Smart micro-grids

Properties, trends and local control of energy sources

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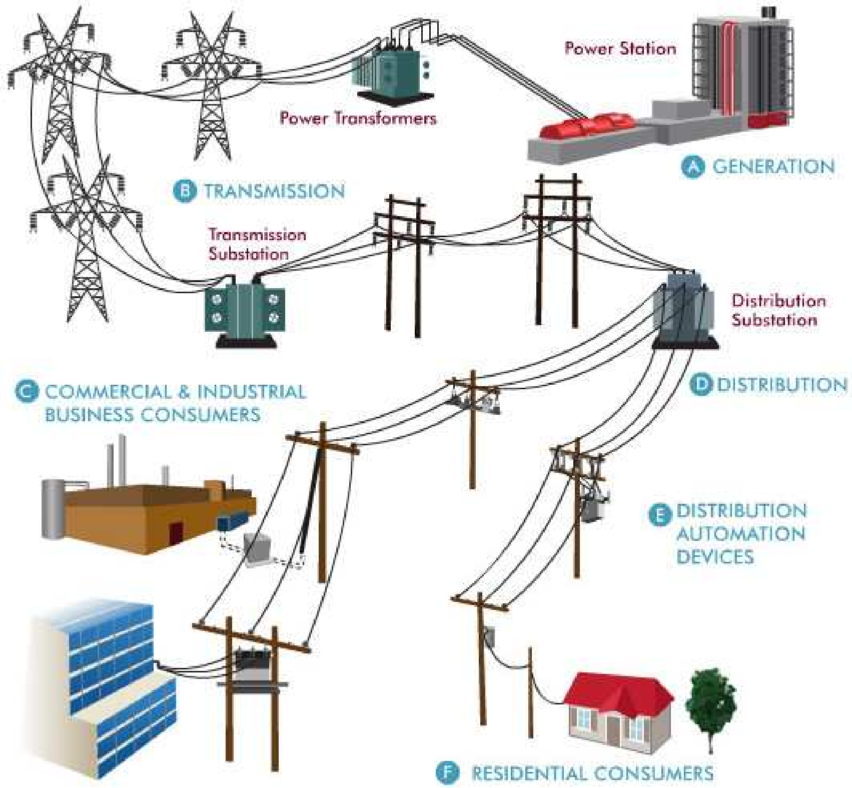
Outline

Smart micro-grids

Properties, trends and local control of energy sources

1. From the traditional grid to the smart grid

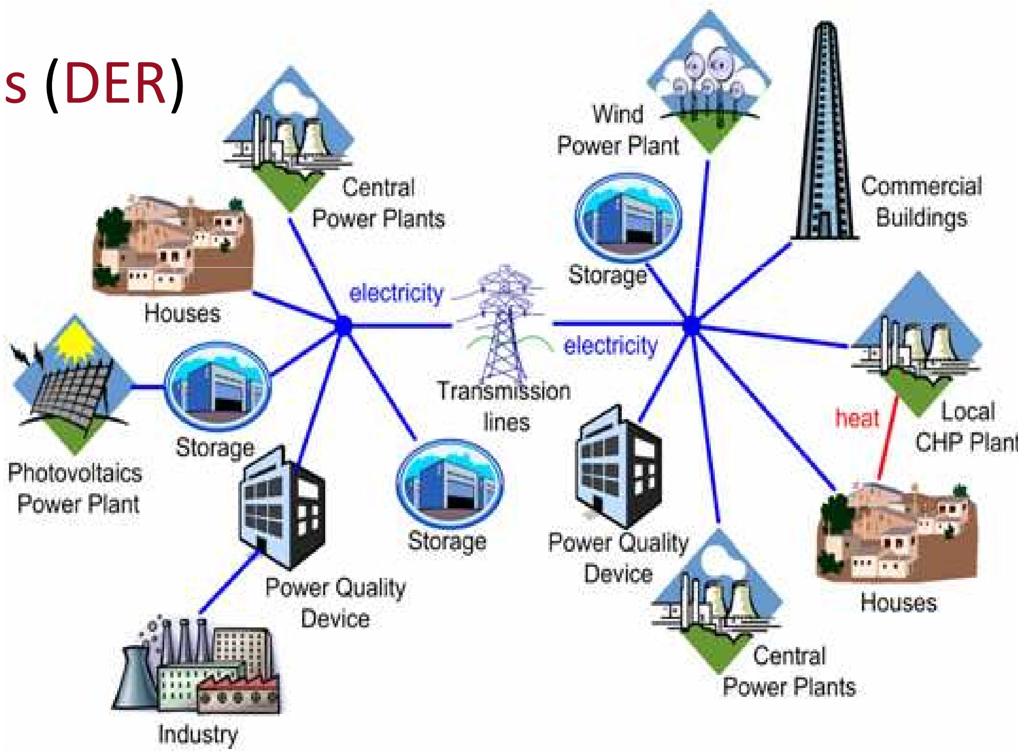
The traditional grid



- Few large power plants feeding large number of end-users
- Power plants located in strategic sites (cost-effective generation, safety)
- Centralized control (dispatcher)
- Unidirectional power flow
- Independent operation of each apparatus (the power grid performs nearly as an ideal voltage source with small internal impedance)
- No customers' participation to power balance

The smart grid

- Local-scale power grids which can operate in utility-connected or islanded mode
- Distributed Energy Resources (DER)
- Bidirectional power flow
- Weak grid, causing interaction of power sources and loads
- Multilateral contribution to power balance
- Intelligent and controllable electronic interfaces between energy sources and grid



Benefits of the smart grid

- Distributed renewable resources
  - lower emission
  - energy cost reduction
- Energy efficiency
  - power sources close to loads, demand response
- Improved utilization of conventional power sources
  - less active, reactive, unbalance and distortion power
- Voltage support
  - distributed injection of active and reactive power
- Increased hosting capacity
  - without investment in grid infrastructure

Challenges of the smart grid

- Bidirectional power flow
  - new control and protection strategies
  - conventional voltage stabilization techniques not applicable
- Weak grid (non-negligible internal impedance)
  - voltage distortion due to nonlinear loads
  - voltage asymmetry due to unbalanced loads and single-phase DER units (PV, batteries, …)
- Irregular power injection by renewable energy sources
  - need for power flow regularization and peak power shaving
  - need for energy storage devices

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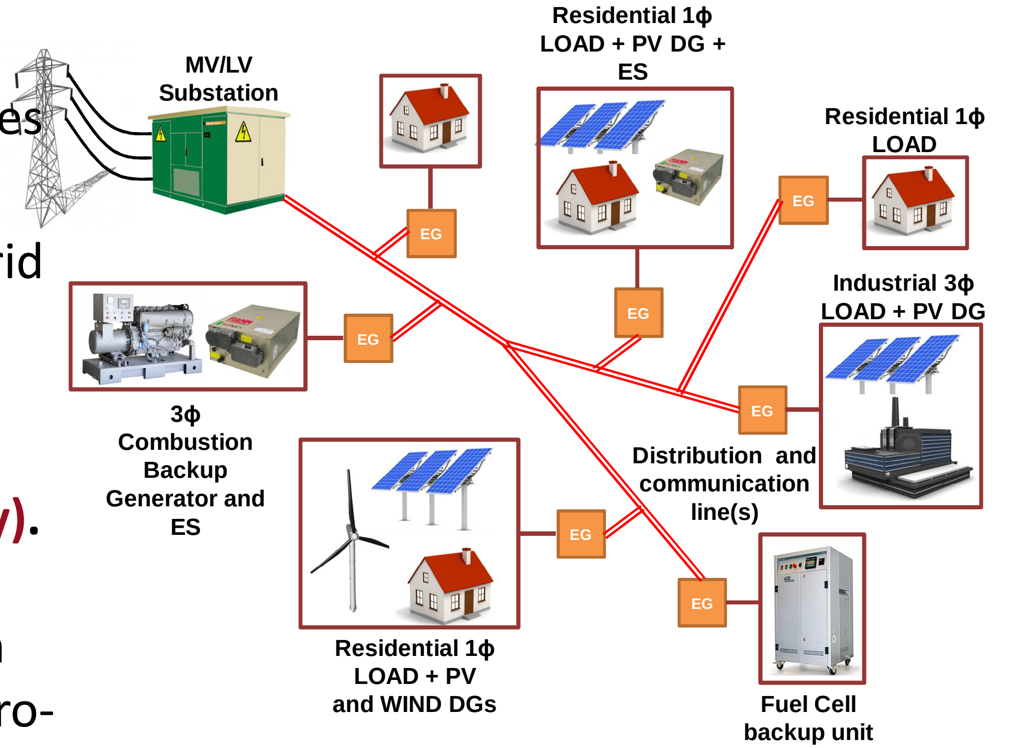
2. The potential revolution of the smart micro-grid

LV residential micro-grids

General Definition: A Smart Grid is an electrical power delivery system where power quality, efficiency and energy cost are **optimized** by pervasive use of **information and communication technology** to control **distributed energy resources**

Low-voltage Microgrid = distribution system connecting a MV/LV substation with loads & distributed energy resources (DERs).

- DERs interface with the distribution grid by electronic power processors (inverters) equipped with local measurement, control and communication **(EG = Energy Gateway)**.
- EGs may implement **bidirectional power control and communicate** with other generators and loads of the micro-grid



Expected benefits of micro-grids

Environment & savings

- Green power
- Full utilization of distributed energy resources
- Reduced distribution loss
- Increased hosting capacity
- Increased power quality even in remote locations
- Layered grid architecture

Social & economics

- Strengthen consumers role
- Develop communities of prosumers
- New functions and players in the energy market
- New arena for entrepreneurs, manufacturers and service providers
- New jobs for green collars

Paradigm: The **INTERNET of ENERGY**

Technological challenges

- Exploit every available energy source
- Minimize distribution losses and non-renewable energy consumption
- Increase power quality and hosting capacity
- Implement cheap ICT architectures for distributed control and communication
- Integrate micro-grid control and domotics
- Revise accounting principles and methodologies
- Restructure network protection
- Assure data security and privacy
- Pursue flexibility and scalability (from buildings to townships)

The future of micro-grids

- UE Roadmap for micro-grids (CIGRE 2010)
- Smart grid investment forecast (JRC report 2011)

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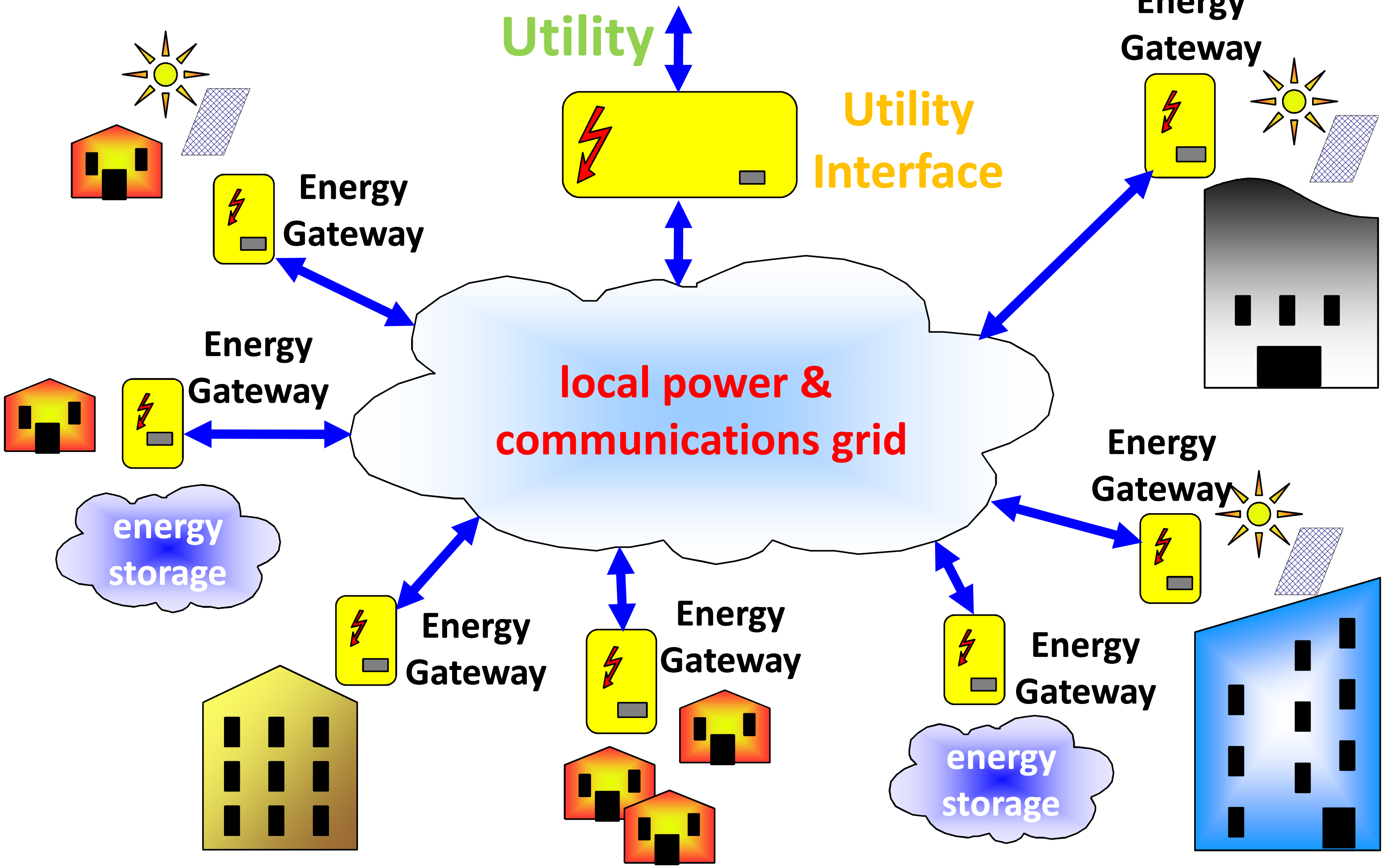
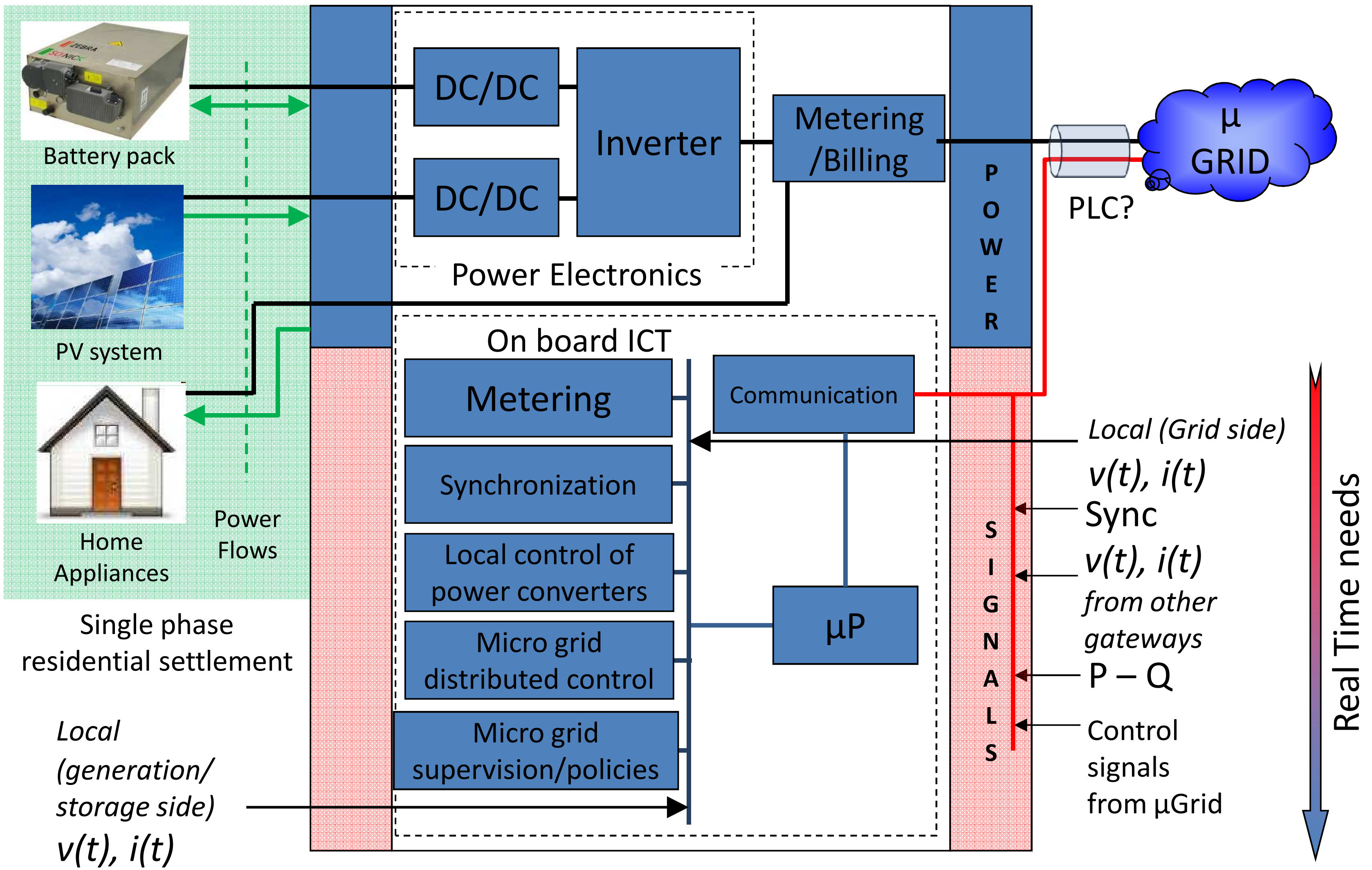
3. Smart micro-grid architecture

General sketch of a micro-grid



Energy Gateway – functional diagram



Utility Interface – functional diagram

Three phase distribution infrastructure

Energy Storage

Power Electronics

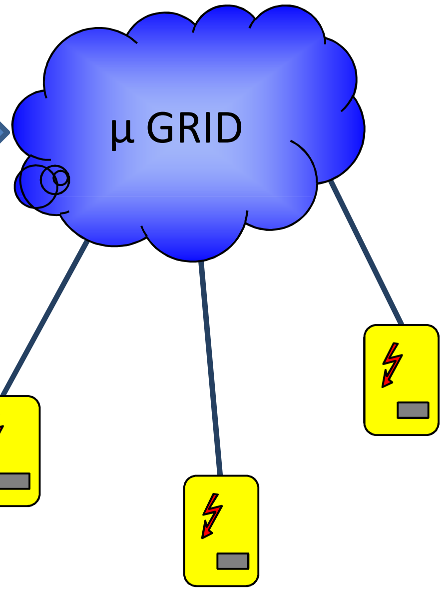
System Policies:

- Aggregator (enabling distributed prosumers to perform cooperative Energy Management & Demand Response)
- Managing Islanded Operation
- Ancillary Services to Grid
  - In a mature Smart Grid scenario: key player to mediate between aggregate customers and market

I/O INTERFACE

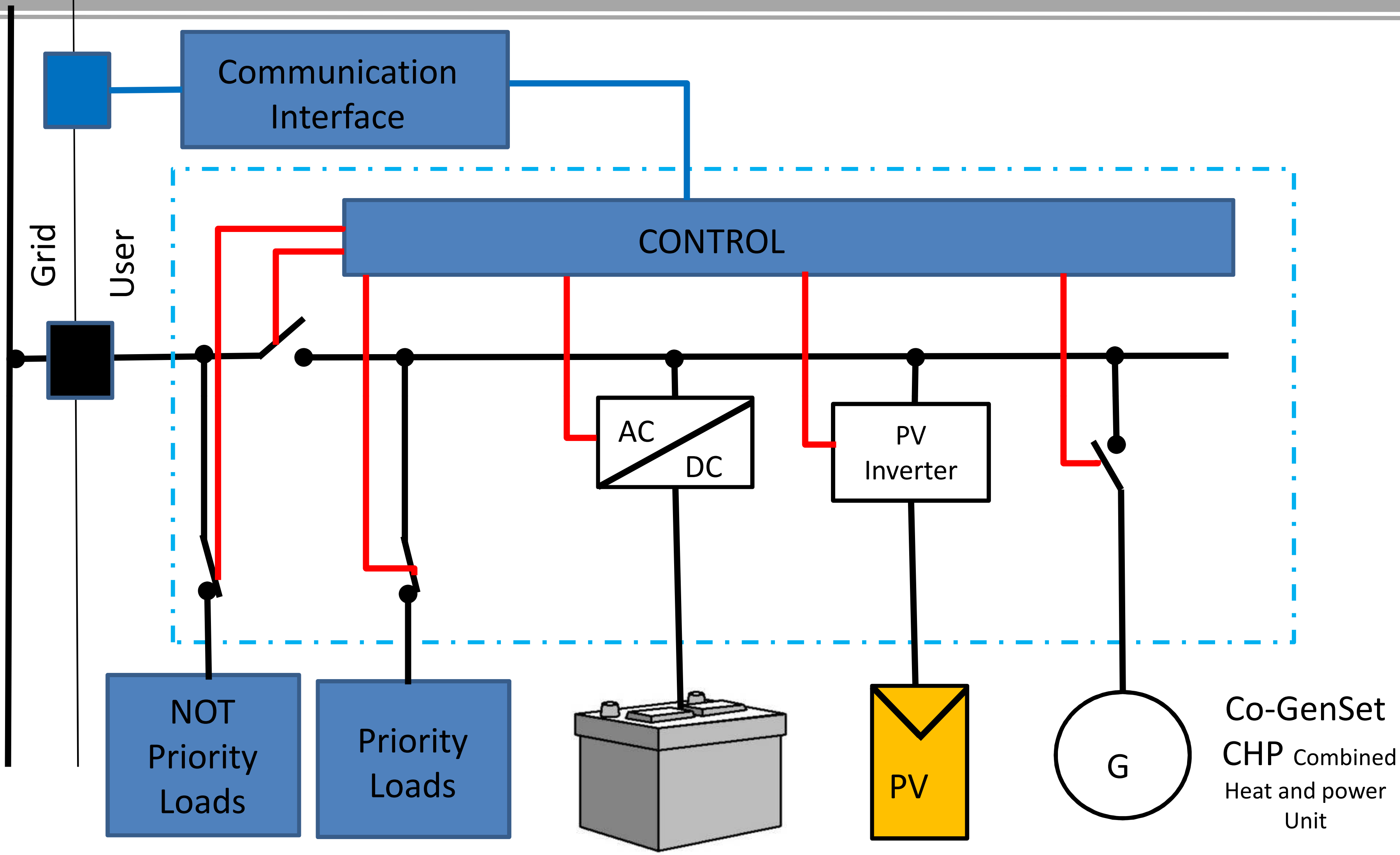
Communication with μ-Grid and utility

Concept idea: micro-grid to appear as an 'ideal' programmable load



energy gateways

Retrofitting existing plants



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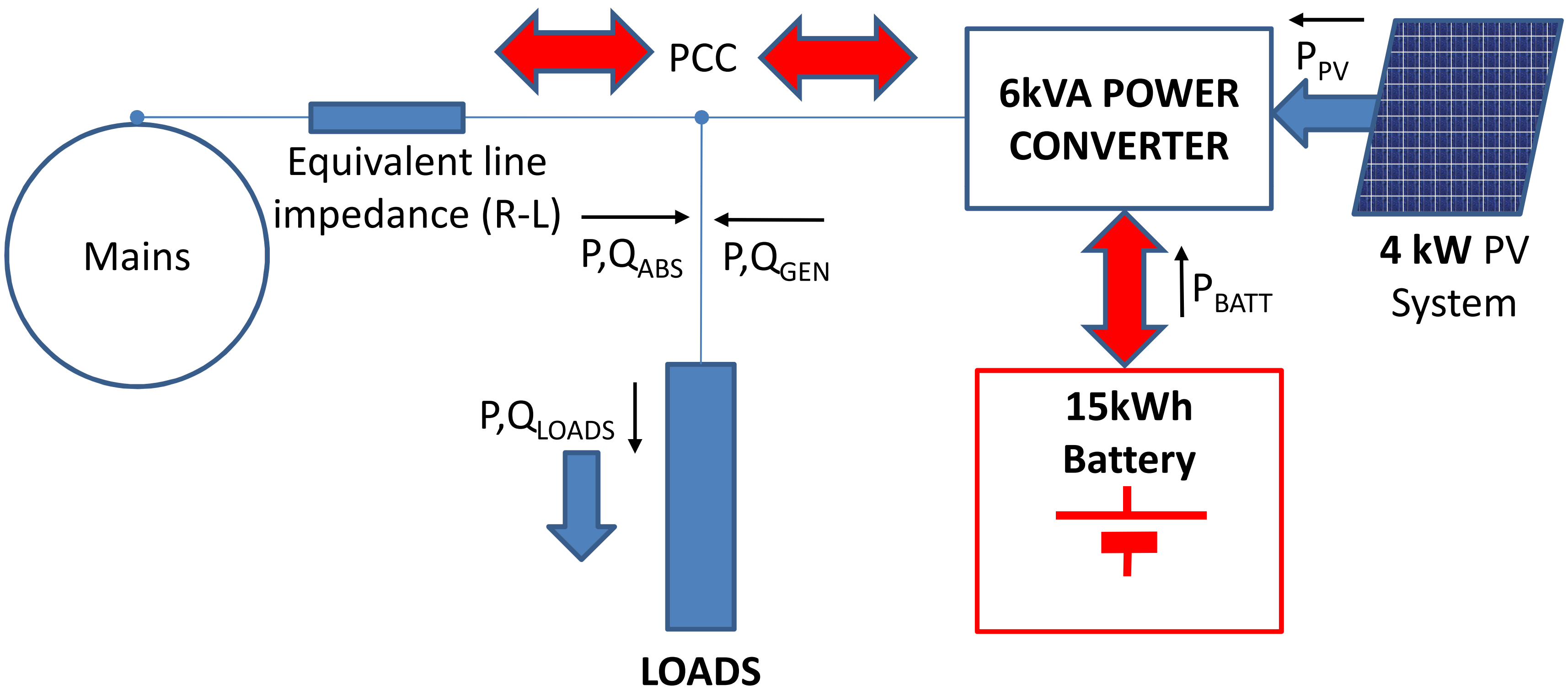
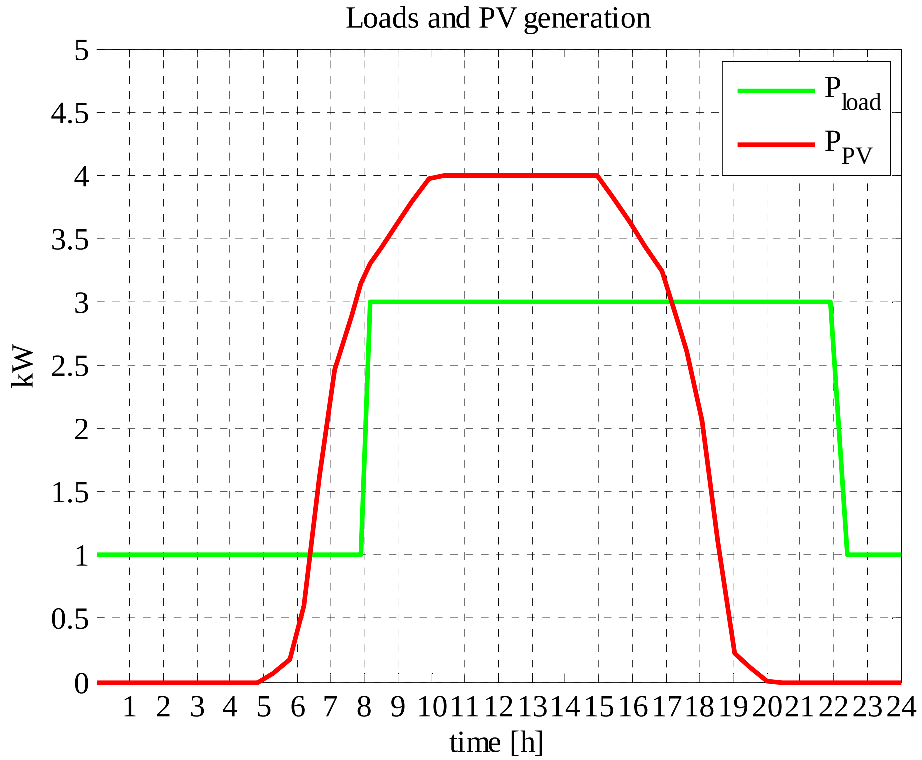
4. The role of energy storage

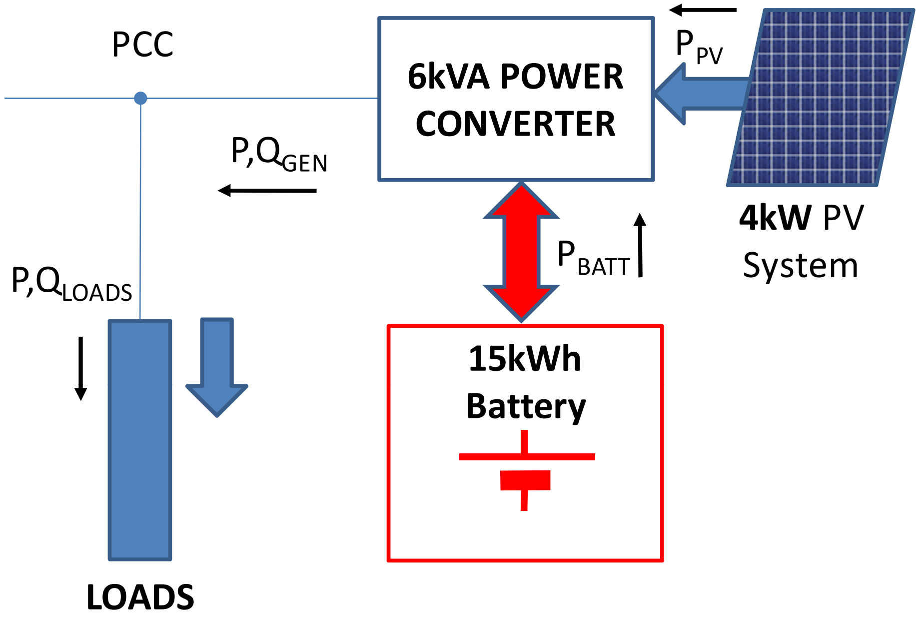
Energy efficiency – local features

Residential settlement with loads, PV generation and energy storage connected to the mains via cabled distribution line



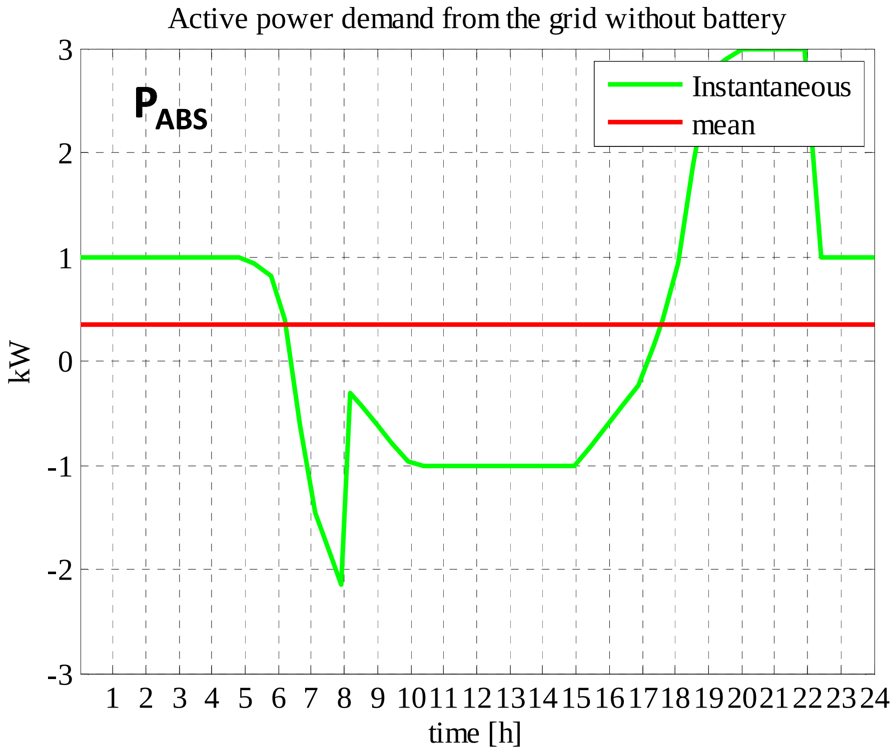
Power profiles

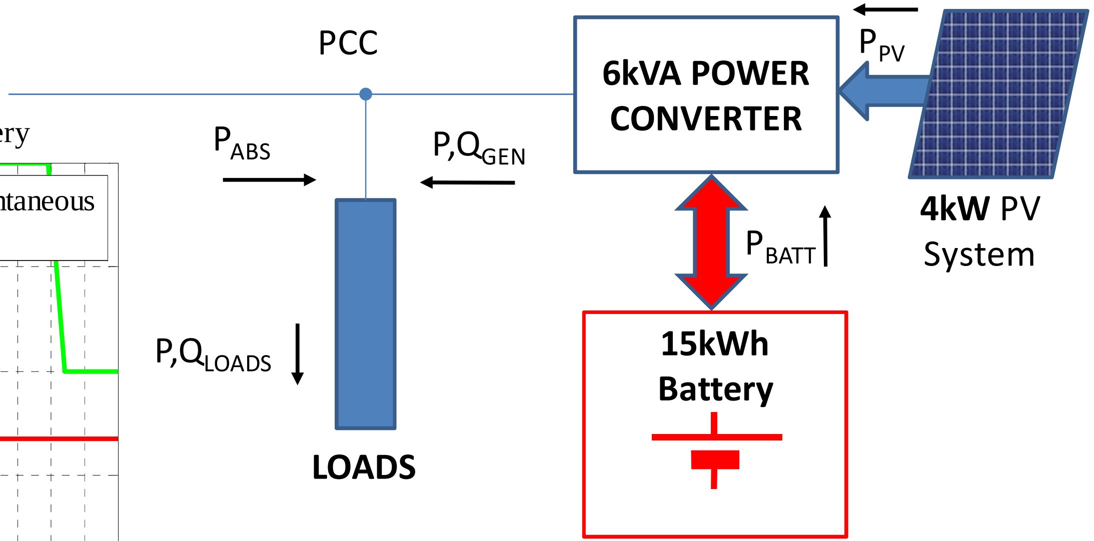




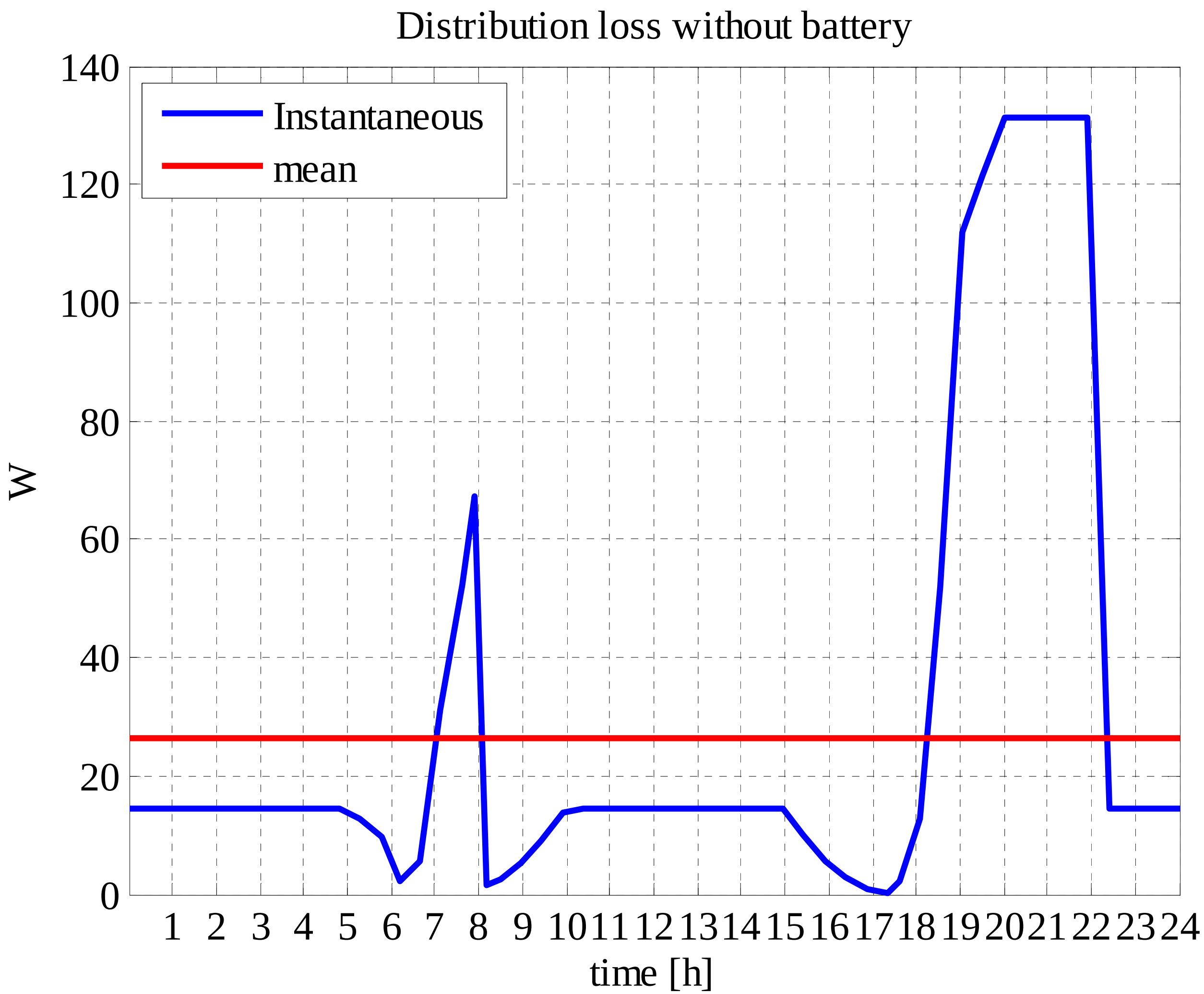
Power absorption without battery

Active power absorbed from the mains assuming $P_{BATT} = 0$: $P_{ABS}=P_{LOADS}-P_{PV}$





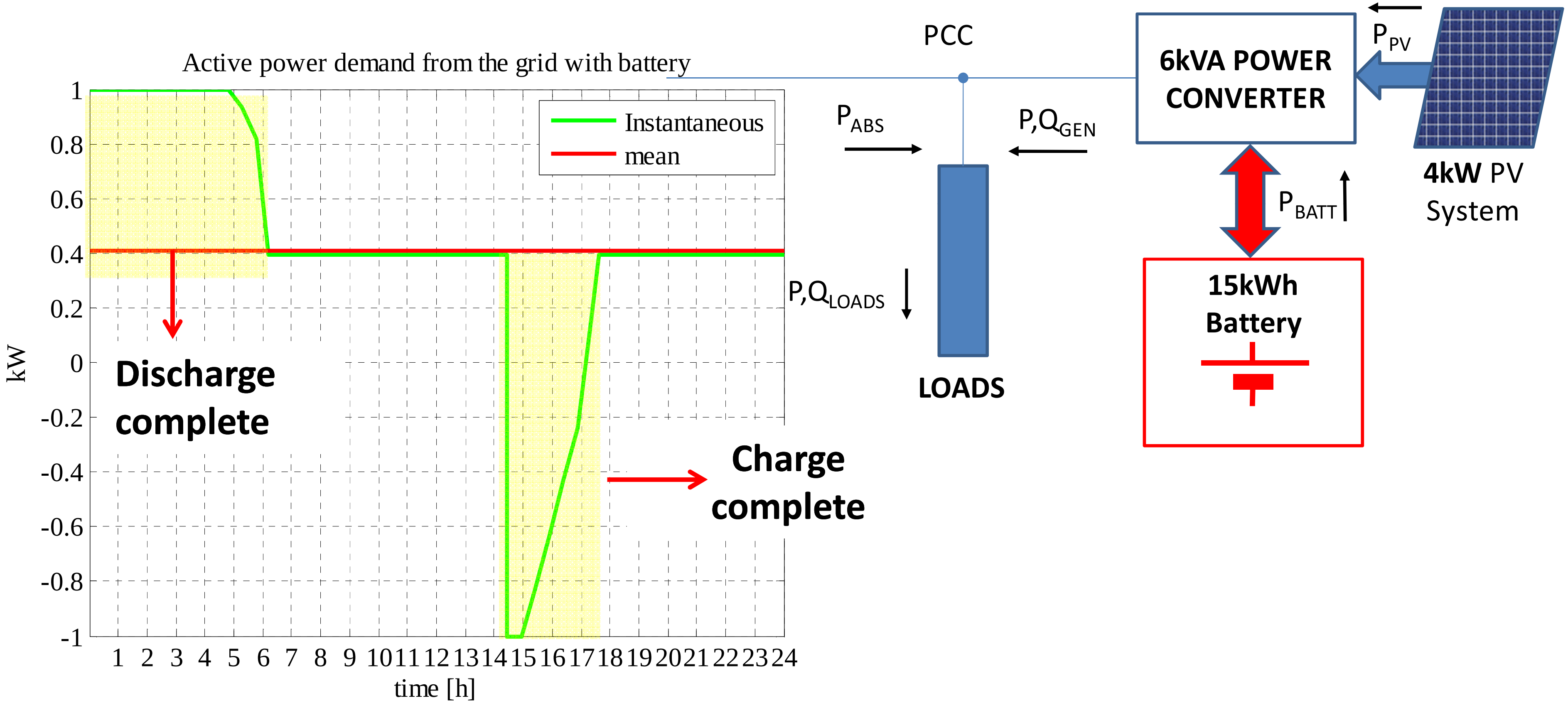
Distribution loss without battery



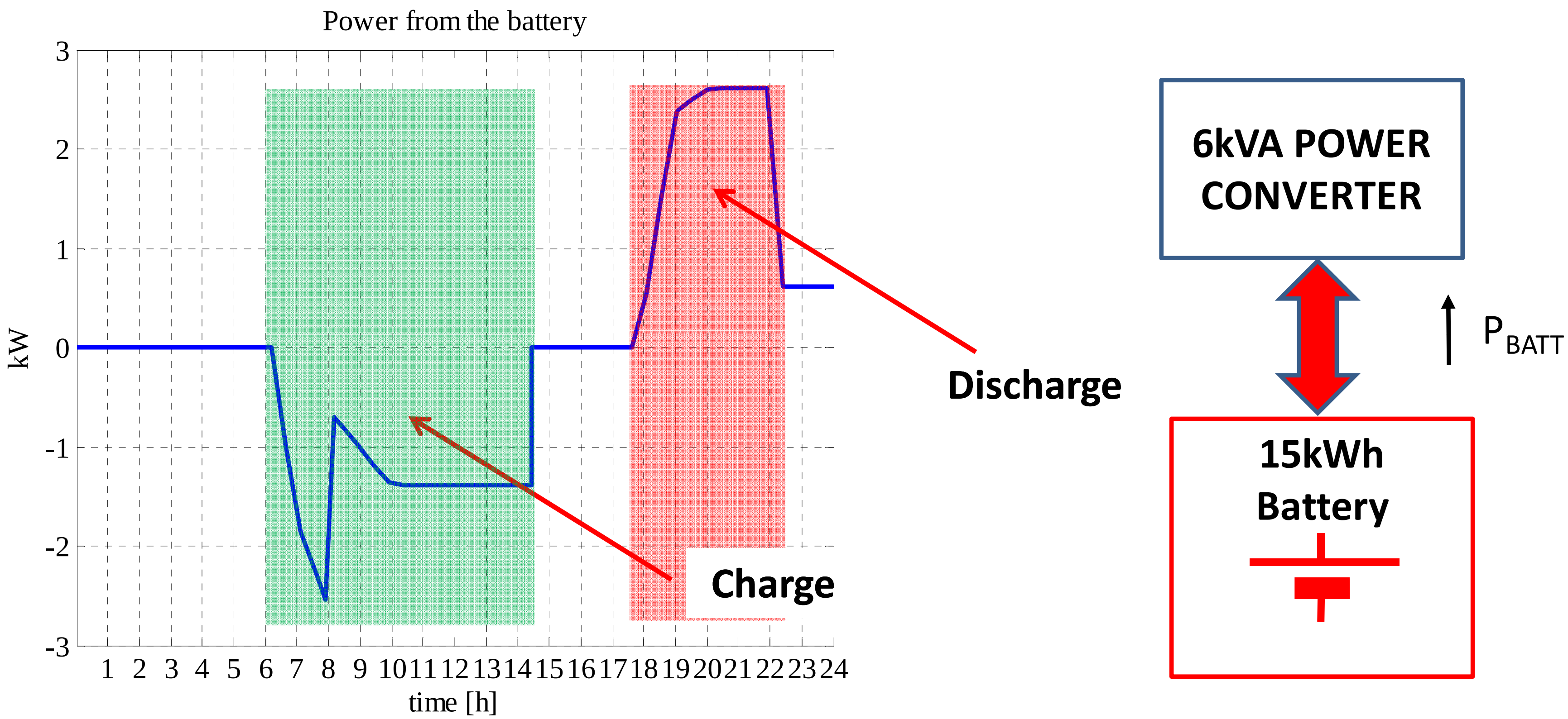
Power absorption with battery

$$P_{ABS}=P_{LOADS}-P_{PV}-P_{BATT}$$

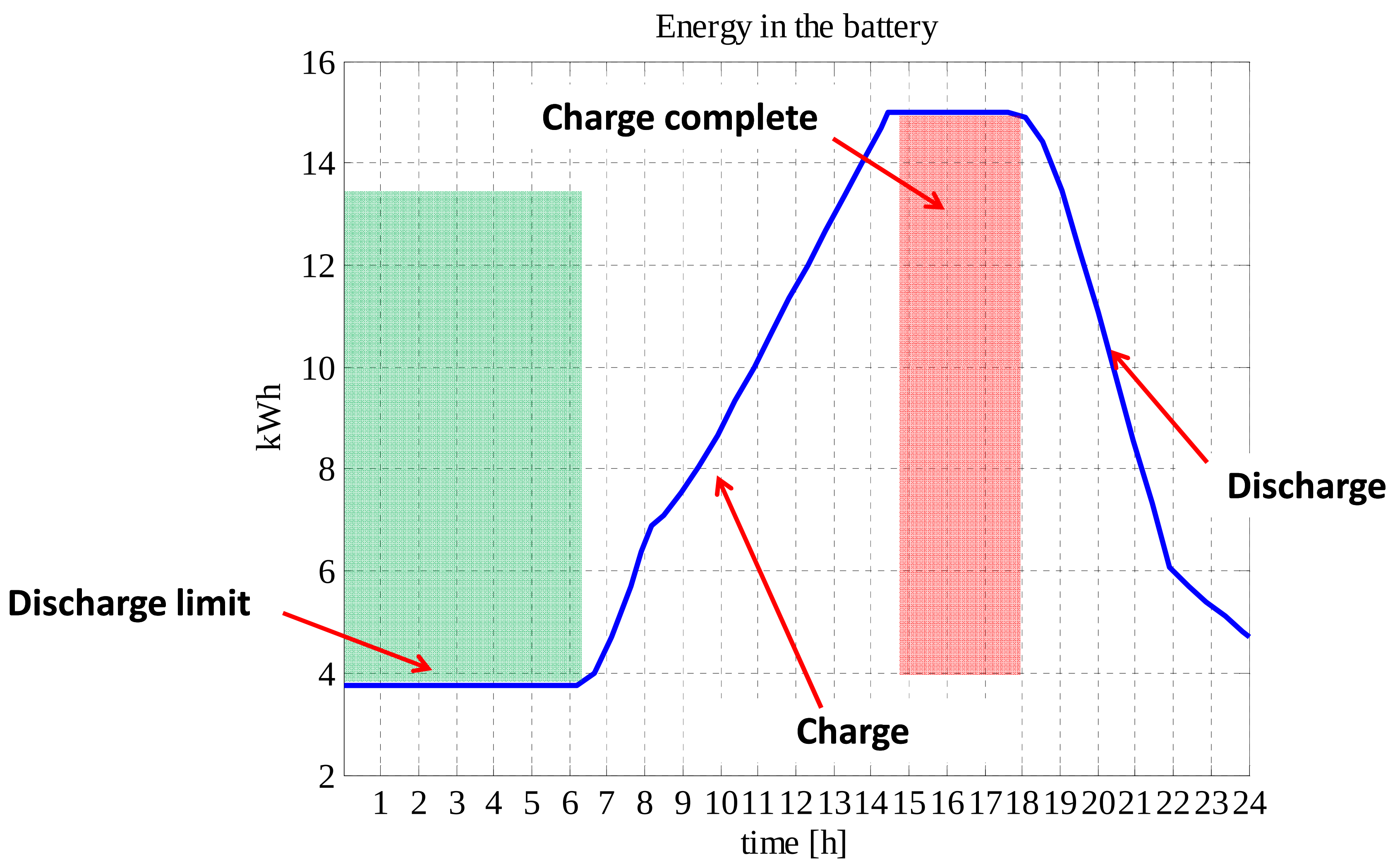
Local control tends to enforce $P_{ABS}= P_{ABS\_AVG}$ (daily average power)



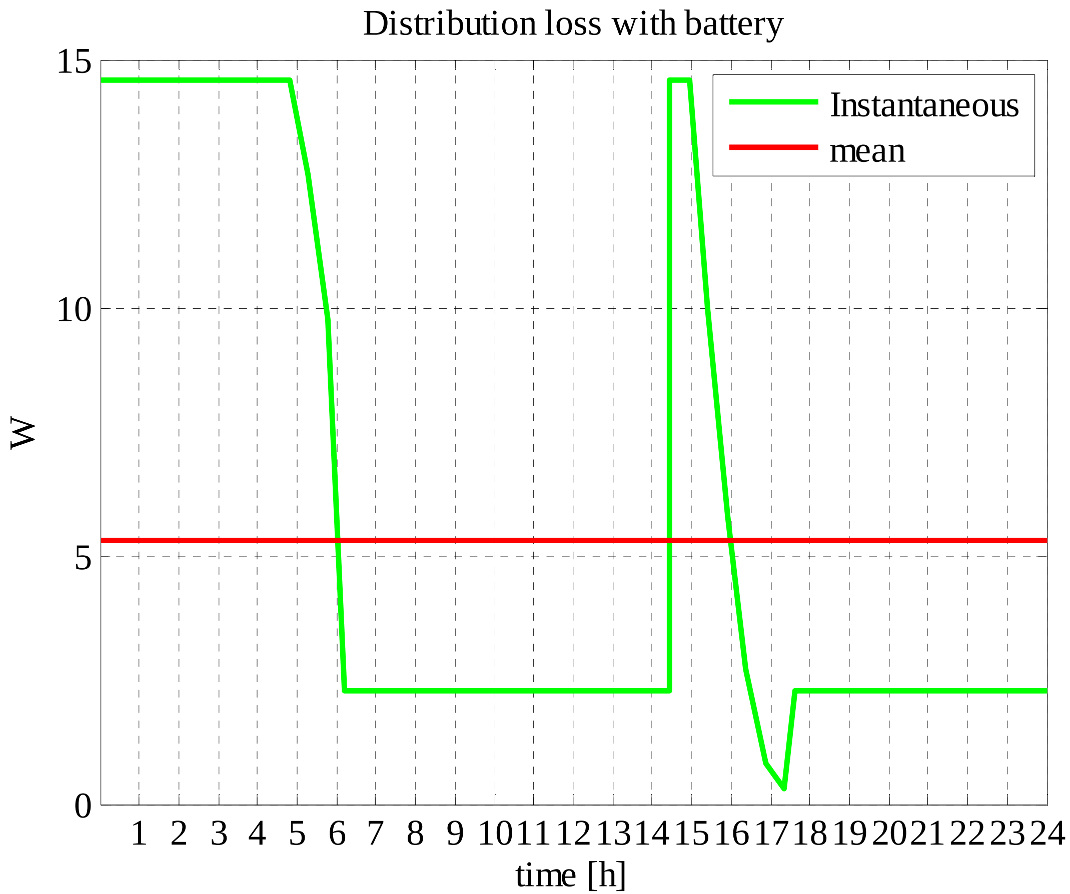
Daily power profile of battery



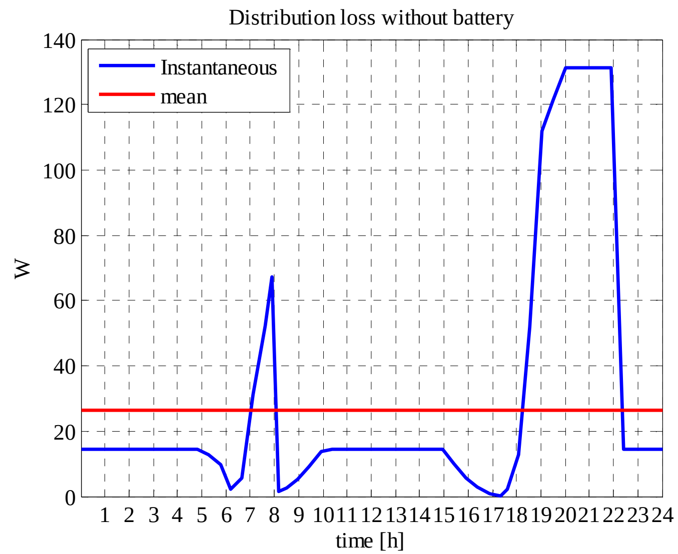
Daily energy profile of battery



Distribution loss without battery



Distribution loss reduced by 85% (active power control only)



Distributed energy storage

Local functions (Energy Gateway)

- Regularization of power absorption
- Reduction of losses in the distribution feeder
- Peak power shaving
- Emergency supply in case of mains outage (UPS operation)
- Voltage stabilization
- **Electrical bill reduction**

Global functions (Utility Interface + Energy Gateways)

- Energy sharing / backup (islanded operation)
- Smoothing of irregular power generation by renewable sources
- Programmable active and reactive power absorption
- **Power delivery on demand (demand response)**

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5. Control issues in smart micro-grids

Control objectives

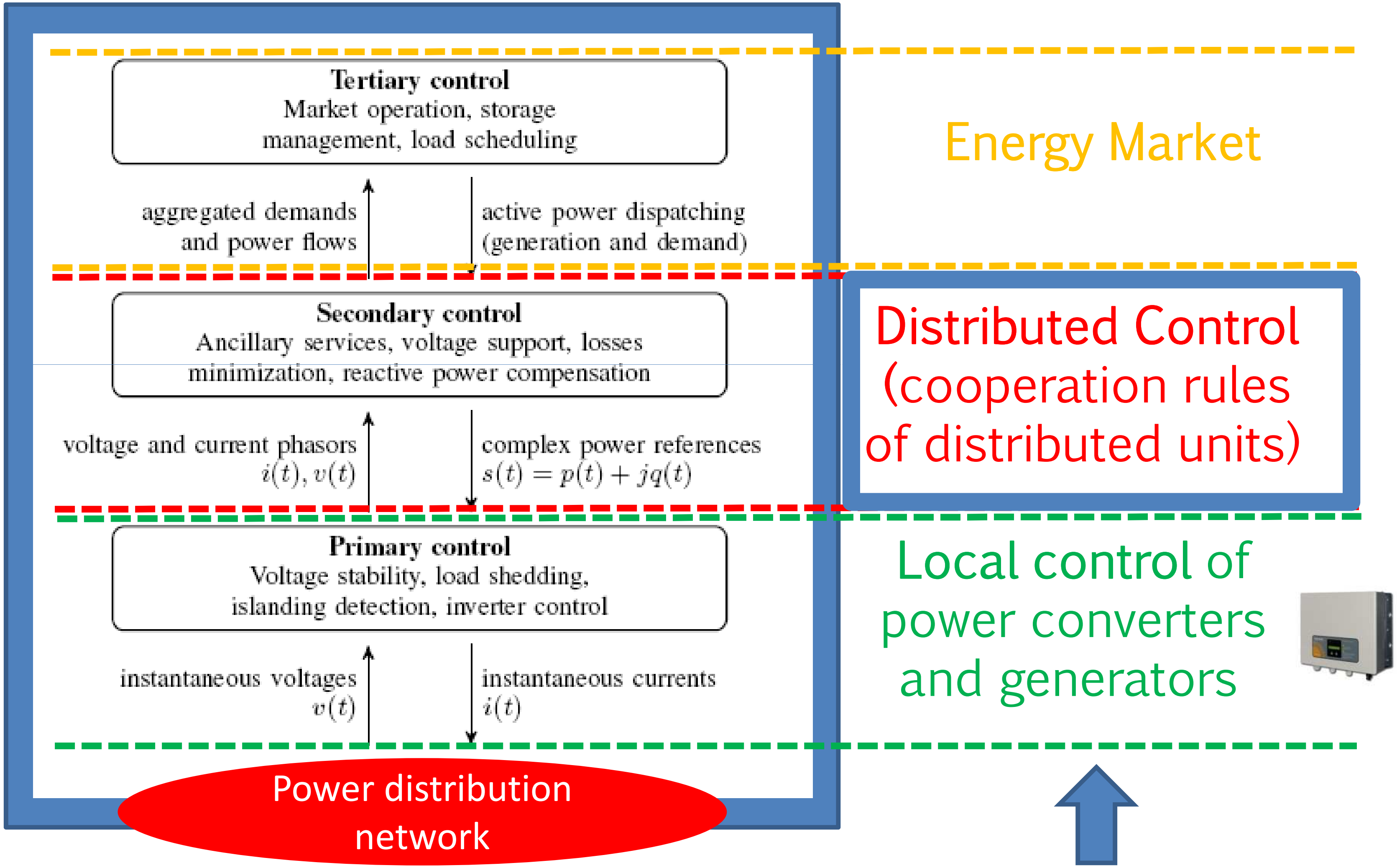
Local functions (Energy Gateways)

- Exploitation of renewable energy sources (active power)
- Management of energy storage
- Voltage support (reactive power)
- Load shedding & shifting

Global functions (Utility Interface + Energy Gateways)

- Optimization of micro-grid resources utilization
- Demand response
- Management of mains outages
- Reaction to grid dynamics
- Load balancing
- Reactive & harmonic compensation

Hierarchic control architecture



ICT architecture and requirements

- Active grid nodes correspond to *prosumers*, i.e., buildings or residential settlements equipped with distributed energy resources (DERs) and Energy Gateways capable to control the active and reactive power fed to the grid
  - Energy gateways are equipped with smart power meters providing measurement, communication, synchronization
- Passive grid nodes correspond to traditional consumers and may be equipped with smart meters too
- **Plug & play operation** of energy gateways is necessary to ensure flexibility and scalability of control & power architecture
- **Distributed control and communication** is necessary to ensure cooperative operation of energy gateways
- A micro-grid controller manages the Utility Interface at the point of common coupling and the system-level functions

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6. Inverter modeling and control

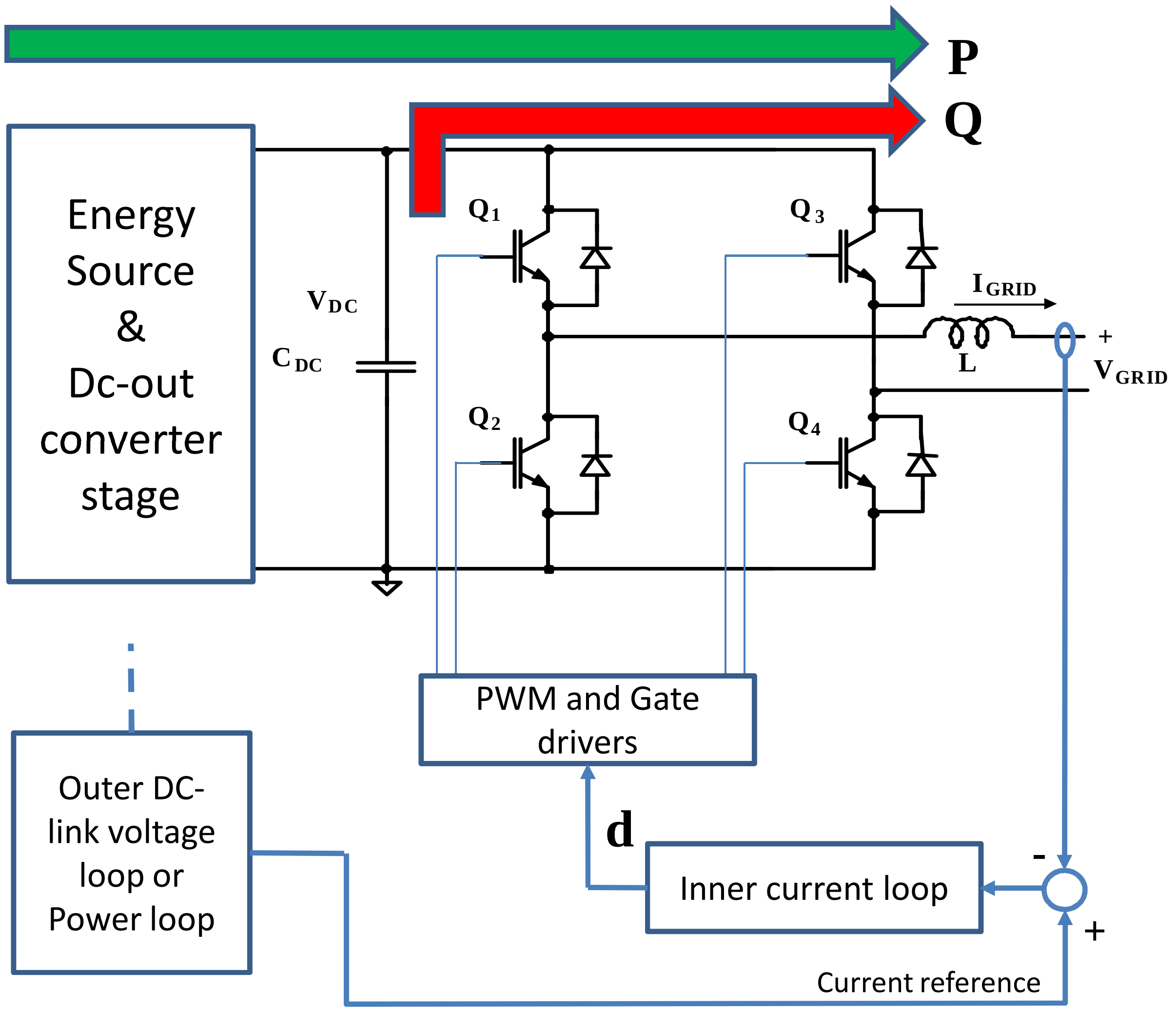
Inverter control modes

Single-phase voltage-fed full-bridge inverter configurations can be driven according to different control modes:

1. **Current-mode control:** the inductor current is controlled to track a current reference defined by a DC link voltage controller (typical configuration of PV systems) or by an external power loop. The inverter appears as a **Controlled current (or Power) source**.

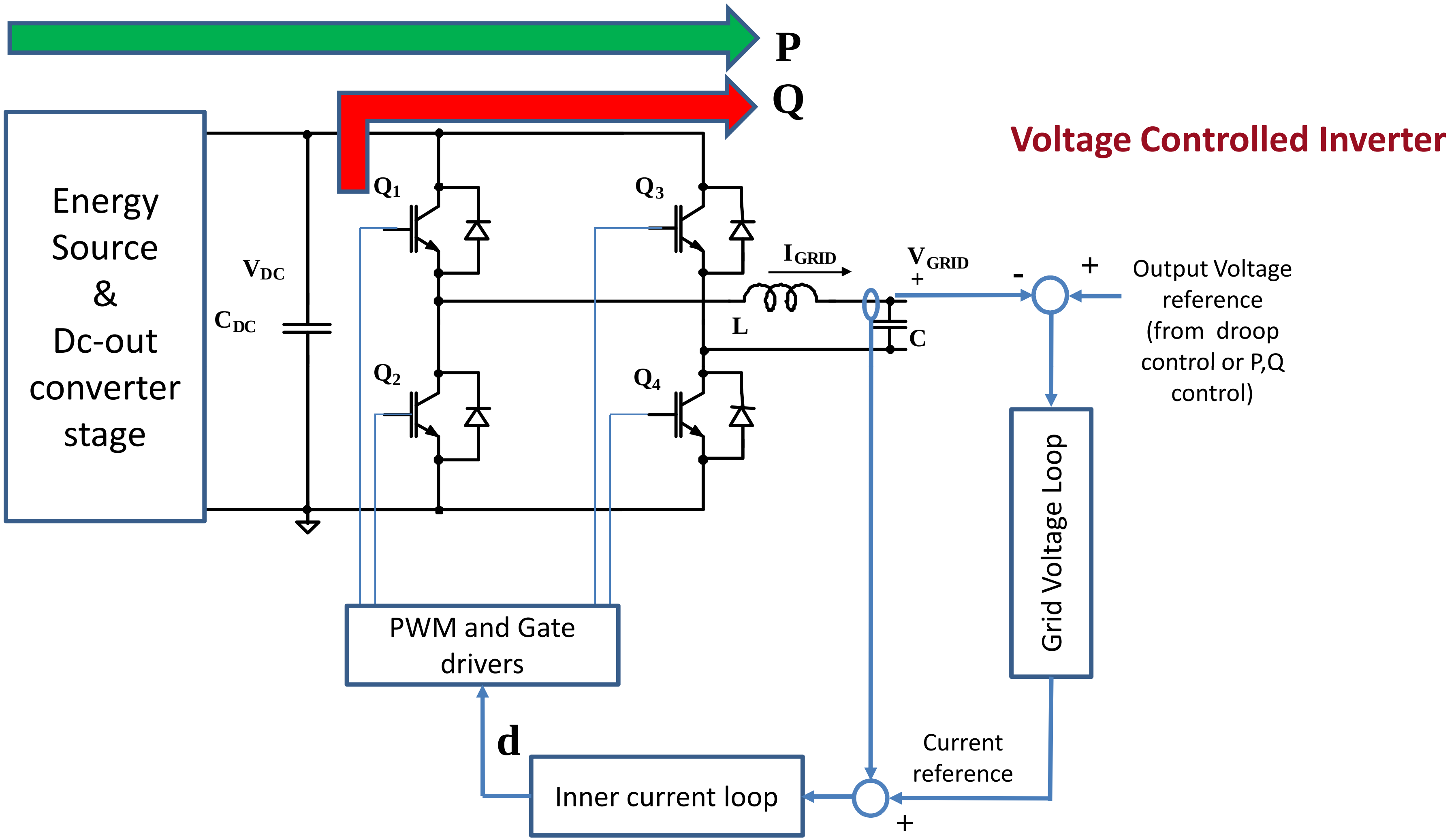
2. **Voltage-mode control:** the inner current loop is driven by an external voltage loop that tracks a voltage reference (UPS applications or droop-controlled inverters, where the power flows are controlled by acting on module and phase of the inverter output voltage). The inverter appears as a **Controlled voltage source**.

Inverter control: current-mode



Current (Power) Controlled Inverter

Inverter control: voltage-mode

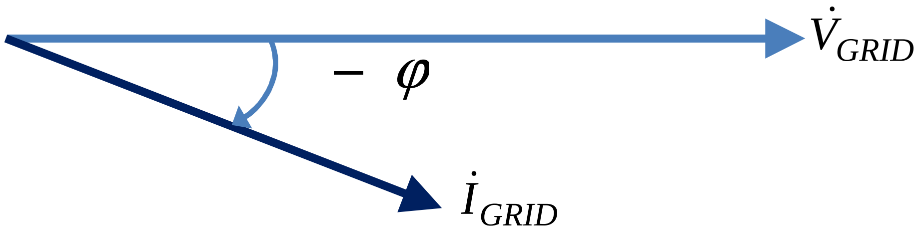


Inverter control: current injection

For current-controlled inverters the traditional approach in grid connected applications is the **injection of pure active power**, i.e. an injected current with **cosφ=1**;

If $\mathbf{V_{GRID}}$ is the equivalent grid voltage (neglecting the impedance) and $\mathbf{I_{GRID}}$ is the fundamental component of the injected current, the corresponding Phasorial representation is:

In general, **the injected current can be leading or lagging** the grid voltage



$$\varphi = \varphi_v - \varphi_i$$

RMS values

$$\dot{V}_{GRID} = \boxed{V_{GRID}} e^{j\varphi_i}$$

$$\dot{I}_{GRID} = \boxed{I_{GRID}} e^{j\varphi_v}$$

Inverter control: power injection

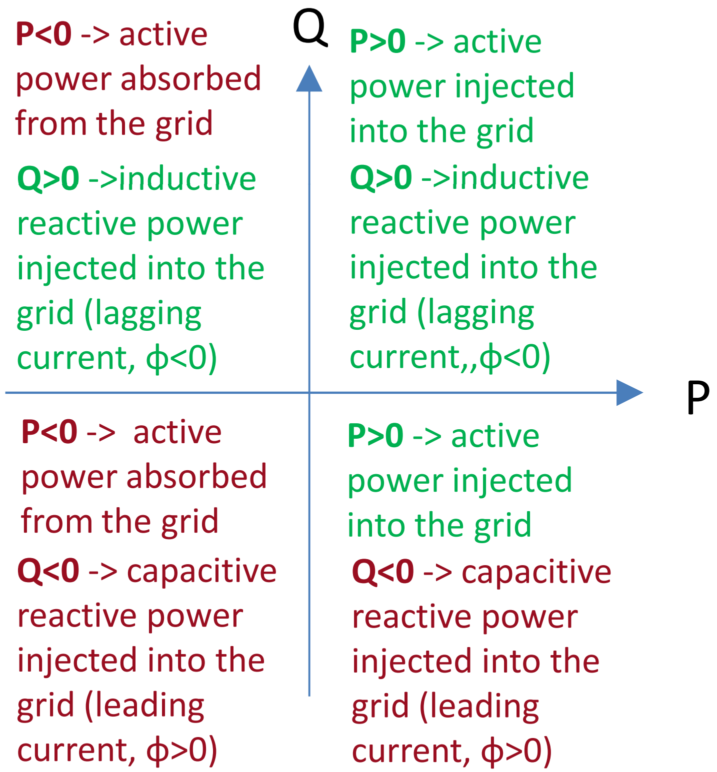
Complex Power: $\dot{S} = \dot{V}_{GRID}\dot{I}^{*}_{GRID} = P + jQ$

Setting on **V_{GRID}** the reference for the phasorial representation :

$$\dot{S} = \dot{V}_{GRID}\dot{I}^{*}_{GRID} = P + jQ$$

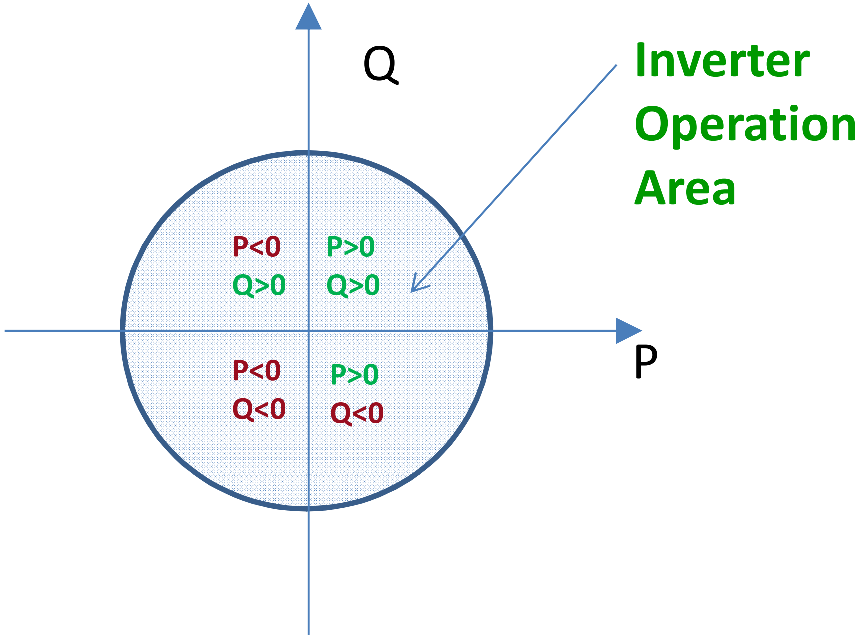
$$\dot{S} = V_{GRID}\left(I_{GRID}e^{-j\varphi}\right)^{*} = V_{GRID}I_{GRID}e^{j\varphi} =$$
$$= V_{GRID}I_{GRID}\cos\varphi + V_{GRID}I_{GRID}\sin\varphi$$

$$P = V_{GRID}I_{GRID}\cos\varphi$$
$$Q = V_{GRID}I_{GRID}\sin\varphi$$



Inverter control: power capability

In distributed generation, the inverters operate in the **I and IV quadrants,** injecting **positive active power** and **either positive or negative reactive power**



POWER RATING:

The **complex power that can be injected by an inverter is limited by the current and voltage rating of the components** (V and I limits for the switches, I limits for the output inductors, V limit for the capacitors etc) →

For a given interval of grid voltage, these limits are represented by the apparent power

$$A = V_{GRID\_MAX}\, I_{GRID\_MAX} = |\dot{S}| [VA]$$

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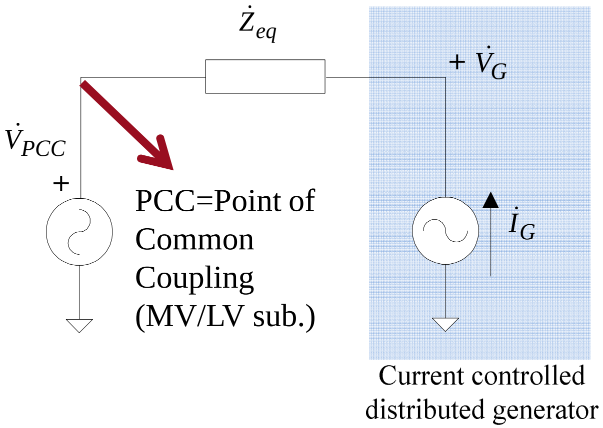
7. Micro-grid modeling and distribution loss analysis

Micro-grid modeling (1)

To study the distribution loss, a **model** of the Microgrid is required.

Power Systems approach: Network elements are represented as constant power loads / distributed generators, constant current loads, constant impedance loads. The grid is therefore a **nonlinear system** requiring numeric solvers (Newton-Raphson , etc.) to solve **Power Flow** equations.

LV distribution systems: the voltage is impressed at the Point of Common Coupling with the mains and its variation along the LV grid is within ±5% of rated value. Thus, under steady-state conditions, the constant-power loads / sources can be represented as constant-current (or constant-impedance) elements. Thus, the system model is linear and can be solved analytically (based on Kirchhoff's and load equations).



Moreover the LV distribution is usually made by **cables** with **constant section**, i.e. impedances with constant phase (modelled as R-L series). This further simplifies the analysis, making possible the analytical solution of meshed grids too.

Micro-grid modeling (2)

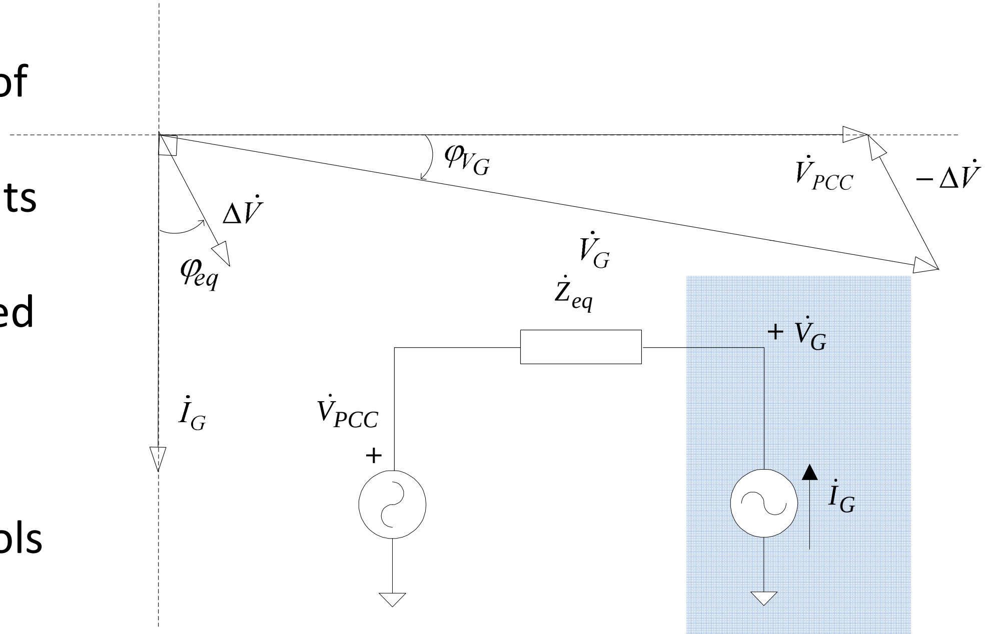
Assumption: the PCC voltage is taken as phase reference for the phasorial representation

$$\boxed{\dot{V}_{PCC} = U_{rated} + j0 = 230 + j0\,V}$$

Approximation: based on the assumption of negligible voltage variations, the **real and imaginary** components of the node currents closely approach the **active and reactive** components absorbed by the loads /injected by the generators.

↓

- The **real part** of the node currents controls the **active power**
- The **imaginary part** of the node currents controls the **reactive power**



Current controlled distributed generator

$$\Delta V << V_{PCC}$$

Loss analysis in radial µG

Distribution loss (general definition):

$$\boxed{P_d = \dot{\underline{J}}^T \underline{R} \dot{\underline{J}}^*}$$

$\dot{\underline{J}}$ =vector of branch currents

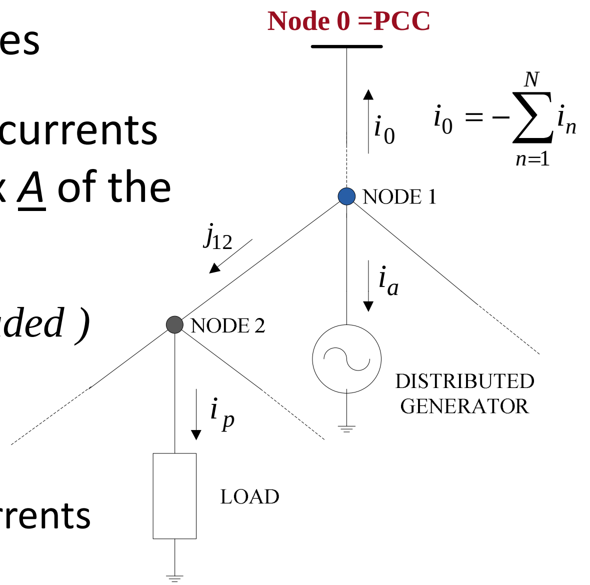
$\underline{R}$ = diagonal matrix of branch resistances

The branch currents can be expressed as a function of the node currents (either injected or absorbed) given the reduced incidence matrix $\underline{A}$ of the grid

$$\underline{A}(\ell,n)=\begin{cases}-1 & \text{if branch b exits node n}\\ +1 & \text{if branch b enters node n}\\ 0 & \text{otherwise}\end{cases} \qquad 1 \le \ell, n \le N \;(\,node\ 0\ excluded\,)$$

$$\boxed{\dot{\underline{I}} = \underline{A}^T \dot{\underline{J}} \quad \Leftrightarrow \quad \dot{\underline{J}} = \left(\underline{A}^T\right)^{-1} \dot{\underline{I}} = \left(\underline{A}^{-1}\right)^T \dot{\underline{I}}}$$

$\dot{\underline{I}}$ = vector of node currents

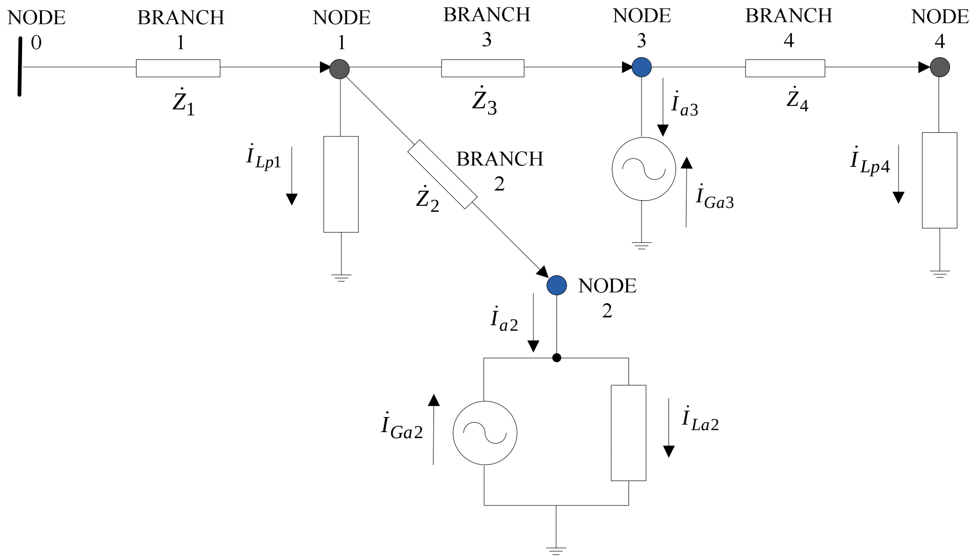


Therefore:

$$\boxed{P_d = \dot{\underline{J}}^T \underline{R} \dot{\underline{J}}^* = \dot{\underline{I}}^T \underline{A}^{-1} \underline{R} \left(\underline{A}^{-1}\right)^T \dot{\underline{I}}^* = \dot{\underline{I}}^T \underline{B} \dot{\underline{I}}^*}$$

Note: $\underline{B}$ is a real and symmetric matrix, whose element (m,n) represents the resistance of the common part of the paths connecting the PCC with nodes m and n

Example (1)



Branch impedances	
Z_1	1+j1 Ω
Z_2	2+j2 Ω
Z_3	3+j3 Ω
Z_4	4+j4 Ω
Load currents	
I_{Lp1}	5+j5 A
I_{La2}	10+j10 A
I_{Lp4}	15+j15 A

Simple microgrid, with 2 generators and 3 loads

REDUCED INCIDENCE MATRIX

$$\underline{A}(b,n)=\begin{cases}-1 & \text{if branch b exits node n}\\ +1 & \text{if branch b enters node n}\\ 0 & \text{otherwise}\end{cases}$$

$$\begin{array}{cc} & \text{Nodes} \\ \underline{A}= & \begin{bmatrix}1 & 0 & 0 & 0\\ -1 & 1 & 0 & 0\\ -1 & 0 & 1 & 0\\ 0 & 0 & -1 & 1\end{bmatrix} \text{Branches}\end{array}$$

Note that **Node 0**, i.e. the PCC, **is excluded**

Example (2)

Matrix $\underline{R}$ of branch resistances:

$$\underline{R} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 4 \end{bmatrix} \Omega$$

$$\underline{B} = \underline{A}^{-1} \underline{R} \left(\underline{A}^{-1}\right)^T \in R^{NxN} \qquad \underline{A}^{-1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 \end{bmatrix} \qquad \underline{B} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 3 & 1 & 1 \\ 1 & 1 & 4 & 4 \\ 1 & 1 & 4 & 8 \end{bmatrix} \Omega$$

Notes:

1. The k^{th} element of the n^{th} row of matrix $\underline{A}^{-1}$ is 1 if branch k owns to the path connecting node 0 with node n; otherwise it is 0.
2. The generic element (n,m) of $\underline{B}$ (with $n \neq m$) is the resistance of the common part of the paths connecting node n and node m with node 0, while the element (n,n) is the resistance of the path connecting node n and node 0.

Loss analysis in meshed µG (1)

The analysis proposed for radial micro-grids can be applied to meshed micro-grids too, with a slightly different formulation.

In particular, the reduced incidence matrix is split in two sub-matrices: the tree sub-matrix $\underline{A}_t$ and the co-tree sub-matrix $\underline{A}_\ell$.

A *tree* is a generic subset of the micro-grid branches which connects all nodes and has a radial structure; the *co-tree* is the complementary subset of the micro-grid. The tree branches are called *twigs*, the co-tree branches are called *links*.

$$A = \begin{bmatrix} A_t \\ A_\ell \end{bmatrix}$$

$A_t \leftarrow$ Tree sub-matrix (includes all rows corresponding to twigs)

$A_\ell \leftarrow$ Co-tree sub-matrix (includes all rows corresponding to links)

The total distribution loss can be split in two terms corresponding to the tree and the co-tree, giving:

$$P_d = \underline{\dot{J}}^T \underline{R}\,\underline{\dot{J}}^* = \begin{vmatrix} \underline{\dot{J}}_t^T & \underline{\dot{J}}_\ell^T \end{vmatrix} \begin{vmatrix} \underline{R}_t & \underline{0} \\ \underline{0} & \underline{R}_\ell \end{vmatrix} \begin{vmatrix} \underline{\dot{J}}_t^* \\ \underline{\dot{J}}_\ell^* \end{vmatrix} = \underline{\dot{J}}_t^T \underline{R}_t \underline{\dot{J}}_t^* + \underline{\dot{J}}_\ell^T \underline{R}_\ell \underline{\dot{J}}_\ell^*$$

Loss analysis in meshed µG (2)

In general, the twig currents can be expressed as a function of the node currents (supplied to the loads/injected by the generators) and the link currents (flowing in the co-tree).

Application of the the superposition principle gives:

$$\underline{\dot{J}}_t{}' = \left(\underline{A}_t^{-1}\right)^T \underline{\dot{I}} = \underline{Q}_i \, \underline{\dot{I}}$$

Twig currents due to node currents

$$\underline{\dot{J}}_t{}'' = \left(\underline{A}_t^{T}\right)^{-1} \underline{A}_\ell^T \, \underline{\dot{J}}_\ell = \underline{Q}_\ell \, \underline{\dot{J}}_\ell$$

Twig currents due to link currents

$$\underline{\dot{J}}_t = \underline{\dot{J}}_t{}' + \underline{\dot{J}}_t{}'' = \underline{Q}_i \, \underline{\dot{I}} + \underline{Q}_l \, \underline{\dot{J}}_l$$

Total twig currents

Loss analysis in meshed µG (3)

Correspondingly, the distribution loss can be rewritten as:

$$P_d = \left(\dot{\underline{I}}^T \underline{Q}_i^T + \dot{\underline{J}}_\ell^T \underline{Q}_\ell^T \right) \underline{R}_t \left(\underline{Q}_i \dot{\underline{I}}^* + \underline{Q}_\ell \dot{\underline{J}}_\ell^* \right) + \dot{\underline{J}}_\ell^T \underline{R}_\ell \dot{\underline{J}}_\ell^* =$$

$$= \dot{\underline{I}}^T \underbrace{\underline{Q}_i^T \underline{R}_t \underline{Q}_i}_{\underline{S}_i} \dot{\underline{I}}^* + \dot{\underline{I}}^T \underbrace{\underline{Q}_i^T \underline{R}_t \underline{Q}_\ell}_{\underline{S}_i^\ell} \dot{\underline{J}}_\ell^* + \dot{\underline{J}}_\ell^T \underbrace{\underline{Q}_\ell^T \underline{R}_t \underline{Q}_i}_{\underline{S}_\ell^i} \dot{\underline{I}}^* + \dot{\underline{J}}_\ell^T \left(\underbrace{\underline{Q}_\ell^T \underline{R}_t \underline{Q}_\ell}_{\underline{S}_\ell} + \underline{R}_\ell \right) \dot{\underline{J}}_\ell^*$$

In a more synthetic form:

$$\boxed{P_d = \dot{\underline{I}}^T \underline{S}_i \dot{\underline{I}}^* + 2 \dot{\underline{J}}_\ell^T \underline{S}_\ell^i \dot{\underline{I}}^* + \dot{\underline{J}}_\ell^T \left(\underline{S}_\ell + \underline{R}_\ell \right) \dot{\underline{J}}_\ell^*}$$

The distribution loss depends therefore on the **node currents** and the **link currents**.

In fact, the node currents distribute among twigs and links depending on their respective impedances.

Loss analysis in meshed µG (4)

To eliminate the dependence on the link currents it can be observed that, **if all distribution cables have the same section** (R/X constant) , the node currents distribute among links and twigs depending on the branch resistances in a way that necessarily minimizes the distribution losses:

$$\frac{\partial P_d}{\partial \underline{\dot{J}}_\ell} = 0 \quad \Rightarrow \quad 2\,\underline{S}_\ell^i\,\underline{\dot{I}}^* + 2\left(\underline{S}_\ell + \underline{R}_\ell\right)\underline{\dot{J}}_\ell^* = 0 \quad \Rightarrow \quad \underline{\dot{J}}_\ell = -\left(\underline{S}_\ell + \underline{R}_\ell\right)^{-1}\underline{S}_\ell^i\,\underline{\dot{I}}$$

$$\boxed{P_d = \underline{\dot{I}}^T\,\underline{S}_i\,\underline{\dot{I}}^* + 2\,\underline{\dot{J}}_\ell^T\,\underline{S}_\ell^i\,\underline{\dot{I}}^* + \underline{\dot{J}}_\ell^T\left(\underline{S}_\ell + \underline{R}_\ell\right)\underline{\dot{J}}_\ell^*}$$

$$\downarrow$$

$$\boxed{P_d} = \underline{\dot{I}}^T\,\underline{S}_i\,\underline{\dot{I}}^* - \underline{\dot{I}}^T\,\underline{S}_i^l\left(\underline{S}_\ell + \underline{R}_\ell\right)^{-1}\underline{S}_\ell^i\,\underline{\dot{I}}^* \boxed{= \underline{\dot{I}}^T\,B_{mesh}\,\underline{\dot{I}}^*}$$

This latter expression is formally equivalent to that applicable for radial micro-grids

Smart micro-grids

Properties, trends and local control of energy sources

8. Optimum control of smart micro-grids

Optimization goals

In the basic optimization process, the **distribution loss in the micro-grid** is taken as the quantity to be minimized (cost function). The motivations are:

- This is an optimum choice in terms of *energy efficiency*
- The *power consumption* of the micro-grid is minimized
- The *currents flowing in the distribution grid are minimized*; this implies that:
- The *loads are fed by the nearest sources*, which corresponds to the most *effective load power sharing among distributed generators*
- The voltage drops across the branch impedances are minimized, resulting in a *voltage stabilization* effect at all nodes of the micro-grid.

In a more advanced optimization process, the *inverter losses* shall also be considered together with the boundaries set by the *inverters ratings*, the *intermittent power generation* by renewable sources, the *lifetime optimization of storage batteries*, the *cost of energy* and the *revenues from power generation*.

Distribution Loss Minimization (1)

Ideal Minimization:

- Linear micro-grid model
- **Unconstrained active and reactive current injection** of grid-connected inverters

Let $\dot{\underline{I}}_a = \underline{K}_a \dot{\underline{I}}$ currents injected at active nodes (**energy gateways**)

$\dot{\underline{I}}_p = \underline{K}_p \dot{\underline{I}}$ currents absorbed at passive nodes (**loads**)

Distribution loss: $\boxed{P_d = \dot{\underline{I}}^T \underline{B}\, \dot{\underline{I}}^*} \longrightarrow \boxed{P_d = \dot{\underline{I}}_a^T \underline{B}_{a,a} \dot{\underline{I}}_a^* - 2\Re\left(\dot{\underline{I}}_a^T \underline{B}_{a,p} \dot{\underline{I}}_p^* \right) + \dot{\underline{I}}_p^T \underline{B}_{p,p} \dot{\underline{I}}_p^*}$

where:

$$\underline{B}_{a,a} = \underline{K}_a \underline{B}\underline{K}_a^T, \quad \underline{B}_{a,p} = \underline{K}_a \underline{B}\underline{K}_p^T$$
$$\underline{B}_{p,a} = \underline{K}_p \underline{B}\underline{K}_a^T, \quad \underline{B}_{p,p} = \underline{K}_p \underline{B}\underline{K}_p^T$$

$$\underline{B}_{a,p} = \underline{B}_{p,a}^T$$

Optimization: Find currents $\underline{I}_a$ that minimize P_d for a given set of load currents $\underline{I}_p$

Distribution Loss Minimization (2)

Let: $\dot{\underline{I}}_a = \underline{x} + j\,\underline{y} \qquad \dot{\underline{I}}_p = \underline{a} + j\,\underline{b}$

$$\frac{\partial P_d}{\partial \dot{\underline{I}}_a} = 0 \;\Rightarrow\; \begin{cases} \dfrac{\partial P_d}{\partial \underline{x}} = 0 \;\Rightarrow\; 2\,\underline{B}_{a,a}\,\underline{x} - 2\,\underline{B}_{a,p}\,\underline{a} = 0 \\[2ex] \dfrac{\partial P_d}{\partial \underline{y}} = 0 \;\Rightarrow\; 2\,\underline{B}_{a,a}\,\underline{y} - 2\,\underline{B}_{a,p}\,\underline{b} = 0 \end{cases} \;\Rightarrow\; \underline{B}_{a,a}\,\dot{\underline{I}}_a - \underline{B}_{a,p}\,\dot{\underline{I}}_p = 0$$

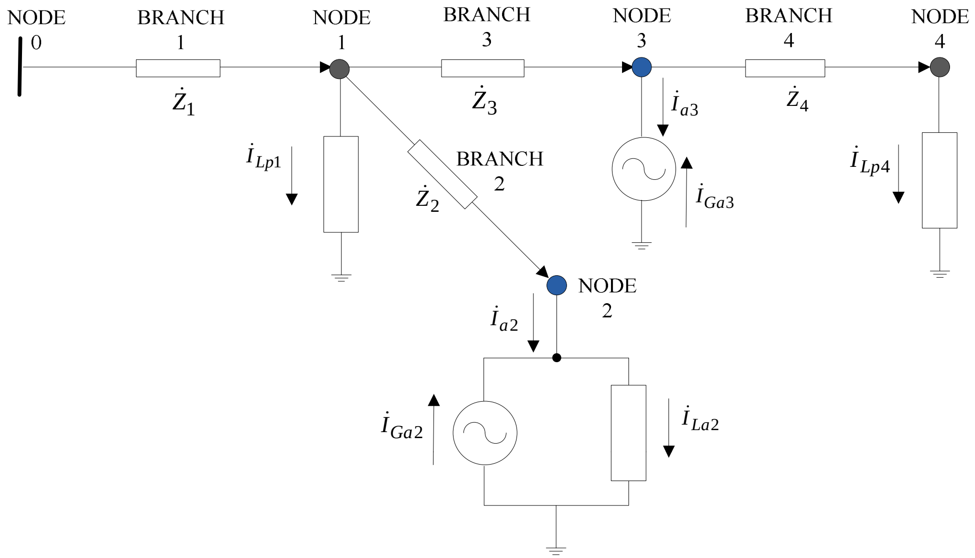
$$\Downarrow$$

$$\boxed{\dot{\underline{I}}_{a,opt} = \underline{B}_{a,a}^{-1}\,\underline{B}_{a,p}\,\dot{\underline{I}}_p}$$

Observe that:

- A **centralized controller** which knows topology and impedances of the micro-grid, given the load currents, can directly drive the micro-grid in the minimum distribution loss condition by feed-forward control
- The distribution loss minimization can be done separately for the real (active) and imaginary (reactive) part of the injected currents. This is **important because only reactive currents can generally be used for loss minimization**, the active currents being constrained by local power or energy limitations (renewable sources, batteries).

Application example (1)



Branch impedances	
Z_1	1+j1 Ω
Z_2	2+j2 Ω
Z_3	3+j3 Ω
Z_4	4+j4 Ω
Load currents	
I_{Lp1}	5+j5 A
I_{La2}	10+j10 A
I_{Lp4}	15+j15 A

Simple microgrid, with 2 generators and 3 loads

Step 1: REDUCED INCIDENCE MATRIX

$$\underline{A}(b,n)=\begin{cases}-1 & \text{if branch b exits node n}\\ +1 & \text{if branch b enters node n}\\ 0 & \text{otherwise}\end{cases}$$

$$\begin{array}{cc} & \text{Nodes} \\ \underline{A}= & \begin{bmatrix}1 & 0 & 0 & 0\\ -1 & 1 & 0 & 0\\ -1 & 0 & 1 & 0\\ 0 & 0 & -1 & 1\end{bmatrix} & \text{Branches}\end{array}$$

Note that **Node 0**, i.e. the PCC, **is excluded**

Application example (2)

STEP 2: The matrix of the branch resistances is:

$$\underline{R} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 4 \end{bmatrix} \Omega$$

STEP 3: Calculation of matrix $\underline{B} = \underline{A}^{-1} \underline{R} \left(\underline{A}^{-1}\right)^T \in R^{NxN}$

$$\underline{A}^{-1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 \end{bmatrix} \qquad \underline{B} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 3 & 1 & 1 \\ 1 & 1 & 4 & 4 \\ 1 & 1 & 4 & 8 \end{bmatrix} \Omega$$

Application example (3)

Given the above matrices, the inherent distribution loss (with all inverters switched off) can be derived as a function of load currents $\underline{I}_{\mathrm{L}}$:

$$P_{dMAX} = \underline{\dot{I}}_L^T \underline{B}\, \underline{\dot{I}}_L^* = \begin{bmatrix} 5+j5 & 10+j10 & 0 & 15+j15 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 3 & 1 & 1 \\ 1 & 1 & 4 & 4 \\ 1 & 1 & 4 & 8 \end{bmatrix} \begin{bmatrix} 5-j5 \\ 10-j10 \\ 0 \\ 15-j15 \end{bmatrix} = 5350\ \mathrm{W}$$

STEP 4: K matrices

$$\underline{K}_a = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad \underline{K}_p = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

STEP 5: B matrices

$$\underline{B}_{a,a} = \underline{K}_a \underline{B}\, \underline{K}_a^T, \quad \underline{B}_{a,p} = \underline{K}_a \underline{B}\, \underline{K}_p^T$$

$$\underline{B}_{p,a} = \underline{K}_p \underline{B}\, \underline{K}_a^T, \quad \underline{B}_{p,p} = \underline{K}_p \underline{B}\, \underline{K}_p^T$$

$$\underline{B}_{a,a} = \begin{bmatrix} 3 & 1 \\ 1 & 4 \end{bmatrix}, \quad \underline{B}_{a,p} = \begin{bmatrix} 1 & 1 \\ 1 & 4 \end{bmatrix}$$

$$\underline{B}_{p,a} = \begin{bmatrix} 1 & 1 \\ 1 & 4 \end{bmatrix}, \quad \underline{B}_{p,p} = \begin{bmatrix} 1 & 1 \\ 1 & 8 \end{bmatrix}$$

Application example (4)

STEP 6: Calculation of the optimum injected currents

$$\underline{\dot{I}}_{Ga,opt}^{grid} = \underline{B}_{a,a}^{-1}\underline{B}_{a,p}\underline{\dot{I}}_{p} + \underline{\dot{I}}_{La} = \begin{bmatrix} 3 & 1 \\ 1 & 4 \end{bmatrix}^{-1} \begin{bmatrix} 1 & 1 \\ 1 & 4 \end{bmatrix} \begin{bmatrix} 5+j5 \\ 15+j15 \end{bmatrix} + \begin{bmatrix} 10+j10 \\ 0 \end{bmatrix} = \begin{bmatrix} 11.3636+j11.3626 \\ 15.9091+j15.9091 \end{bmatrix} \Rightarrow$$

$$\begin{cases} \dot{I}_{Ga2,opt} = 11.3636 + j11.3626 \\ \dot{I}_{Ga3,opt} = 15.9091 + j15.9091 \end{cases}$$

(I_{Ga} are the generated currents injected at the active grid nodes, I_{La} are the load currents absorbed at the active grid nodes, I_p are the load currents absorbed at the passive grid nodes)

STEP 7: Calculation of the minimum distribution loss

$$\begin{cases} \dot{I}_a = \begin{bmatrix} \dot{I}_{La2} - \dot{I}_{Ga2} \\ -\dot{I}_{Ga3} \end{bmatrix} = \begin{bmatrix} -1.3636 - j1.3626 \\ -15.9091 - j15.9091 \end{bmatrix} \\ \dot{I}_p = \begin{bmatrix} \dot{I}_{Lp1} \\ \dot{I}_{Lp4} \end{bmatrix} = \begin{bmatrix} 5+j5 \\ 15+j15 \end{bmatrix} \end{cases}$$

$$P_{dMIN} = \underline{\dot{I}}_a^T \underline{B}_{a,a} \underline{\dot{I}}_a^* + 2\Re\left(\underline{\dot{I}}_a^T \underline{B}_{a,p} \underline{\dot{I}}_p^* \right) + \underline{\dot{I}}_p^T \underline{B}_{p,p} \underline{\dot{I}}_p^* = 1827.3\text{W}$$

Smart micro-grids

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9. On-line Identification of micro-grid parameters

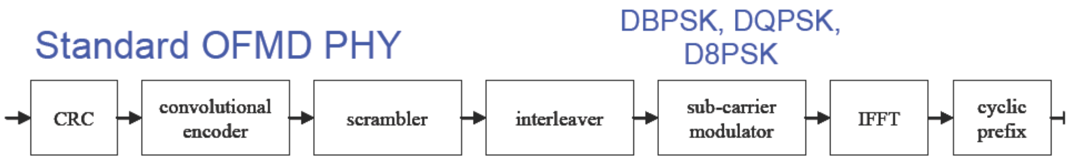
Node-to-node communication

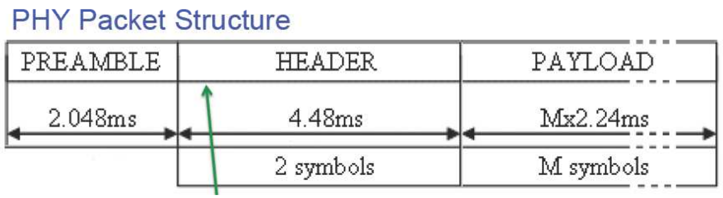
- Node-to-node **communication architecture**
- Node-to-node **distance measurement**

Standard PRIME
(**P**owe**R**line **I**ntelligent **M**etering **E**volution)

PRIME overview:

- Designed for outdoor applications
- OFDM physical layer
- Maximum bit rate **128kbps**
- Transmission over CENELEC A band, in the range 45kHz-92kHz with 97 equally spaced sub-carriers
- MAC layer needs to be "customized" to fit our implementation (PRIME is originally master-slave)





Symbols=OFDM 288bits
symbols – **M<64**

Node-to-node **distance measurement:** PLC enables the use of **TOA (Time Of Arrival)** techniques, currently under testing over ≈1km of real distribution cables in the Smart Micro-Grid Facility at DEI

Node-to node distance measurement

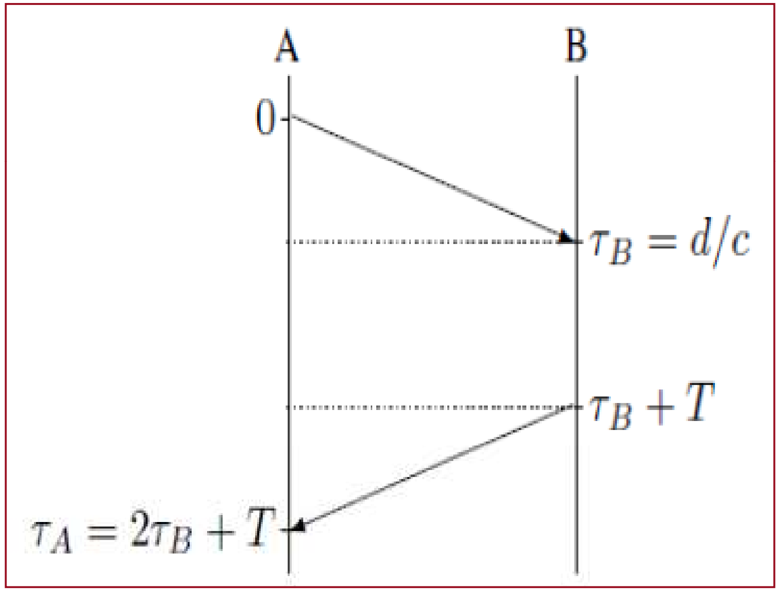
The knowledge of **incidence matrix, neighbours map**, node-to-node **distances** and **branch impedances** is generally required to implement loss minimization techniques. In practice, the knowledge of branch impedances is not required if the distribution lines have **constant section**. In this case, node-to-node distances are sufficient.

PLC-based distance measurement
Time of Arrival (TOA) ranging technique

- Node *A* broadcasts a data packet, which is received by node *B* at time τ_B
- Node *B* waits a fixed time *T* and then replies to *A* with another data packet.
- *A* receives the packet at time $\tau_A = 2\,\tau_B + T$
- Time τ_B depends on the distance d_{AB} between nodes *A* and *B* by the relation $\tau_B = d_{AB}/c$, with ***c* the speed of light**.

Thus:

$$\boxed{d_{AB} = \frac{c(\tau_A - T)}{2}}$$



Distance measurement accuracy 1.5-10 m

Neighbours map/Incidence matrix

Identification algorithm

- After the ranging procedure, each node owns a list of the distances from the other grid nodes.
- By collecting these lists from all grid nodes, the *distance matrix* $\underline{D}$ can be determined, whose element d_{mn} gives the distance between nodes m and n.
- Two nodes n and m are neighbors if their distance is the minimum among the length of all paths which can connect them, i.e.:

$$\boxed{d_{nm} < d_{nk} + d_{km}\,, \quad k = 1 \ldots N}$$

- Neighbour nodes are connected by a direct link, thus each pair of them identifies a row of the complete incidence matrix $\underline{A}_c$.
- The reduced incidence matrix $\underline{A}$ is obtained by suppressing the column corresponding to node 0 (slack node).
- The tree and co-tree sub-matrices $\underline{A}_t$ and $\underline{A}_l$ are obtained by partitioning $\underline{A}$ into a full-rank (*tree*) sub-matrix and the residual (*co-tree*) sub-matrix.

Smart micro-grids

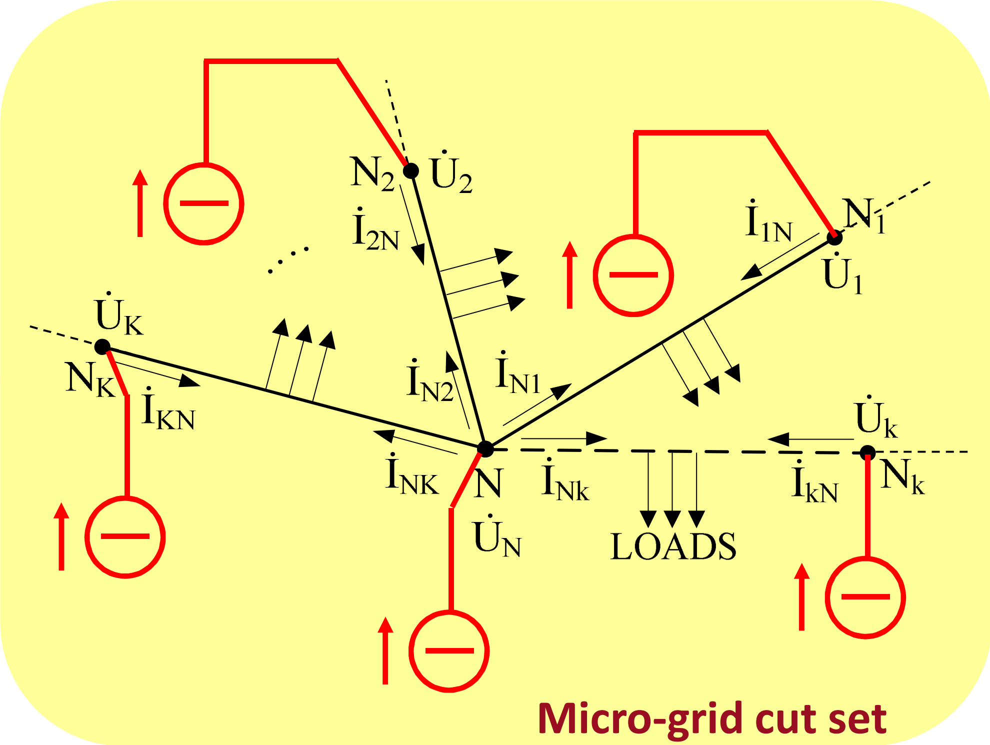
Properties, trends and local control of energy sources

10. Distributed surround control of smart micro-grids

Assumptions

- **Grid nodes coincide with the power meters**, equipped by suitable measurement, synchronization and communication capability (**smart meters**)
  - **Active grid nodes** correspond to **prosumers**, i.e., buildings or residential settlements equipped with energy sources, and interface the grid by means of **energy gateways**, i.e., power processors (inverters) capable to control their active and reactive power and equipped with measurement/control/communication units.
  - **Passive grid nodes** correspond to traditional energy-consuming end users and are equipped with **smart meters**, i.e., metering equipment with data processing and communication capability
- **Communication** occurs only **among neighbor nodes**
- **Distributed plug & play control** techniques are implemented, to ensure **flexibility and scalability** of the micro-grid

Token ring control



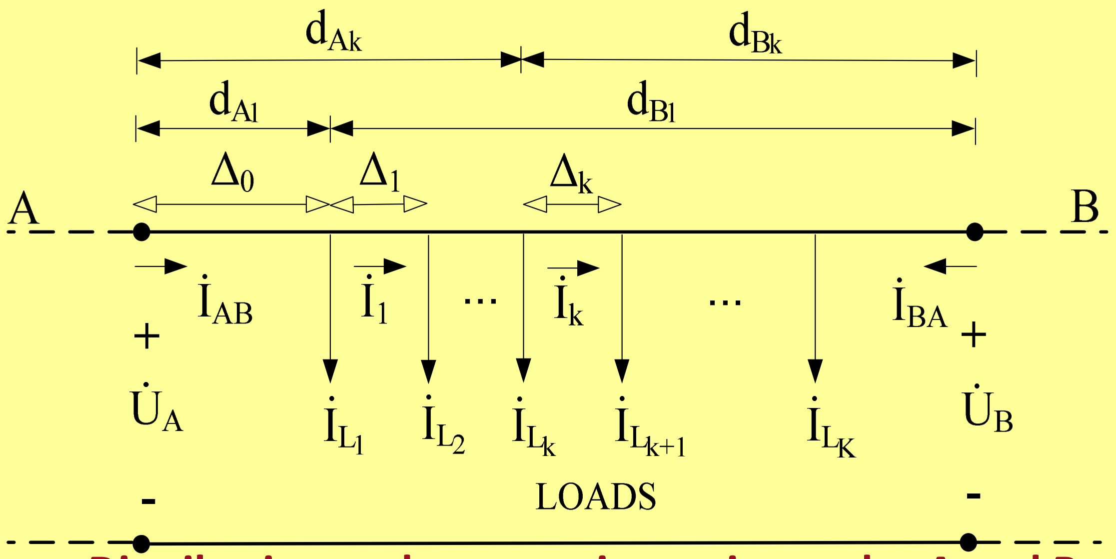
The distributed grid-connected inverters (DGIs) operate as current sources (to stabilize the grid impedances)

- The distributed grid-connected inverters cyclically update their ac current references (**control phase**).
- Outside the control phase, the inverters keep constant their ac current references (**hold phase**).
- When an inverter is in the control phase, the neighbours keep the hold phase. This prevents possible detrimental control interactions.

Loss minimization in distribution lines

Optimization goal: find the values of I_{AB} and I_{BA} that minimize the conduction losses in path A-B

$$\frac{\partial P_{LOSS}}{\partial \dot{I}_{AB}} = 0 \qquad \frac{\partial P_{LOSS}}{\partial \dot{I}_{BA}} = 0$$



Distribution path connecting active nodes A and B

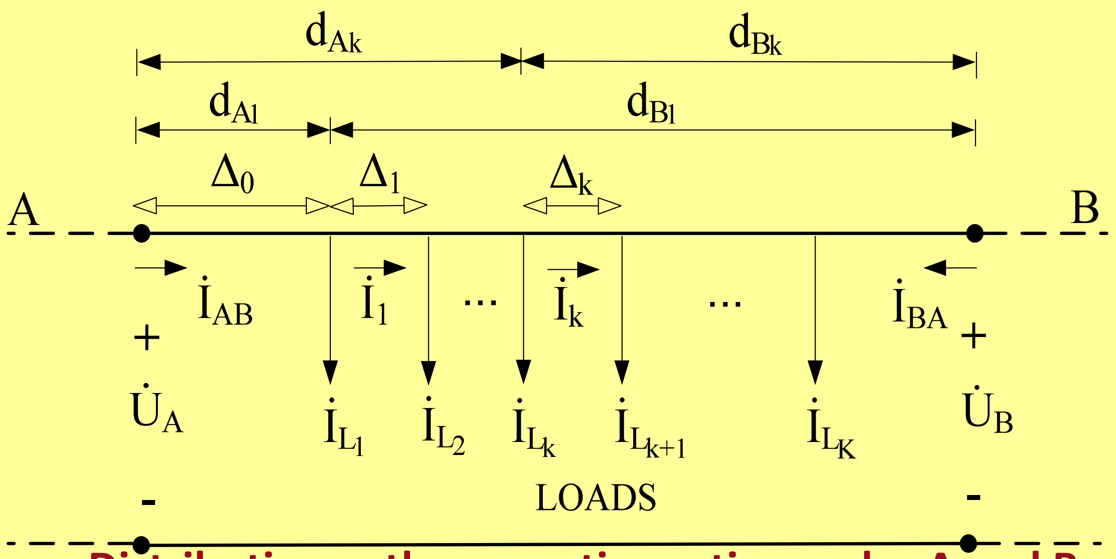
$$\begin{cases} \dot{I}_{AB}^{opt} = \dfrac{1}{d_{AB}} \displaystyle\sum_{k=1}^{K} \dot{I}_{Lk} d_{Bk} \\ \dot{I}_{BA}^{opt} = \dfrac{1}{d_{AB}} \displaystyle\sum_{k=1}^{K} \dot{I}_{Lk} d_{Ak} \end{cases}$$

The optimum node currents depend only on the loads and their distribution along path A-B

Moreover:

$$\begin{cases} \dot{I}_{AB} = \dot{I}_{AB}^{opt} \\ \dot{I}_{BA} = \dot{I}_{BA}^{opt} \end{cases} \Leftrightarrow \quad \dot{U}_A = \dot{U}_B$$

Loss minimization in distribution lines



In general, nodes A and B are not equipotential, thus:

$$\dot{I}_{AB} = \dot{I}_{AB}^{opt} + \frac{\dot{U}_A - \dot{U}_B}{\dot{z}\, d_{AB}} = \dot{I}_{AB}^{opt} + \dot{I}_{AB}^{circ}$$

$$\dot{I}_{BA} = \dot{I}_{BA}^{opt} + \frac{\dot{U}_B - \dot{U}_A}{\dot{z}\, d_{AB}} = \dot{I}_{BA}^{opt} + \dot{I}_{BA}^{circ}$$

Impedance per unit of length of distribution line

Circulation current

Optimum current

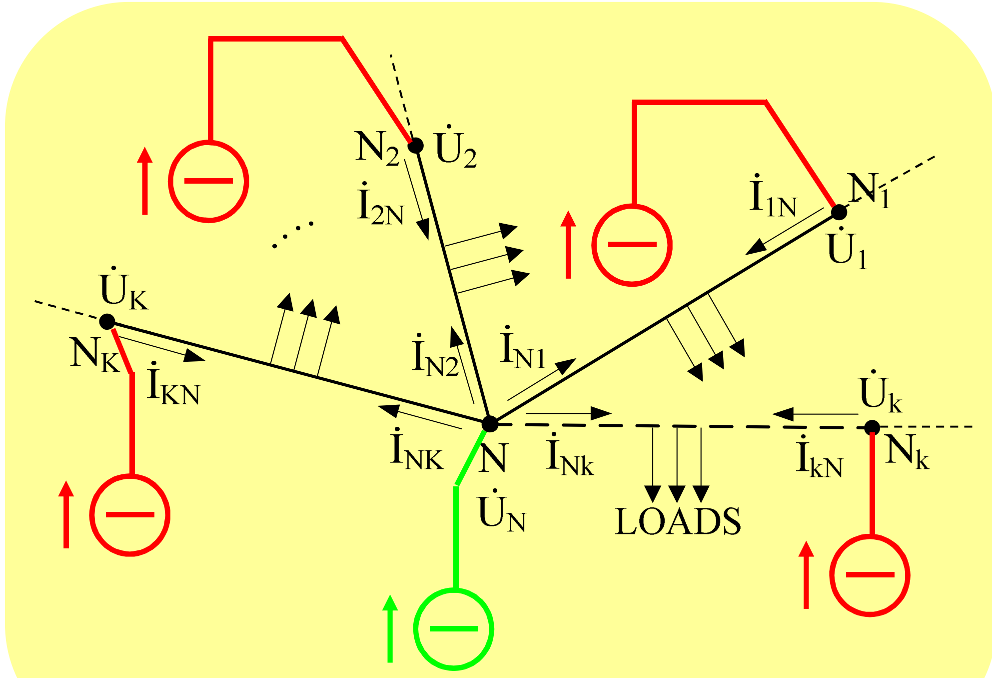
Node current/voltage optimization

Current at node N:

$$\dot{I}_N = \sum_{k=1}^{K} \dot{I}_{Nk} = \underbrace{\sum_{k=1}^{K} \dot{I}_{Nk}^{opt}}_{\dot{I}_N^{opt}} + \underbrace{\sum_{k=1}^{K} \frac{\dot{U}_N - \dot{U}_k}{\dot{Z}_k}}_{\dot{I}_N^{circ}}$$

Depends on loads connected to paths L_1 - L_K

Depends on voltage differences



Micro-grid cut set

Minimum distribution loss condition

$$\dot{I}_N^{circ} = 0 \quad \Rightarrow \quad \begin{cases} \dot{I}_N = \dot{I}_N^{opt} \\ \dot{U}_N = \dot{U}_N^{opt} = \sum_{k=1}^{K} \frac{\dot{U}_k}{\dot{Z}_k} \Big/ \sum_{k=1}^{K} \frac{1}{\dot{Z}_k} \end{cases}$$

GCI in control phase

GCIs in hold phase

Node current/voltage optimization

Node current optimization

$$\dot{I}_N = \dot{I}_N^{opt} = \sum_{k=1}^{K} \dot{I}_{Nk}^{opt} = \sum_{k=1}^{K} \frac{1}{d_{Nk}} \sum_{m=1}^{M_{Nk}} \dot{I}_{L_{Nk}} d_{k_{Nk}}$$

This equation holds separately for active and reactive terms , thus optimization can be done by acting on active currents, reactive currents, or both

The computation of optimum node current (reference current for GCI) requires *distance estimation* (ranging), *local grid mapping*, and *current measurement* at surrounding passive nodes)

Optimum current control does not excite network dynamics !

Node voltage optimization

$$\dot{U}_N = \dot{U}_N^{opt} = \frac{\sum_{k=1}^{K} \frac{\dot{U}_k}{\dot{Z}_k}}{\sum_{k=1}^{K} \frac{1}{\dot{Z}_k}} \approx \frac{\sum_{k=1}^{K} \frac{\dot{U}_k}{d_k}}{\sum_{k=1}^{K} \frac{1}{d_k}}$$

The computation of optimum node voltage (reference voltage for GCI) requires *local grid mapping*, knowledge of *path impedances* (or *node-to-node distances*), and *voltage measurement* at surrounding active nodes

Optimum voltage control does excite network dynamics !

Current/voltage relation at node N

1. Given the optimum node voltage and current, assuming the same impedance per unit of length for all distribution paths, from the measured voltage and current at node N we estimate this impedance as:

$$\dot{z} = \frac{\dot{U}_N - \dot{U}_N^{opt}}{\dot{I}_N - \dot{I}_N^{opt}} \sum_{k=1}^{K} \frac{1}{d_{Nk}}$$

2. The equivalent impedance and no-load voltage at node N can be determined as:

$$\dot{Z}_N^{eq} = \dot{z} \left(\sum_{k=1}^{K} \frac{1}{d_{Nk}} \right)^{-1}$$

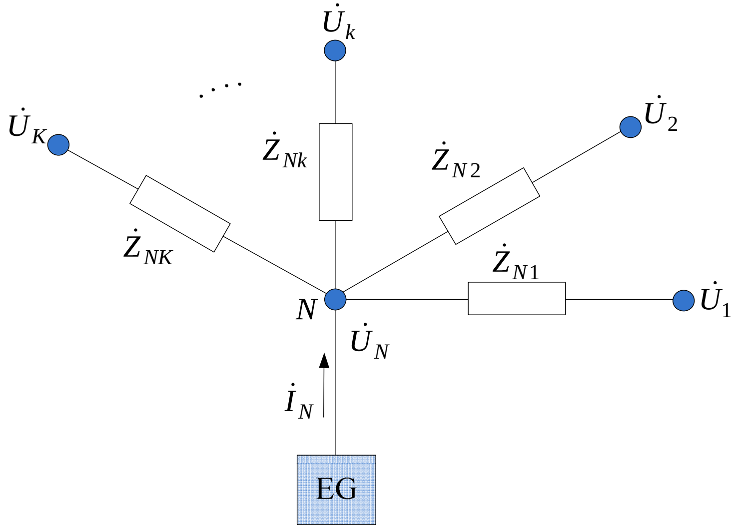
$$\dot{U}_N^{o} = \dot{U}_N^{opt} - \dot{Z}_N^{eq}\ \dot{I}_N^{opt}$$

3. The relation between voltage and current at node N is:

$$\dot{U}_N = \dot{U}_N^{o} + \dot{Z}_N^{eq}\ \dot{I}_N$$

This latter equation allows conversion of voltage references into current references and vice versa (current-mode / voltage-mode control)

Surround control implementation



Token ring control

- A token moves along the micro-grid, and only the active node *(N)* owning the token is enabled to modify its current reference according to the minimum loss criterion

- When an active node receives the token, it:

1. collects voltage phasors from neighbour nodes
2. measures (or recalls) the distances from neighbour nodes
3. computes the optimum voltage reference
4. computes the optimum current reference variation
5. sends the token to the next active node

$$\dot{U}_N^{opt} \approx \sum_{k=1}^{K} \frac{\dot{U}_k}{d_{Nk}} \Bigg/ \sum_{k=1}^{K} \frac{1}{d_{Nk}}$$

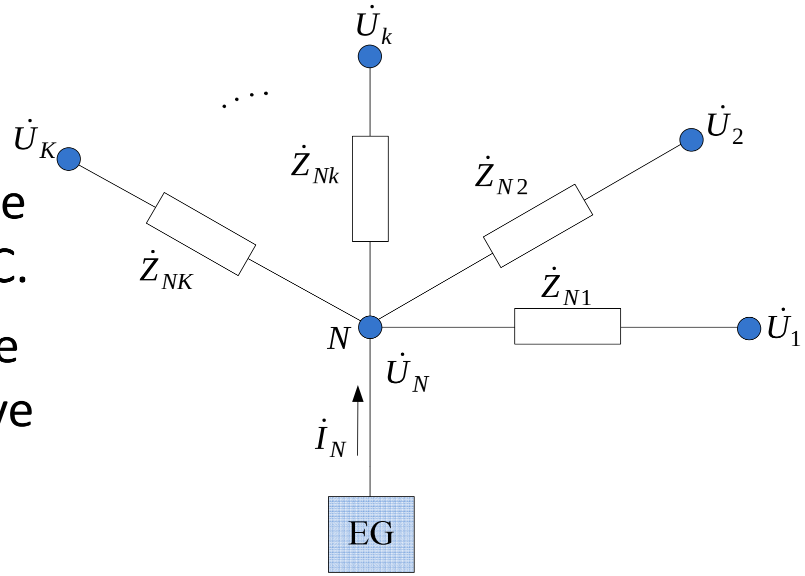
$$\Delta I_N^{opt} = \frac{\dot{U}_N^{opt} - \dot{U}_N^{0}}{\dot{Z}_N^{eq}}$$

Convergence of surround control

Convergence of control algorithm

- **Note:** The minimum loss condition is reached when **all nodes are equipotential**, their voltage being equal to the voltage impressed at the PCC.
- This condition is progressively approached if the nodes which sequentially receive the token drive their voltage toward the value:

$$\dot{U}_N^{opt} = \sum_{k \in [1,K]} b_{Nk} \dot{U}_k$$



- The choice of coefficients b_{Nk} defines **how fast the algorithm converges to the steady state optimum condition**.
- The convergence condition is: $$\sum_{k \in [1,K]} b_{kN} = 1, b_{kN} \geq 0$$
- It is satisfied with surround control since we assume: $$b_{Nk} = \frac{1}{d_{Nk}} \Big/ \sum_{k=1}^{K} \frac{1}{d_{Nk}}$$

Smart micro-grids

Properties, trends and local control of energy sources

11. Distributed cooperative control of smart micro-grids

Cooperative control (1)

Surround Control ensures minimum loss but has **strict requirements** in terms of communication and synchronization (PMU, Phase Measurement Unit), which are not easy to satisfy with cheap commercial technology

Question: there is a different distributed control technique with easier implementation and good performances? (**Sub-optimum** solution)

Remark: Beyond the mathematical analysis, an intuitive interpretation of distribution loss minimization is that **"the distribution loss reduces if the loads are supplied by the generators nearby"**

Cooperative control approach: each load m splits its active and reactive power demand P_m and Q_m among the active nodes n in inverse proportion to their distances:

$$P_m^n = \frac{P_m}{d_m^n}\left(\sum_{n=0}^{N}\frac{1}{d_m^n}\right)^{-1} \qquad Q_m^n = \frac{Q_m}{d_m^n}\left(\sum_{n=0}^{N}\frac{1}{d_m^n}\right)^{-1}$$

Cooperative control (2)

Each active node n, within its current capability, supplies the total power requested by the passive loads:

$$P_n = \sum_{m=1}^{M} P_m^n = \sum_{m=1}^{M} \frac{P_m}{d_m^n} \left(\sum_{n=0}^{N} \frac{1}{d_m^n} \right)^{-1} \qquad Q_n = \sum_{m=1}^{M} Q_m^n = \sum_{m=1}^{M} \frac{Q_m}{d_m^n} \left(\sum_{n=0}^{N} \frac{1}{d_m^n} \right)^{-1}$$

Advantages:

- *Use of PMUs* (phasor measurement units) *can be avoided*, since the loads address their requests in terms of active and reactive power, which are conservative quantities and do not depend on the phase of the node voltages.
- There is *no need for micro-grid topology identification*, since only the node-to-node distances are requested to implement the control algorithm.

Disadvantage:

- The solution can diverge from the optimum condition in case of saturation of the current capability of the inverters.

Solution: The saturation conditions must be properly managed by shifting the power requests from the saturated active nodes into non-saturated nodes.

Cooperative control (3)

Managing saturation. The splitting algorithm of the load power is modified as follows:

$$P_m^n = P_m \frac{\beta_{nP}}{d_m^n} \Big/ \sum_{n=0}^{N} \frac{\beta_{nP}}{d_m^n} \qquad Q_n^m = Q_m \frac{\beta_{nQ}}{d_m^n} \Big/ \sum_{n=0}^{N} \frac{\beta_{nQ}}{d_m^n}$$

where:

$$\beta_{nP}(k) = \beta_{nP}(k-1) \cdot \alpha_{nP}(k) \qquad \beta_{nP\,min} \le \beta_{nP}(k) \le 1$$
$$\beta_{nQ}(k) = \beta_{nQ}(k-1) \cdot \alpha_{nQ}(k) \qquad \beta_{nQ\,min} \le \beta_{nP}(k) \le 1$$

and

$$\alpha_{nP}(k) = P_{n,MAX} / P_n(k-1)$$
$$\alpha_{nQ}(k) = Q_{n,MAX} / Q_n(k-1)$$

k = sampling interval (sampling frequency = 10 Hz)

Advantages

- The power limits of the active nodes are automatically met
- Recovery from saturation happens quickly
- Load power requests are met precisely
- The power splitting criterion approaches the “minimum distance” criterion as close as possible, within the power limits of the active nodes
- Control is inherently stable

Smart micro-grids

Properties, trends and local control of energy sources

12. Simulation results

Simulation approach

Assumptions

- The proposed control techniques have been validated by simulation in the Matlab – Simulink environment
- To minimize the complexity of simulation and to reduce the simulation times a **phasorial simulation** tool has been developed.
- The graphs showing the time behaviour of the system represent must be interpreted as **sequences of steady states** (quasi-stationary behavior), where fast dynamics are neglected

Simulation Example (1)

DG	P_{MAX} kW	S_{MAX} kVA
G1	1	2
G2	1	2
G3	3	5
G4	3	5
G5	3	5
G6	1	2
G7	10	15
G8	10	15
G9	10	15

Load Z=R+jωL	Power @ $230V_{RMS}$
L1	5kW cosφ=0.91
L2	5kW cosφ=0.91
L3	2.5kW cosφ=0.96
L4	2.5kW cosφ=0.96
L5	2.5kW cosφ=0.96
L6	5kW cosφ=0.91
L7	10kW cosφ=0.80
L8	10kW cosφ=0.80
L9	10kW cosφ=0.80

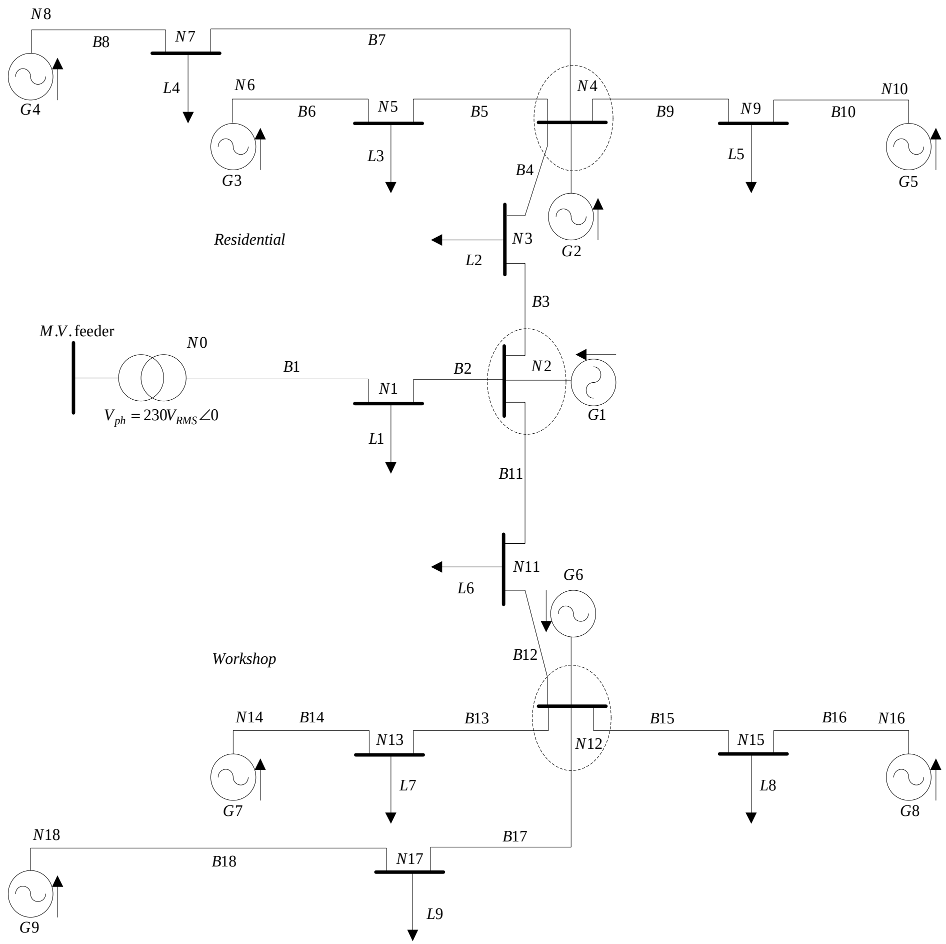
$P_{RL} = 52.5kW$ $\quad \cos\varphi_{RL} = 0.857$ **Total Loads**

$P_{RG} = 55kW$ $\quad S_{RG} = 85kVA$ **Total DERs + EGs**

$S = 240mm^2$

r = 0.08Ω/km
l = 255μH/km
Φ = π/4 rad

18-bus LV network



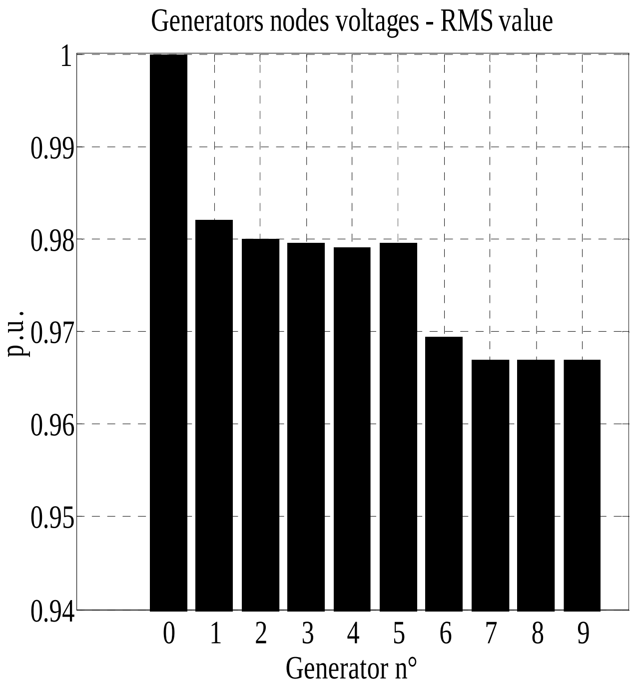
Total length of distribution line **1.8km**

Simulation Example (2)

Initial situation: Inverters OFF

Loss: $P_{R_{\max}} = 1.2\text{kW}$

Voltages:



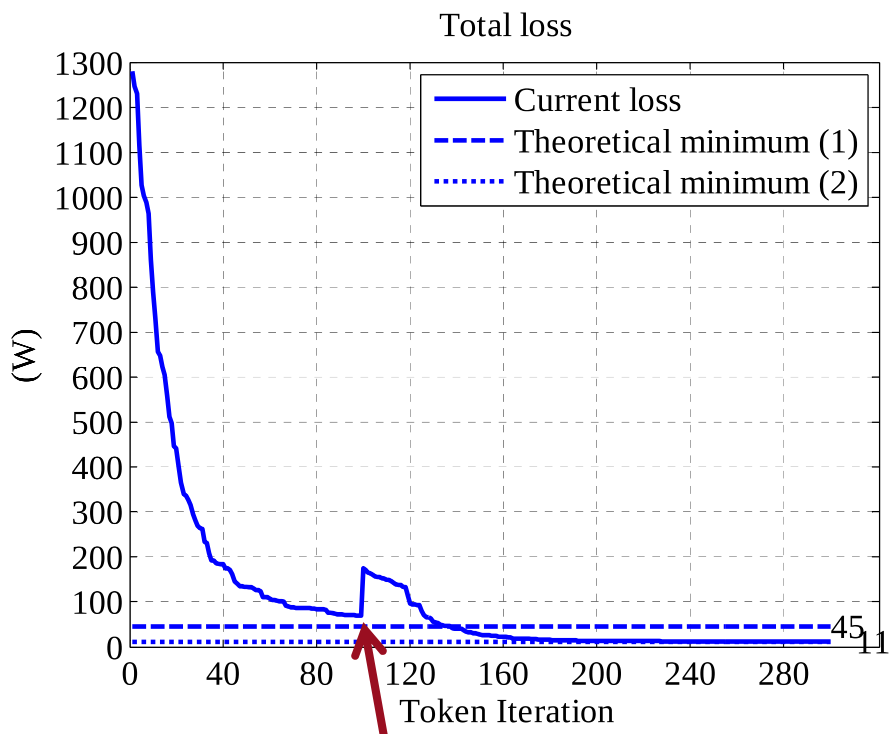
The distributed control techniques are analyzed in specific operating conditions, their performance being compared with those of optimum control.

Two cases are considered:

- **Active and Reactive** current control constrained by **converters saturation** (to show the achievable performances in a real system with energy storage)
- **Purely reactive current control** (to show the achievable improvement without energy storage)

Normally the active power is determined by energy storage & generated power constraints (sun, wind, batteries ,etc), while the reactive power can be regulated, within the current capability of the inverters, to optimize the system operation.
The actual performances are therefore intermediate between the two limit conditions considered above.

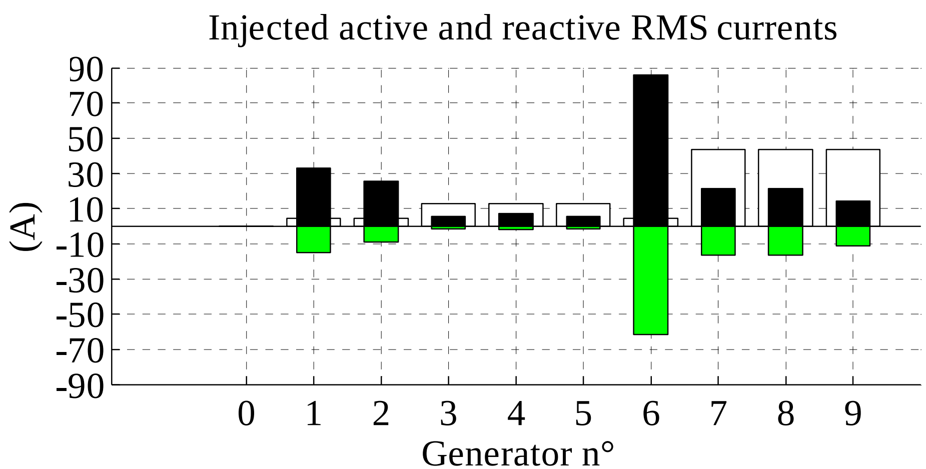
Surround control (1)



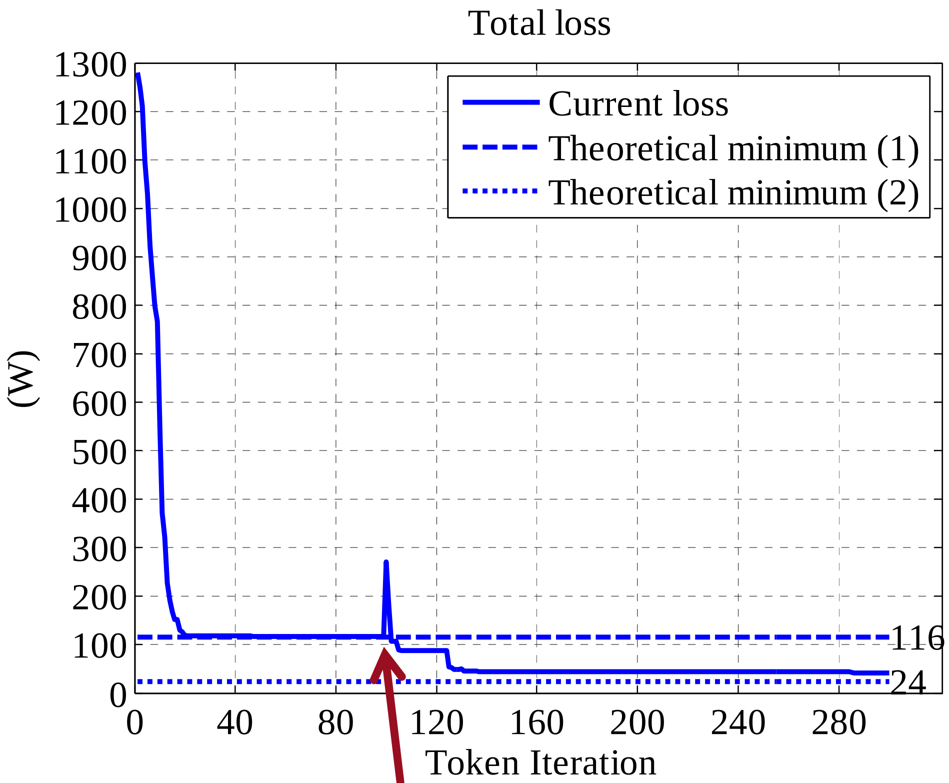
After 100 iterations all loads reduce their power absorption to 50% of the nominal ratings

Surround control neglecting saturation
Active and reactive current control

A Token Ring approach is adopted, where the 9 generators are activated and updated in sequence. Every 9 token jumps, the loads update their current demands.



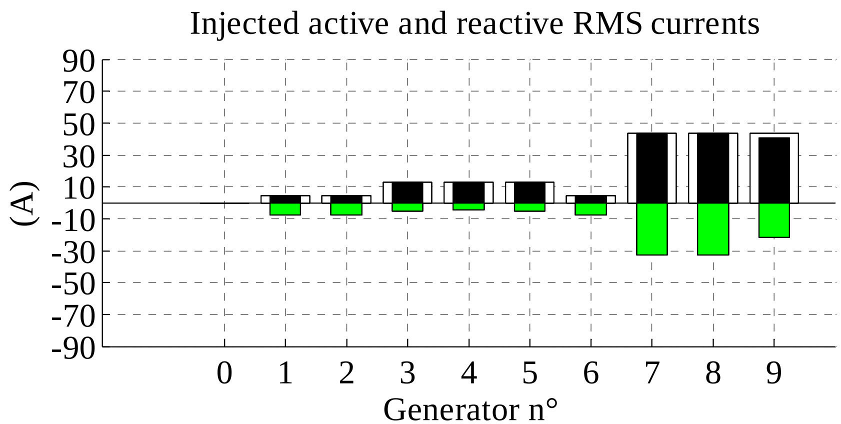
Surround control (2)



Surround control considering saturation
Active and reactive current control

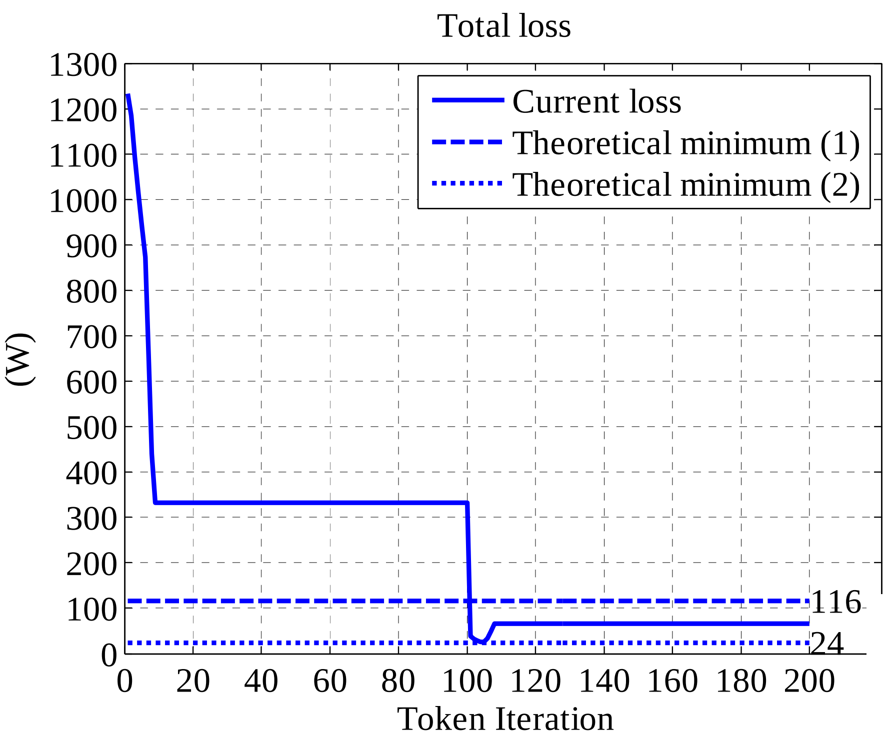
A Token Ring approach is adopted, where the 9 generators are activated and updated in sequence. Every 9 token jumps, the loads update their current demands.

After 100 iterations all loads reduce their power absorption to 50% of the nominal ratings



12. Simulation results

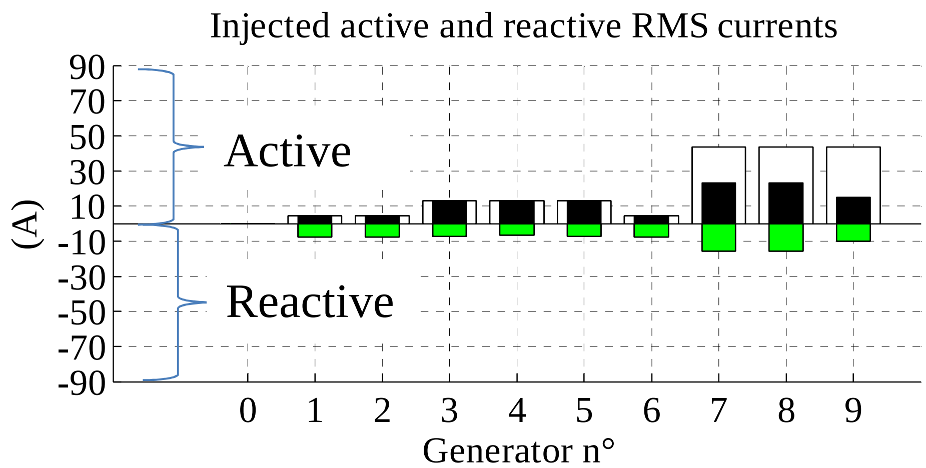
Cooperative Control (1)



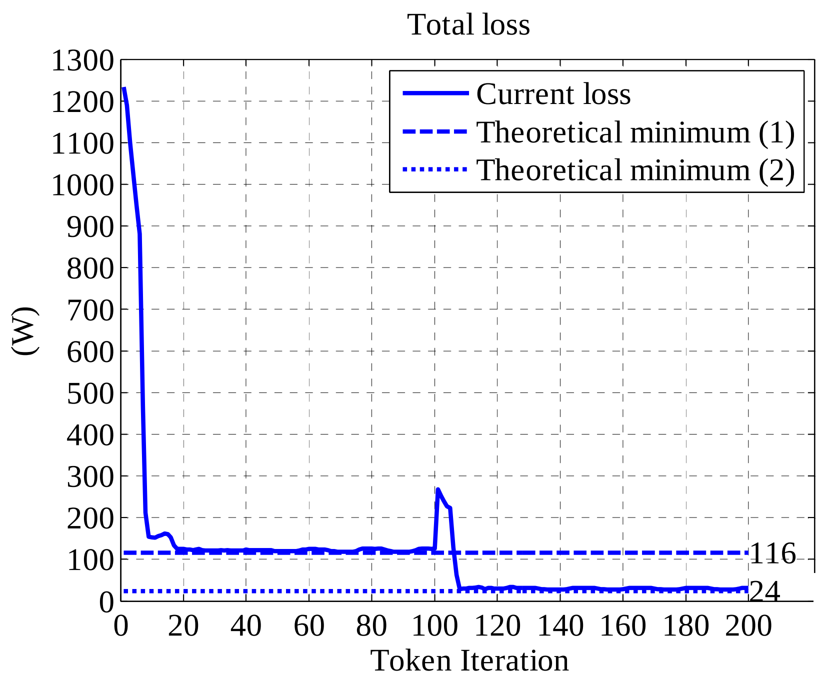
Cooperative control without saturation management
Active and Reactive current control

A Token Ring approach is adopted, where the 9 generators are activated and updated in sequence. Every 9 token jumps, the loads update their current demands.

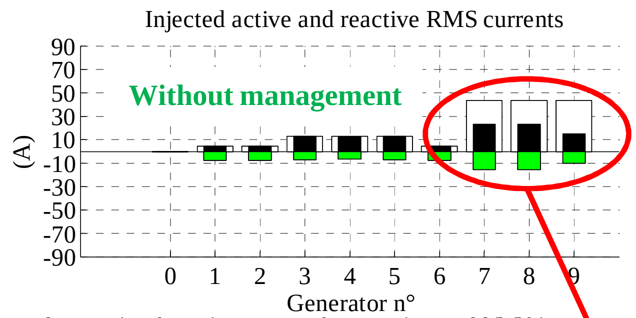
After 100 iterations all loads reduce their power absorption to 50% of the nominal ratings

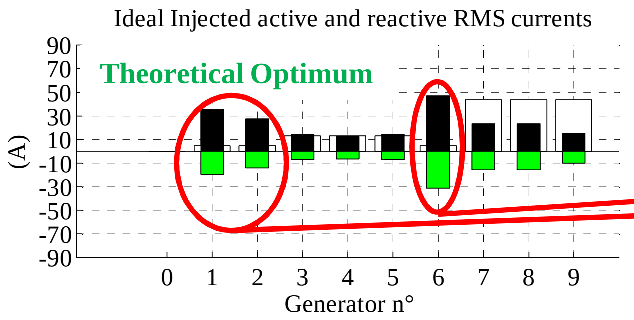


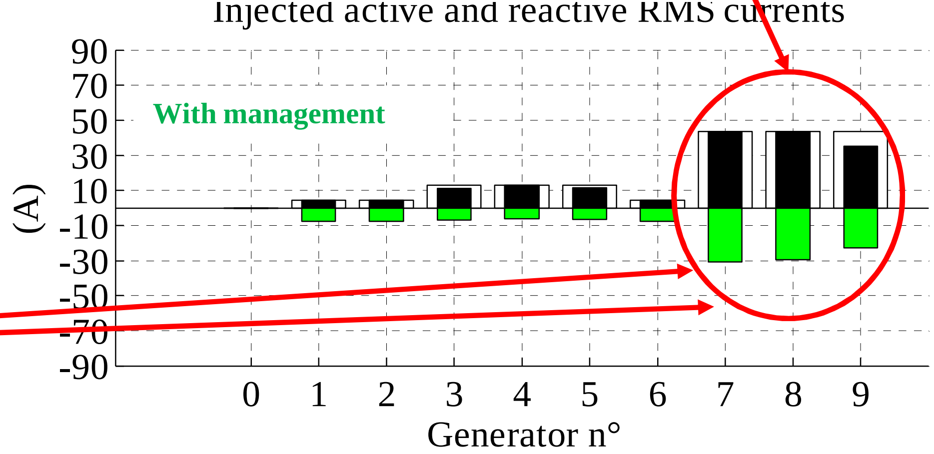
Cooperative control (2)



Cooperative control with Saturation Management (active and reactive current control)







Purely reactive current control

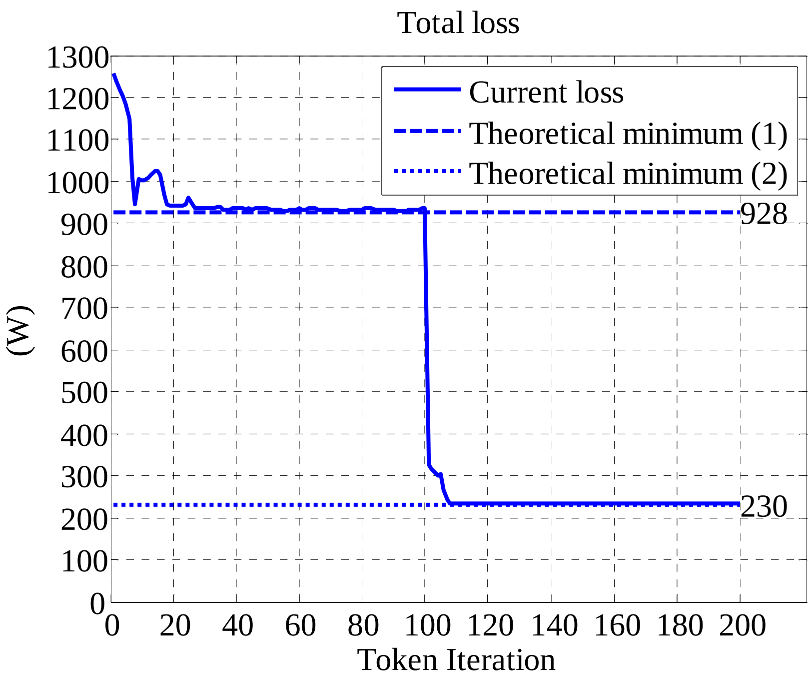
Assuming that **only reactive currents** are injected in the grid by the distributed grid-connected inverters, the distribution losses become:

- **Surround Control** **P_{LOSS}=928W (23% loss reduction)**
- **Cooperative Control** **P_{LOSS}=935W (22% loss reduction)**

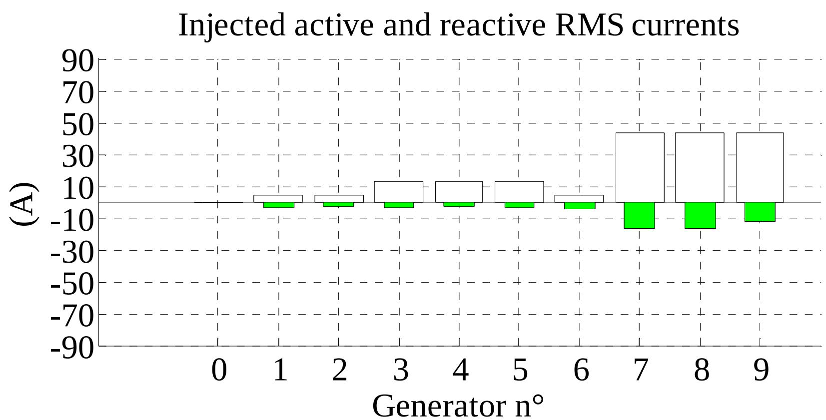
This represents the worst case condition, i.e., the case of a micro-grid without energy storage capability and distributed power generation.

- The presence of distributed power generators allows a first level of improvement, since their active power can partially compensate for the active power demand of local loads.
- The situation is further improved if the grid-connected inverters can manage the energy of storage devices too, because this allows a local compensation for the entire active and reactive power demand by the loads, resulting in minimum distribution losses.

Purely reactive current control



Cooperative control with Saturation Management (pure reactive current control)



After 100 iterations all loads reduce their power absorption to 50% of the nominal ratings

Conclusions

1. Smart micro-grids represent a fast-growing and challenging arena for ICT, power electronics and power systems research and applications
2. The bottom-up revolution made possible by an extensive implementation of the micro-grid paradigm can have a dramatic impact on the entire value chain of the electrical market
3. A structured multi-layer reorganization of the electrical grid can provide huge benefits in terms of energy savings, quality of service and flexibility of operation, without altering the physical infrastructure of the grid
4. The development of suitable distributed control & communication techniques can provide flexibility, scalability, power quality, integration and exploitation of any kind of energy resources, energy efficiency and stability of operation
5. The successful Internet paradigm can possibly be replicated in the domain of distributed energy generation, distribution and utilization

Smart micro-grids

Properties, trends and local control of energy sources

Research activities at DEI

DEI team

DEI smart grid facility