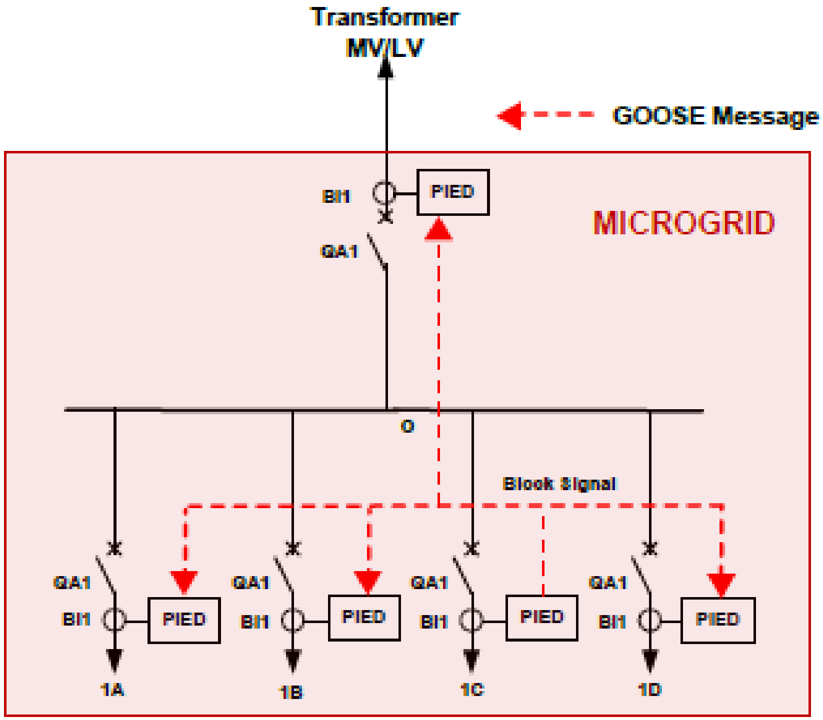
Grid connected



Islanded

Adaptive Protection System for Microgrids
Decentralized approach

- The most significant advantage of a centralized architecture is that local devices don't take decisions, and therefore are simple. The effort of data processing and decision making falls on the central unit based on data received from the local devices.
- The main disadvantage of a centralized architecture is well-known, the dependence on the central unit. A failure in the central unit means the lost of the whole adaptive protection system.
- Decentralized adaptive protection is possible based on p2p communication, considering standard protocols (e.g. IEC 61850 Goose messages) and Ethernet communications.



Fault Current Source
Ensures the fault level in inverter dominated microgrids

- Normally fault current is supplied from MV utility grid
- Local generation in an island may be dominantly inverter-based
- Most commercial LV inverters cannot be overloaded and do not provide fault ride-through
- Network may collapse by a simple fault inside a dwelling
- Do not enforce sophisticated protection in customer's premises. Use classical fuses or CBs
- At least one resource must deliver a fault current high enough to ensure operation and selectivity of protections
- If high-power storage is present, this is an ideal candidate
- If there is no suitable candidate, use a separate Fault Current Source (FCS)

Fault Current Source
Ensures the fault level in inverter dominated microgrids

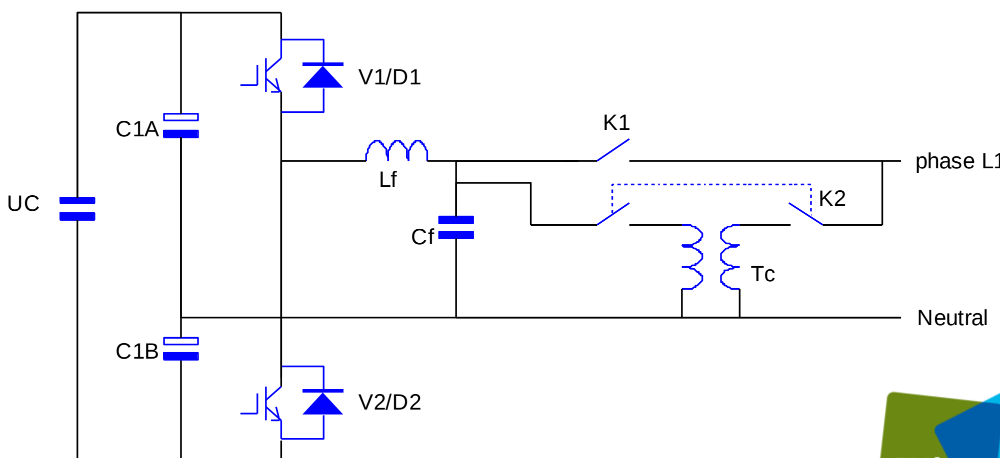
- An FCS is connected to the "main" low voltage bus in parallel to the network and contains:
  - A slow-charge, rapid-release electricity storage
  - An inverter in idle mode, rated to deliver a high current for a few seconds
  - A short-circuit detection unit (measure local voltage)
  - A charging circuit to restore the status of energy storage device

Ultra-capacitor stack storing 100 kJ of energy

IGBT inverter delivering 200 A max

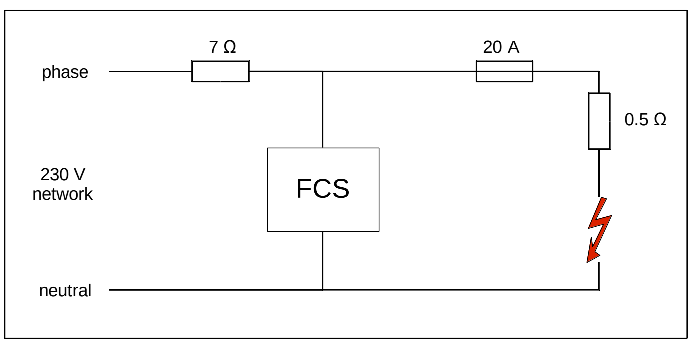
Basic output **filter** (harmonic requiremen ts are of minor importance)

Transformer for pre-charging of energy store



Fault Current Source
Test results

- The principle and effectiveness of an FCS has been demonstrated
- After clearing the fault, the FCS sustains the voltage long enough for inverters to resynchronize and connect
- The FCS is a modular system, multiple units can be installed in parallel for reliability and to suit local fault level requirement

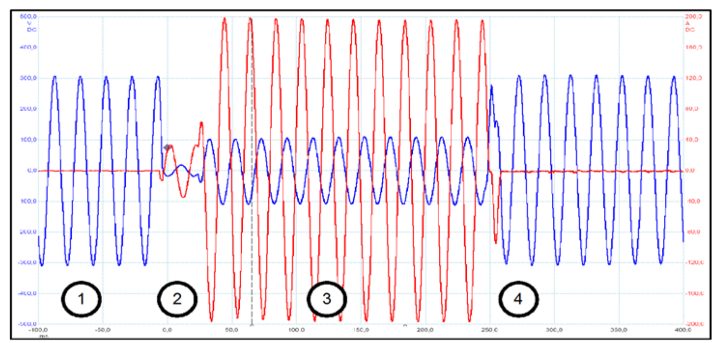


High network impedance

Low-impedance fault

Fault current too low to trip fuse

FCS at “busbar” location to resolve this...



1: undisturbed voltage

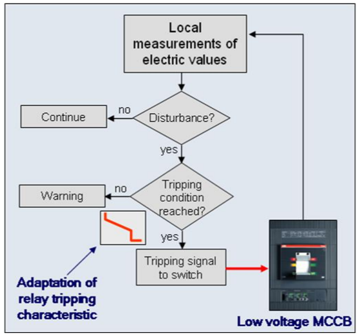
2: short-circuit occurs

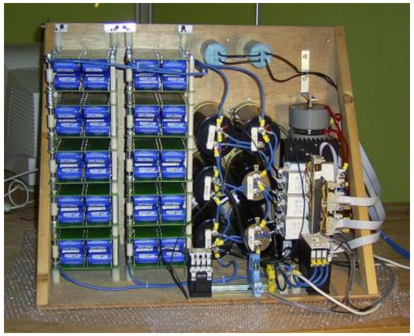
3: FCS kicks in

4: fuse blows, voltage restored

Protection Systems for Microgrids
Exploitable results

- Various protection solutions for microgrids have been developed, implemented and successfully tested:
  - Adaptive protection coordination based on pre-computed settings
  - Adaptive protection coordination based on real-time calculations of relay settings
  - Use of fault current source in the inverter dominated microgrids





Protection Systems for Microgrids
Further reading

- Project deliverable DC2, “Novel Protection Systems for Microgrids”. Available at www.microgrids.eu
- T. Keil, J. Jäger, A. Shustov, T. Degner, “Changing network conditions due to distributed generation – systematic review and analysis of their impacts on protection, control and communication systems”, CIRED2007, Vienna, 21-24 May 2007, paper no. 0527
- F. van Overbeeke, “Fault current source to ensure the fault level in inverter-dominated networks”, CIRED2009, Prague, 8-11 June 2009, paper no. 0369
- Alexandre Oudalov, Antonio Fidigatti, “Adaptive Network Protection in Microgrids”, International Journal of Distributed Energy Resources, Vol.5, No.3, pp.201-226, July-September 2009

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