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SMART RUE smartgrids Research Unit ECE NTUA

ERIGrid Connecting European Smart Grid Infrastructures

Distributed control applications using Virtual Power Plants

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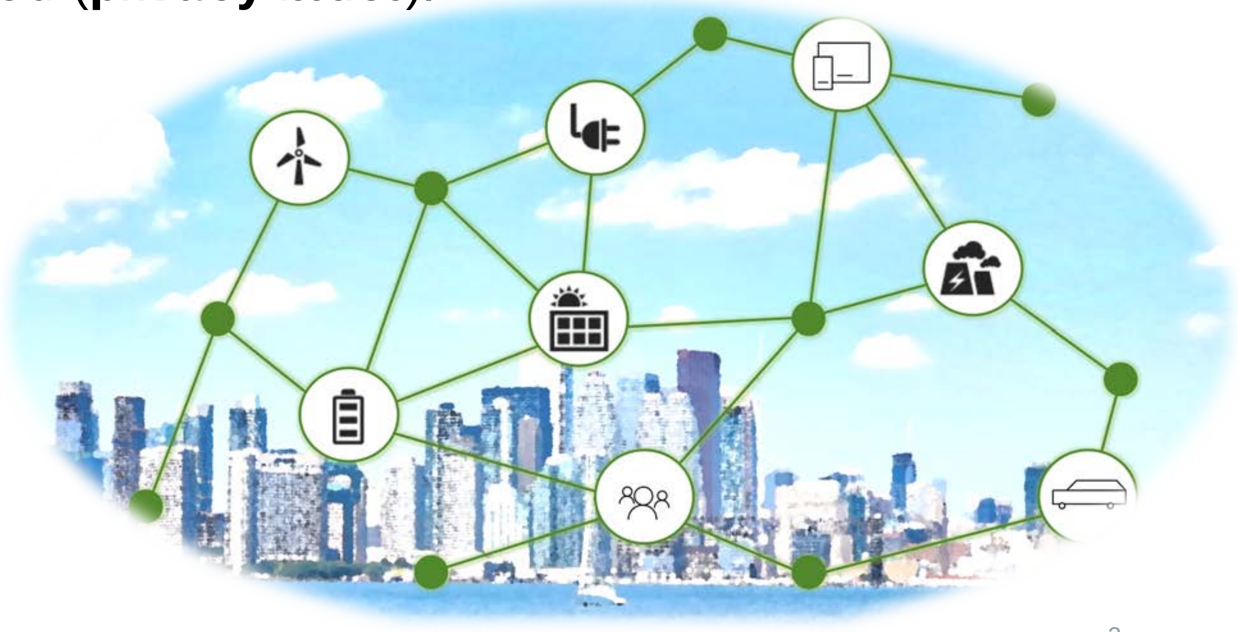
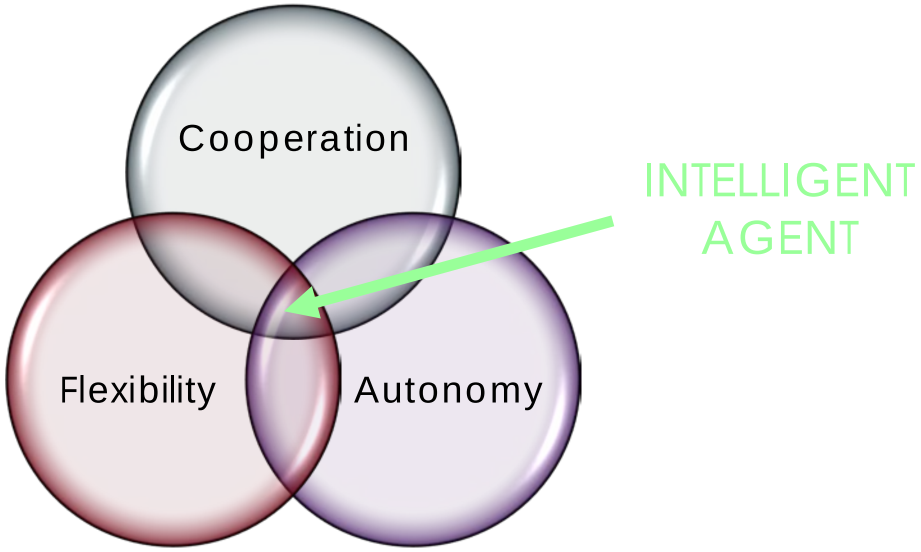
Contents

Introduction

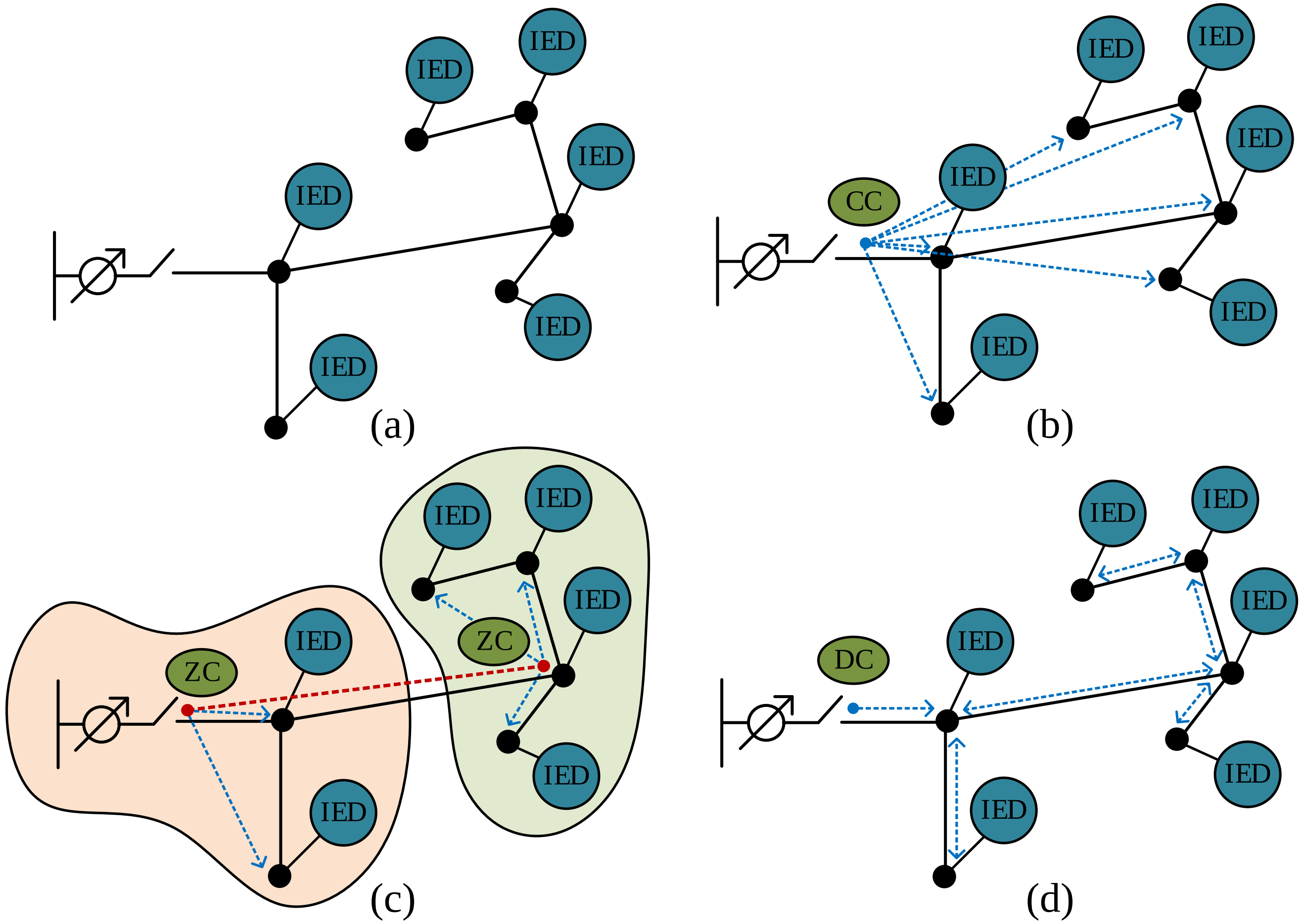
- The drastic increase of distributed intermittent generation introduces several local constraints' violations → should be handled **locally** in **scalable** manner.
- Digitalization of the power system: The transition to active network management has increased the volume of collected data → necessity for efficient **monitoring** and **control** solutions.
- Sensitive consumer data should be protected (**privacy** issues).



Overview of Coordination Architectures



a. Without communication
b. Centralized
c. Decentralized (in zones or areas)
d. Distributed

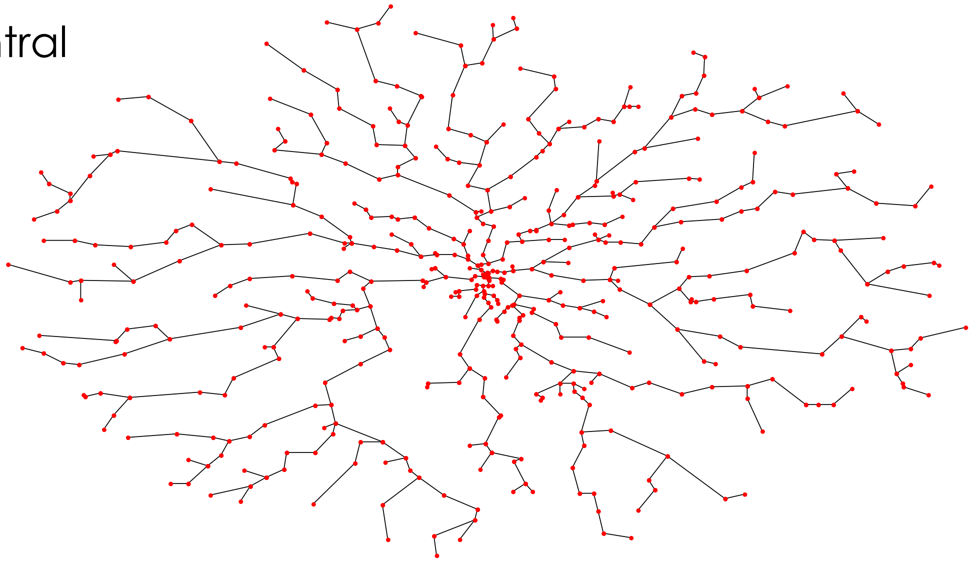


Technical Background

- The wide deployment of smart meters and devices with power electronics interfaces creates the necessary **infrastructure** for the application of distributed algorithms:
  - “low-cost” devices, for monitoring, event detecting and controlling hardware,
  - that can communicate via existing ICT/power networks and
  - execute the distributed software.

Advantages of Distributed Architecture

- Large scale applications → scalability.
- Dispersed solution to locally caused problems → no need for central coordination.
- Increased robustness.
- Tolerance in communication delays.
- Extensibility → “Plug-and-play.
- Privacy.



Applications in Power Systems

- Problems that can be addressed:
  - Economic Dispatch
  - Demand Side Management
  - Voltage control
  - Congestion Management
  - Optimal Power Flow
  - Optimal Scheduling
  - Power Flow
- Formulation as Resource Allocation Problems (in many cases).

- Distributed algorithms:
  - Consensus based optimization
  - Replicator Dynamics/Population Dynamics
  - Lagrangian based techniques
  - Gradient based algorithms
  - DCOP (i.e. ADOPT)
- Interplay of *control theory*, *distributed optimization*, *dynamical systems*, *graph theory* and *algebraic topology*

Distributed resource allocation

- A set of agents must assign their **resources** to a set of **tasks** in order to meet specific **constraints**.
- The distributed optimization techniques use iterative control rules for updating their local state (i.e. decision making).
- Every local new decision that is taken should drive the grid towards the globally optimal solution (taking into account local and global constraints).

Optimally is expressed in terms of minimizing the objective function of the resources:	$\min_{x \in \mathbb{R}^n} \sum_{i=1}^{N} f_i(x)$
Grid constraints are introduced as constraints in the control variables of the nodes:	$s.t.\, g(x) \leq 0 \; h(x) = 0 \; x \in \cap_{i=1}^{N} X_i$
Update rules are designed that require exchange of information only between neighbors:	$x_i(k+1) = W_i\big(x(k)\big)$

Consensus algorithm – Application on Economic Dispatch

$$\min C_{total}(\boldsymbol{p}) = \min \sum_{i \in V} C_i\,(p_i)$$

Subject to:

$$p_{Load} = \sum_{i \in V} p_i$$

$$p_{min_i} \leq p_i \leq p_{max_i}$$

Given:

$$C_i(p_i) = a_i + b_i \cdot p_i + c_i \cdot p_i^2$$

Model:

$$\boxed{\dot{x}_i(t) = \sum_{j \in N_i} a_{ij}\big(x_j(t) - x_i(t)\big)}$$

Initialization:

$$\begin{cases} \lambda_i(0) = & \text{any fixed admissible value} \\ x_i(0) = & \text{any fixed admissible value} \\ y_i(0) = & \begin{cases} \frac{D}{|N_0^-|} - x_i(0) & \text{if } i \in N_0^- \\ -x_i(0) & \text{otherwise} \end{cases} \end{cases}, \forall i \in V.$$

Iteration:

$$\lambda_i(k+1) = \sum_{j \in N_i^+} p_{i,j}\lambda_j(k) + \epsilon y_i(k)$$

$$x_i(k+1) = \beta_i \lambda_i(k+1) + \alpha_i$$

$$y_i(k+1) = \sum_{j \in N_i^+} q_{i,j} y_j(k) - (x_i(k+1) - x_i(k))$$

Global (consensus) Variable

Production of generator

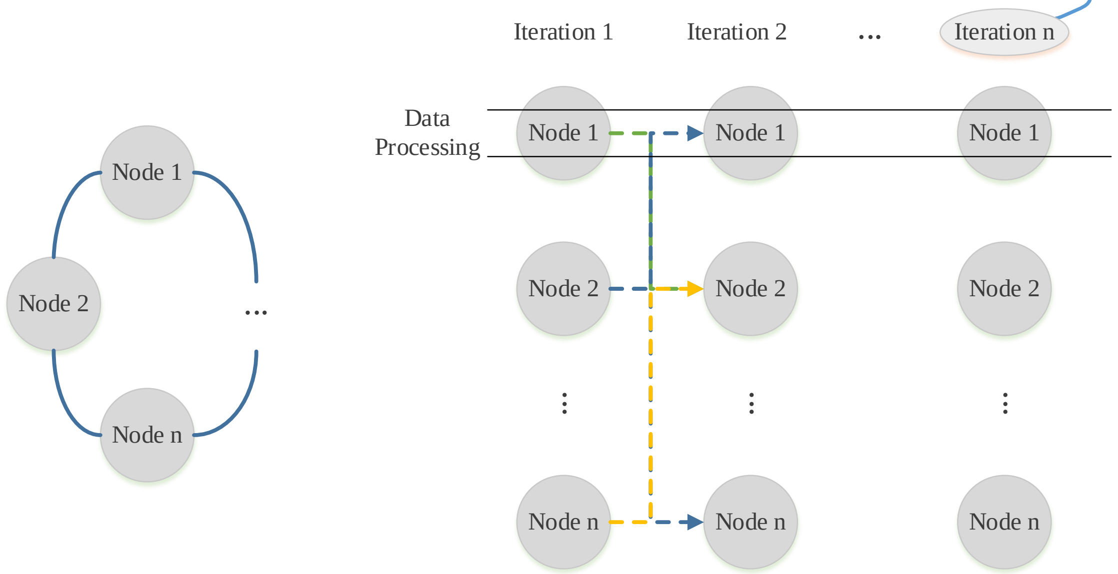
Production mismatch (internal variable)

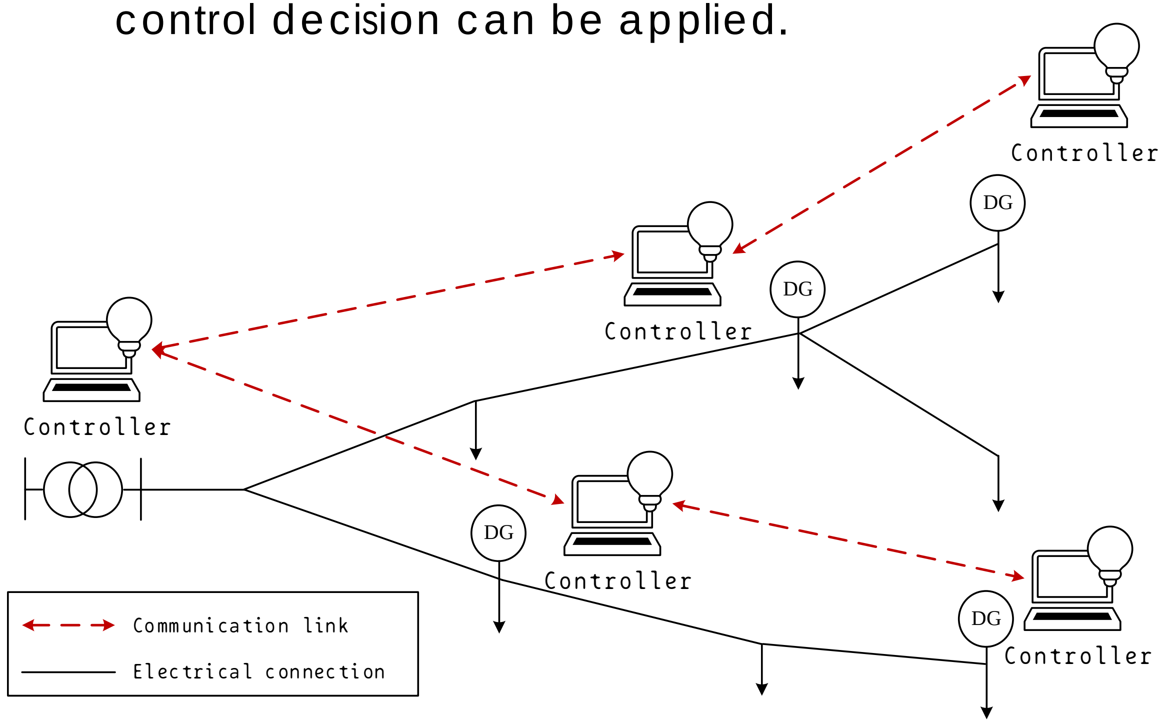
Applications (Consensus)

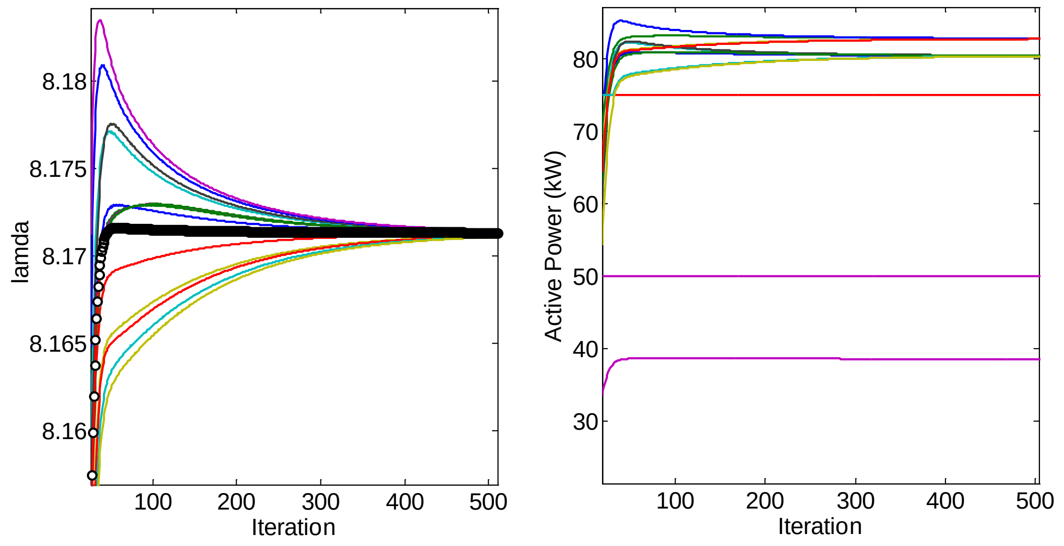
In each iteration every node performs the following steps until convergence:

- Communication with neighbors.
- Update the values of the their internal variables.

When convergence is detected, the control decision can be applied.







Optimal Voltage Control

- Based on an Optimal Power Flow formulation:

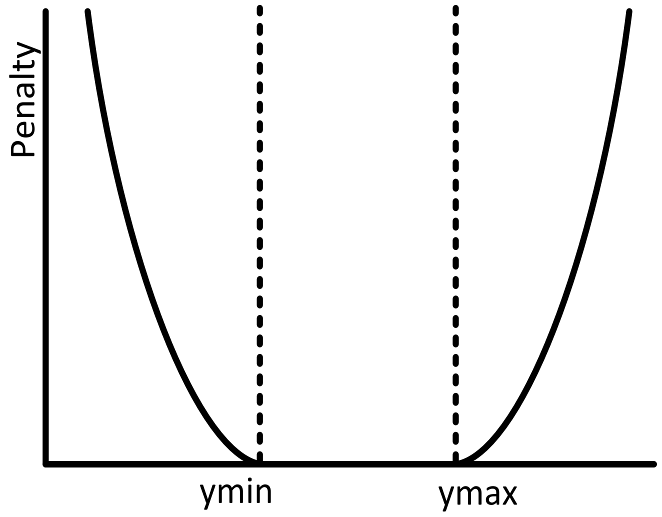
$$\min\big(F(\boldsymbol{x},\boldsymbol{u})\big) = \min\left\{\sum_{i\in N\setminus\{1\}} f_i\big(P_{C_i},Q_{C_i}\big) + f_{ref}\big(\mathcal{P}_1(\boldsymbol{V},\boldsymbol{\delta}),\mathcal{Q}_1(\boldsymbol{V},\boldsymbol{\delta})\big)\right\}$$

Subject to the power flow equations:

$$\mathcal{P}_i(\boldsymbol{V},\boldsymbol{\delta}) - P_{NET_i} = 0$$

$$\mathcal{Q}_i(\boldsymbol{V},\boldsymbol{\delta}) - Q_{NET_i} = 0$$

And the voltage constraints: $V_{min} \leq V_i \leq V_{max}$



- The nodes adjust their active and reactive power in order to avoid voltage violations.
- The voltage limits are introduced as soft constraints;
- This way the local violations affects the cost function of a specific node (that participates in the global optimization).

Distributed solution (Voltage Control)

- Langrangian formulation:

$$\mathcal{L}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{\rho}) = \sum_{i\in N\backslash\{1\}} \left(f_i\left(P_{C_i}, Q_{C_i}\right) + w_i\right) + f_{ref}(\mathcal{P}_1, \mathcal{Q}_1) + \boldsymbol{\lambda}^T \mathbf{g}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{\rho})$$

- Minimization of the Langrangian:

$$\nabla\mathcal{L} = 0 \Rightarrow \left.\begin{array}{r} \nabla\mathcal{L}_{\boldsymbol{x}} = 0 \\ \nabla\mathcal{L}_{\boldsymbol{u}} = 0 \\ \nabla\mathcal{L}_{\boldsymbol{\lambda}} = 0 \end{array}\right\} \Rightarrow \left.\begin{array}{c} \left[\frac{\partial F}{\partial x}\right] + \left[\frac{\partial g}{\partial x}\right]^T \boldsymbol{\lambda} = 0 \\ \left[\frac{\partial F}{\partial u}\right] + \left[\frac{\partial g}{\partial u}\right]^T \boldsymbol{\lambda} = 0 \\ \mathbf{g}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{\rho}) = 0 \end{array}\right\} \Rightarrow$$

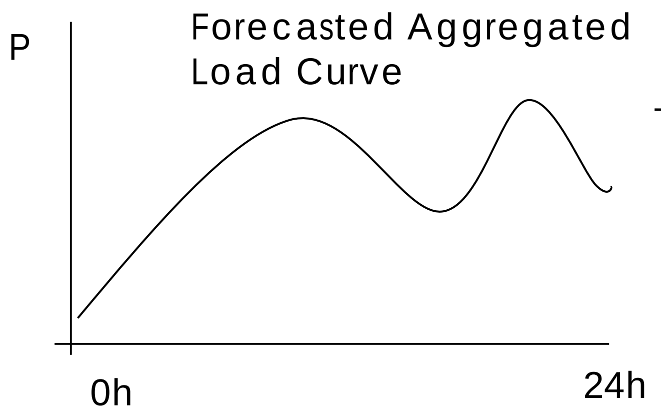
- Each node calculates:

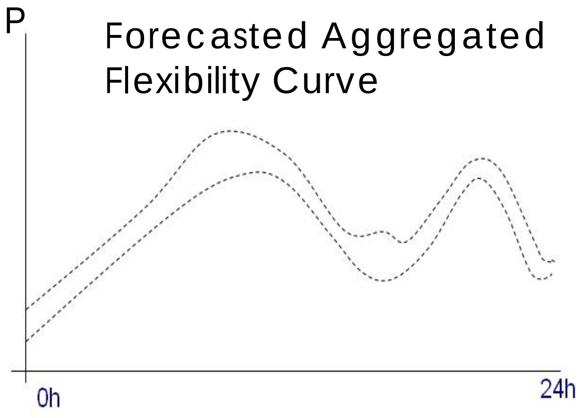
$$\nabla\mathcal{L}_{\boldsymbol{u}_i} = \begin{bmatrix} 2c_{P_i}P_{C_i} \\ 2c_{Q_i}Q_{C_i} \end{bmatrix} + \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \lambda_{P_i} \\ \lambda_{Q_i} \end{bmatrix}$$

- And uses a convex distributed optimization model to calculate λ_{P_i} and λ_{Q_i}.

[I. N. Kouveliotis-Lysikatos, D. I. Koukoula and N. D. Hatziargyriou, "**A Double-layered Fully Distributed Voltage Control Method for Active Distribution Networks**," in *IEEE Transactions on Smart Grid*.]

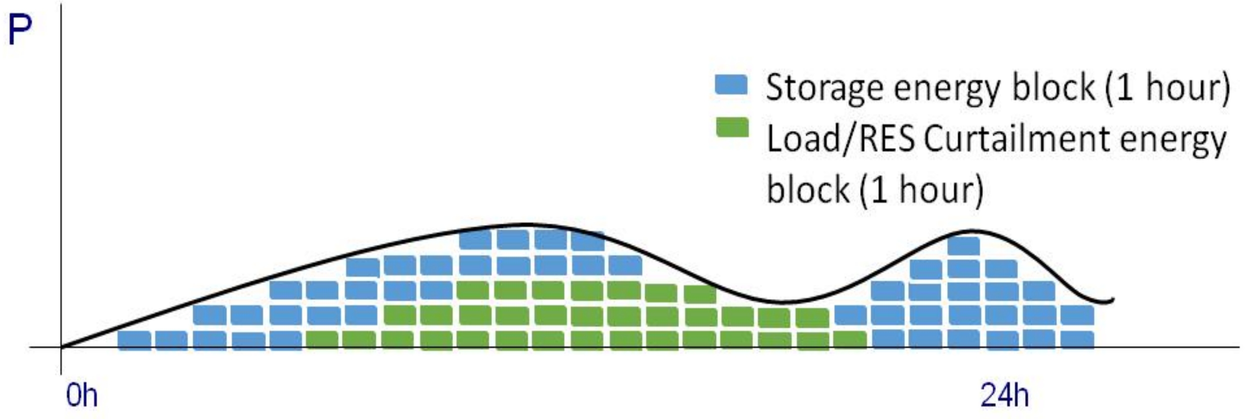
Virtual Power Plants



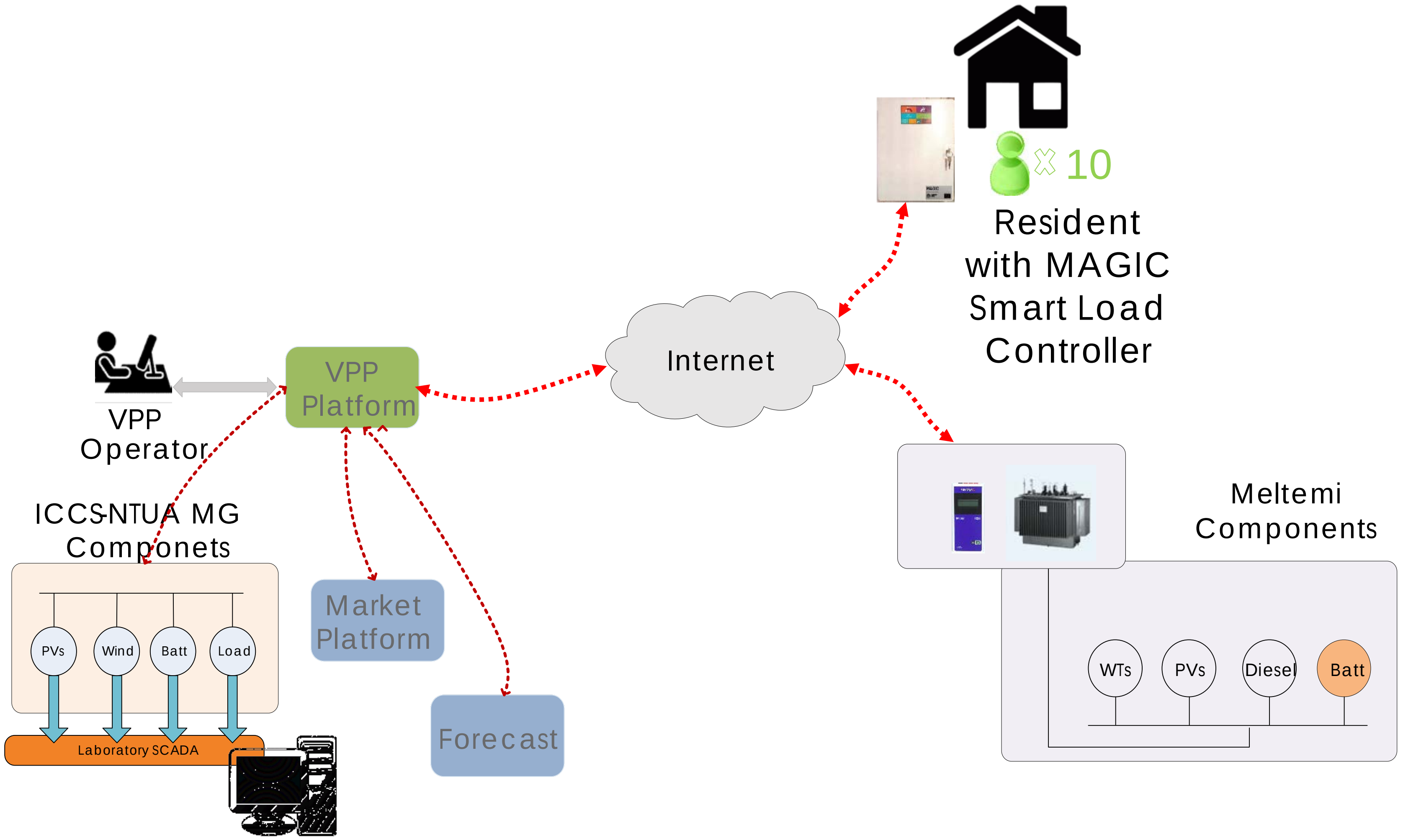


Combine several units in order to act as a single unit

Calculate Modified Production – Demand Curve according to Day-ahead energy market

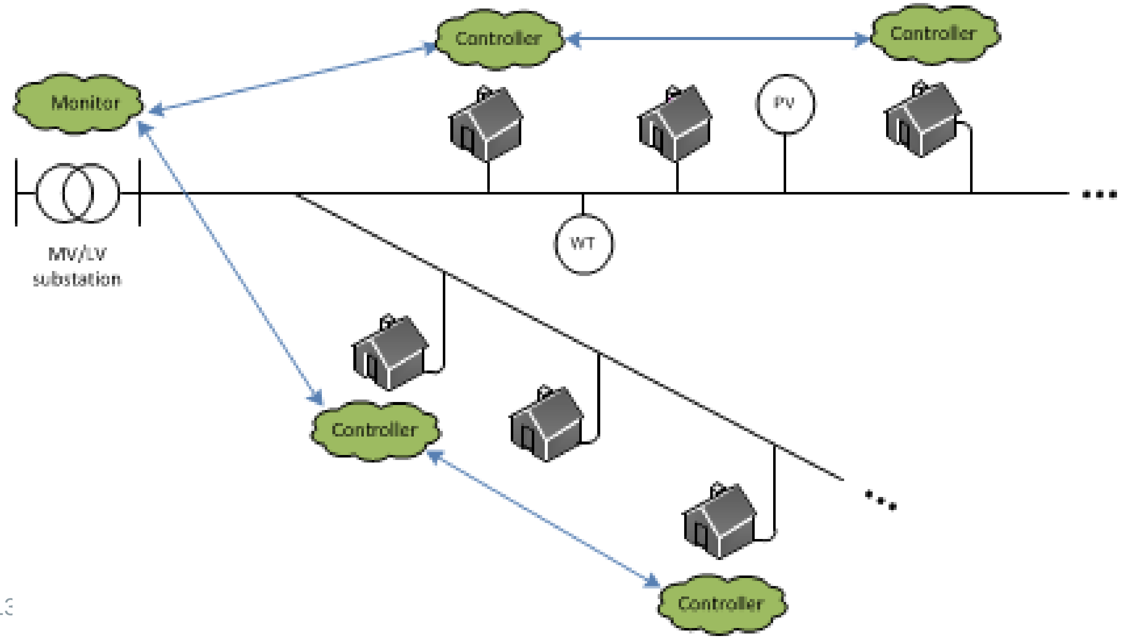


The ICCS VPP platform



Demonstrations in Meltemi Community Smart Grids pilot site

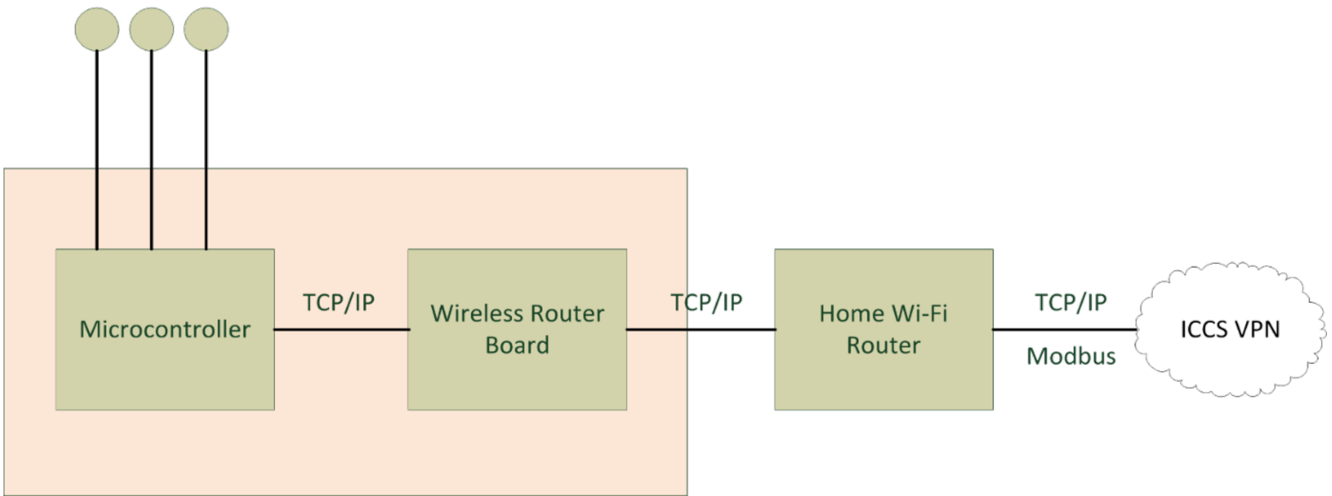
- Congestion Management and Voltage Control are tested.
- Intelligent load controllers have been installed in a number of households.
- Peer-to-peer communication between the controllers utilizing the local LAN.
- Active power curtailment by controlling the household appliances.
- The distributed algorithms are developed using JADE.

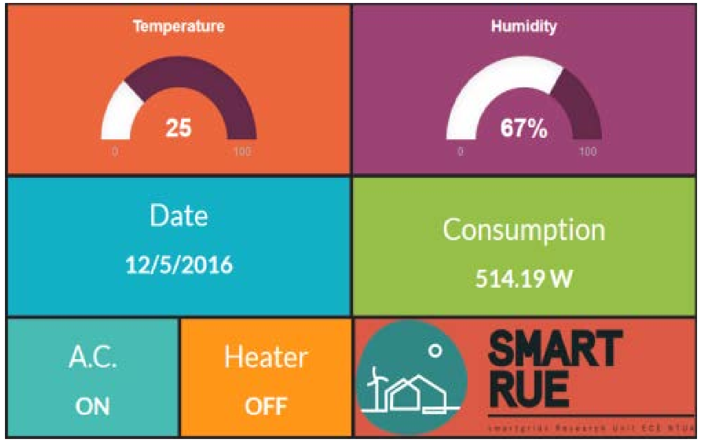


EU H2020 Programme GA No. 654113

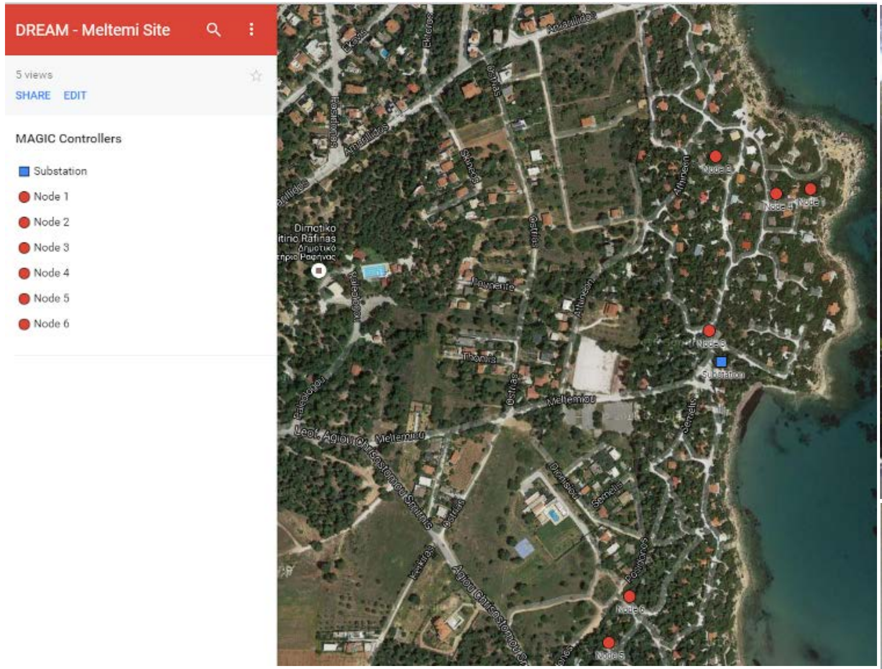
Intelligent Load Controllers

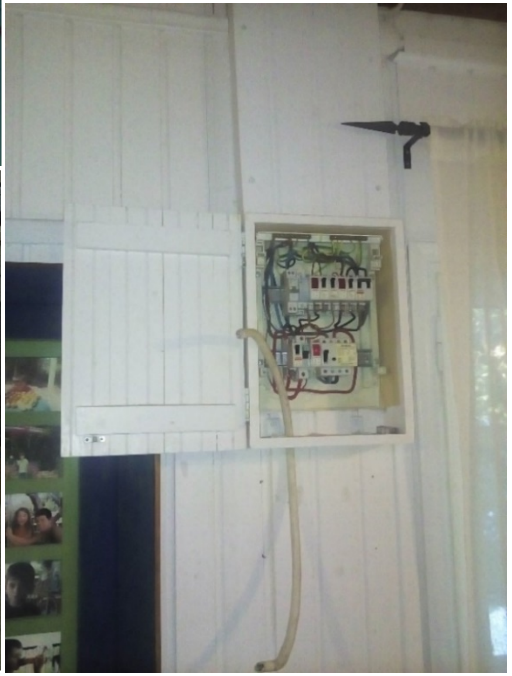
- The Load Controllers:
  - Are connected on the electrical boards of the house.
  - Measure the power consumption of the household.
  - Control household appliances (water heaters and A/C units).
  - Communicate using the local LAN.
  - Execute the distributed algorithms.
  - Make decisions and take control actions.





Meltemi test site: Decentralized Operation





Meltemi test site: Decentralized Operation

Number of Household	Type of controllable load	Active Power Flexibility (kW)
1	Water Heater Oven	2 2.5
2	Water Heater	2
3	A/C	3
4	Water Heater	2
5	Water Heater	2.5
6	Water Heater	2

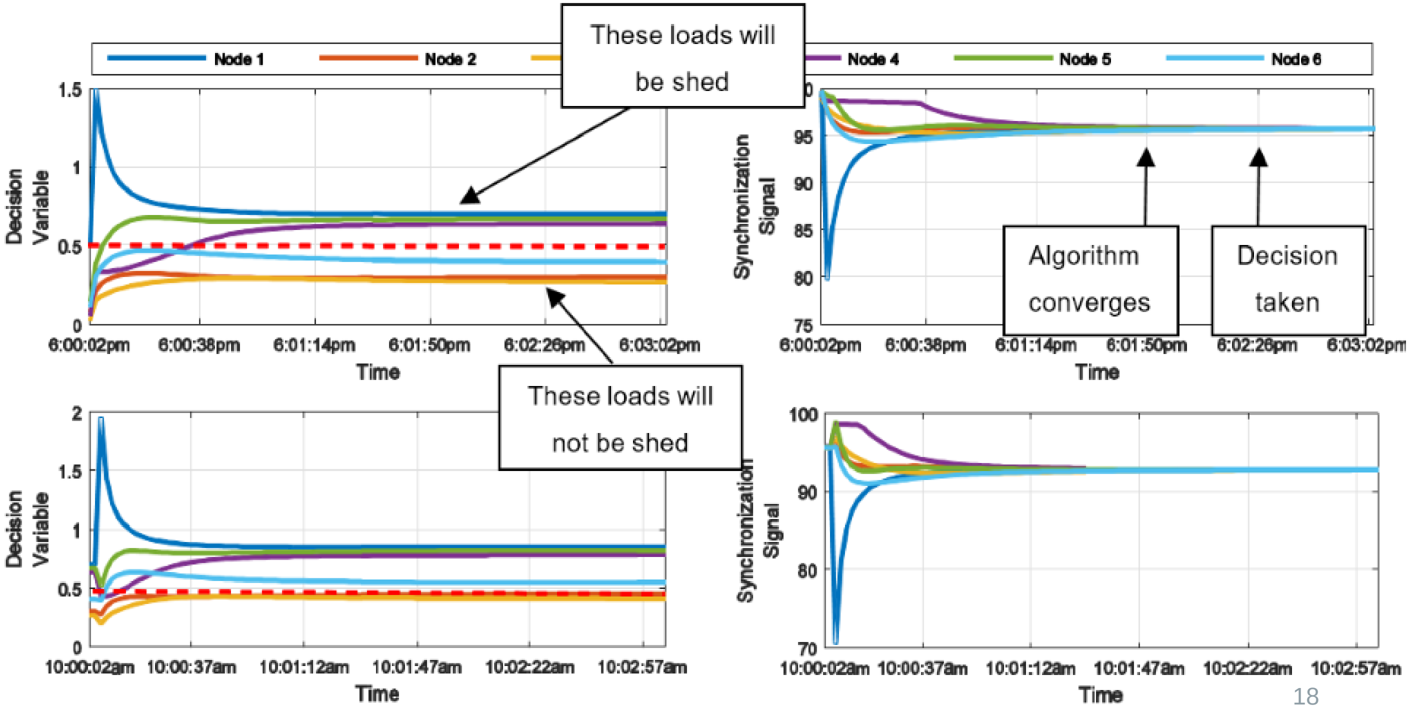
- Households with controllable loads:
  - Types of controllable devices.
  - Active power flexibility per device per household.

- Mapping of Customer Flexibility.
- Need for modelling of the customer's willingness to alter its consumption profile.

User Defined Priority:	Interpretation by the algorithm:
High	The load should not be shed except in case of grid emergency.
Medium	The load could be shed in case that lower priority loads are not sufficient to solve the problem.
Low	The load can be shed to help in order to facilitate the energy balancing of the grid.

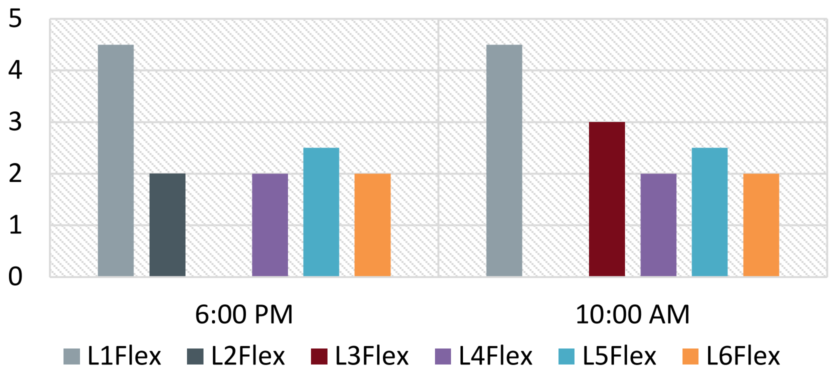
Decentralized Congestion Management

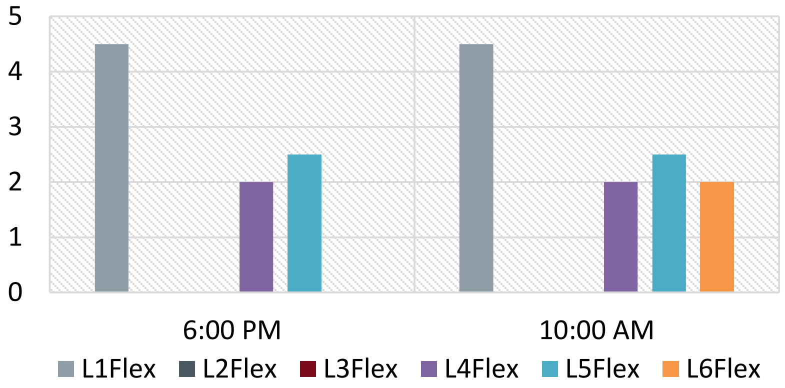
- The triggering event is a **deviation** from the initially scheduled aggregated demand curve.
- The **DSO agent** (monitors the pilot site substation) informs the household agents, to proceed to a reduction of power.
- The prosumers negotiate in order to arrive at an agreement regarding the amount of power to be altered.
- The algorithm **terminates** when convergence is **detected** (all agents reach the same value in the synchronization signal).
- The decision for curtailment is calculated in a **distributed manner.**



Congestion Management

- The algorithm was triggered in two timeslots:
  - 06.00 PM – 7 PM with an imbalance of 9.0kW and
  - 10.00 AM – 11.00 AM with an imbalance of 12.0kW





Available flexibility per customer for the two timeslots (available load that can be curtailed pre household)

Flexibility that was finally activated by the algorithm (loads that were actually shed)

HIL Experiments?

- Testing distributed control algorithms as well as the VPP architecture is really challenging:
  - Actual conditions for different demonstration sites can vary dramatically
  - Customer engagement? (at least for testing of specific functionalities...)

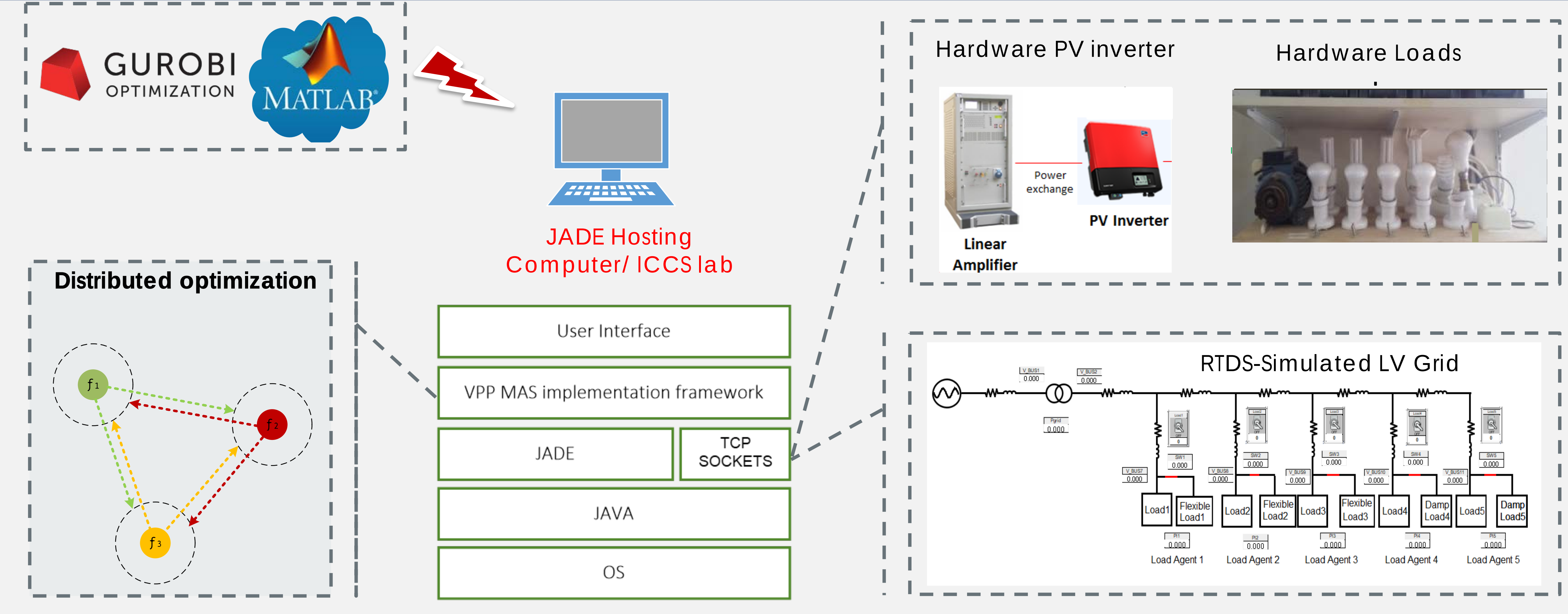
✓ More realistic tests can be performed using PHIL and CHIL experiments in a laboratory environment, by integrating the VPP platform in the Real Time Digital Simulator (RTDS) (hardware devices can be also used).

✓ Co-simulations can also be performed, e.g. for studying the effect of communication delays on the distributed control models.

...To be continued in the Lab!

Virtual Power Plant laboratory platform using Multi Agent Systems

VPP setup



Thank you!

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