Distributed optimization for demand-side management in *smart grids*

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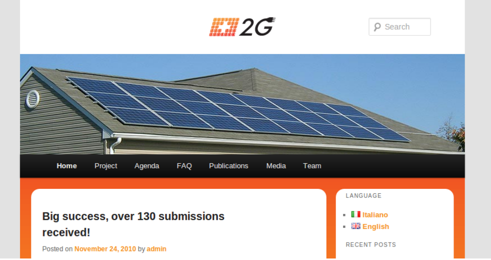
Context: S2G Project

Pilot & Demonstration project financed by the Swiss Federal Office of Energy and the Swiss Electric Research council.

Purpose: evaluate with “on the field” experiments the feasibility and impact of demand-side load management on low voltage networks.



Big success, over 130 submissions received!

Posted on November 24, 2010 by admin

Figure : `http://www.s2g.ch`

Project partners

Project partners and main task:

- ISAAC: Project mgt, PV-System, B2G, data acquisition
- ISEA: Development of a HAC - household measurements, data communication
- ISIN: Interaction panel, data gateway
- **IDSIA: Control algorithms and simulations**
- BFH: Grid simulation - Digsilent
- Bacher: Grid measurements
- DSAS: Business Models (tariffs)
- AIM: Local distributor of Mendrisio

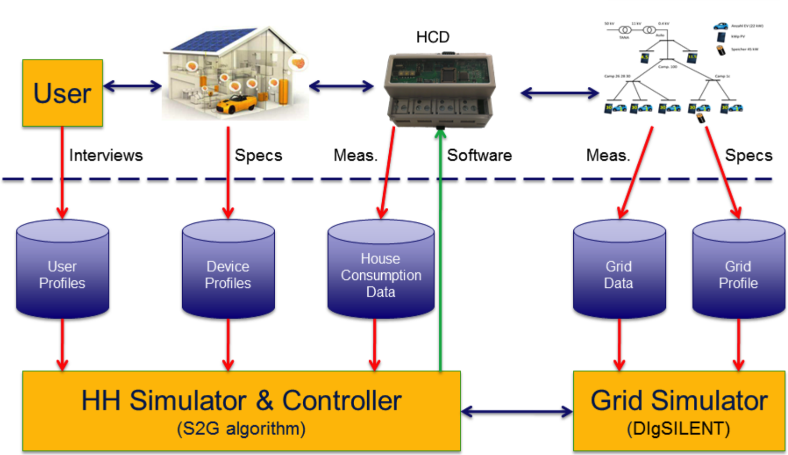
Motivation

Alternative control concepts for smart-grids: Centralized control by massive ICT vs. **Decentralized** algorithms exploiting **local** information.

Expected outcomes:

- Impact of load shifting on grid stability
- Potential of load shifting/household storage for own consumption
- Economic advantage of load shifting
- Determine max. PV or load on present grid infrastructure
- Compare performances of different levels of communication

Structure of the project


User

HCD

Interviews

Specs

Meas.

Software

Meas.

Specs

User Profiles

Device Profiles

House Consumption Data

Grid Data

Grid Profile

HH Simulator & Controller
(S2G algorithm)

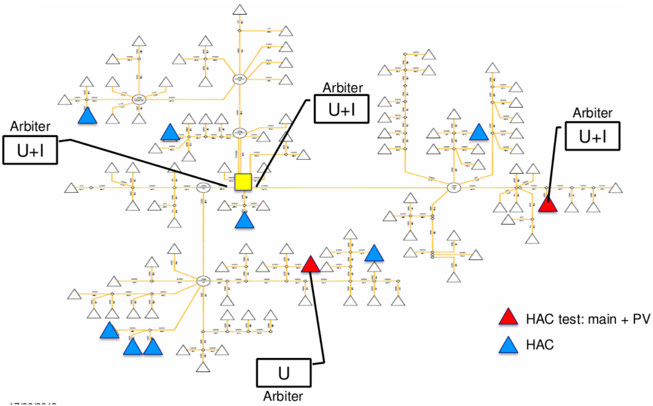
Grid Simulator
(DIgSILENT)

Participants

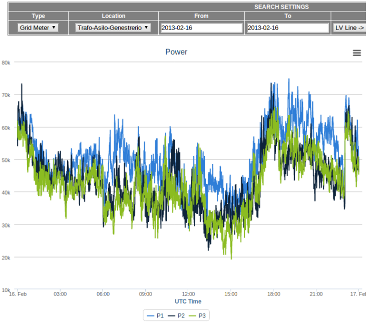
The town of **Mendrisio** hosts the P&D project.

Monitored neigborhood

About 10% of a local branch is monitored.

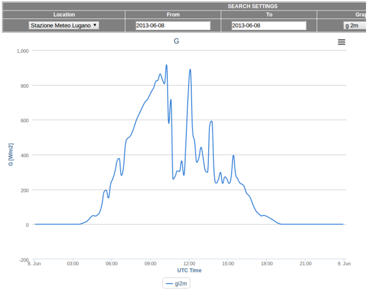


Reliable and comprehensive data acquisition



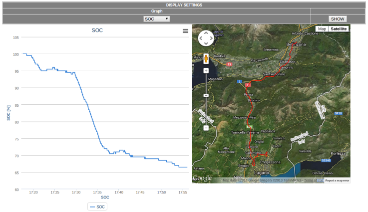
SEARCH SETTINGS

Type	Location	From	To	
Grid Meter ▾	Trafo-Asilo-Genestrerio ▾	2013-02-16	2013-02-16	LV Line ->



SEARCH SETTINGS

Location	From	To	Gra
Stazione Meteo Lugano ▾	2013-06-08	2013-06-08	g 2m

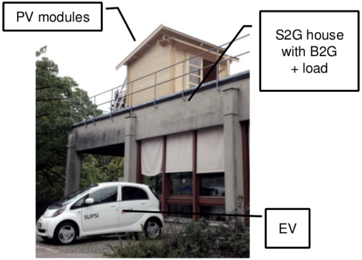


DISPLAY SETTINGS

Graph	
SOC ▾	SHOW

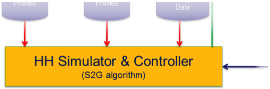
Data is collected for accurate calibration of users' and grid's simulation models.

A test site



- 1.5kWp
- EV HCD
- B2G System
- 2kW controllable load

Control algorithm



The scheduler performs load shifting optimizing:

- Cost of energy for the end user
- Network stability (flatness of the overall load)

Subject to:

- Preserved users' comfort
- Network balance constraints

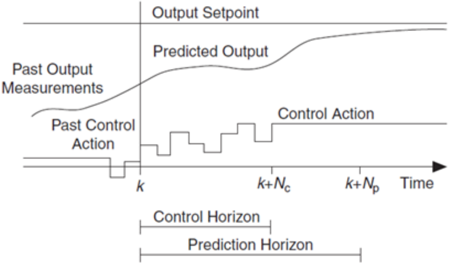
Controllable and non-controllable entities:

- Non-preemptible load jobs (e.g., dishwashers)
- Energy buffers (e.g., AC or water heaters)
- B2G and EV tasks
- PV production (forecast)
- Base load (simulated)

Rolling Horizon Control

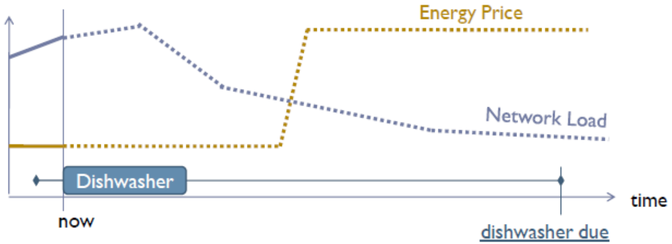
The scheduler implements a rolling horizon control scheme:

- Randomized control horizon of avg. 30 minutes
- Prediction horizon is set to 24 hours

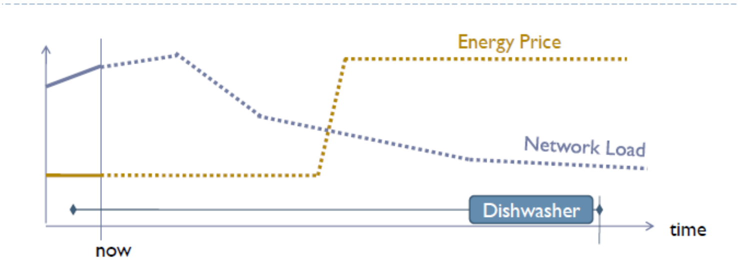


- Optimal control is computed via MILP
- Time is discretized (15 minutes in the experiments)

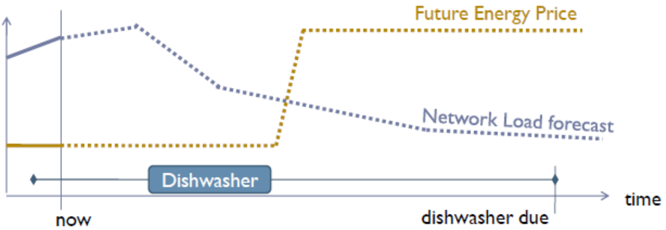
Contrasting objectives



Contrasting objectives



Contrasting objectives



Multi-objective optimization addressed with a Lexicographic approach.

Lexicographic multi-objective optimization

Two contrasting objectives:

$$\min[z_c(\mathbf{e}, t), z_s(\mathbf{e}, t)] \tag{1}$$

Primary objective is energy cost:

$$z_c^* = \min z_c(\mathbf{e}, t) \tag{2}$$

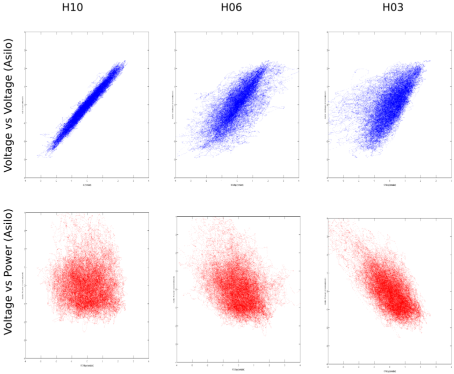
Secondary objective is network load:

$$z_s^* = \min z_s(\mathbf{e}, t) \tag{3}$$

$$s.t. \quad z_c(\mathbf{e}, t) \leq (1 + \eta) z_c^* \tag{4}$$

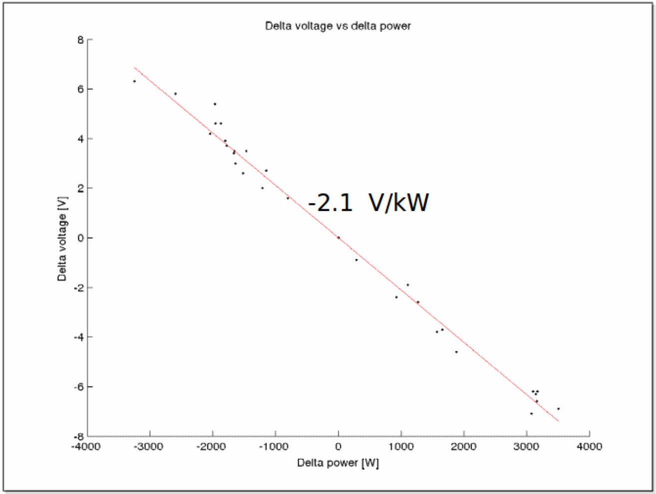
We define z'_{si}, the forecast voltage profile at each node i, as a proxy for z_s.

Field tests - Voltage/Power correlation



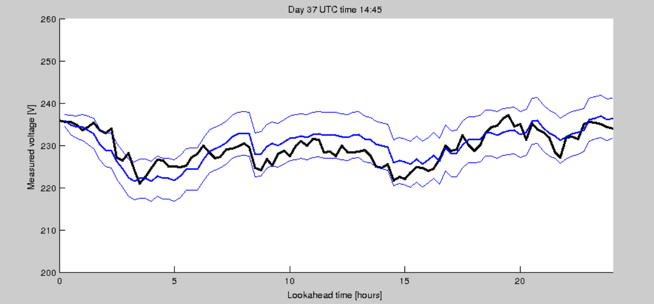
Extensive simulations with logged data in 2013.
Predictability of voltage profiles, regularity of voltage profiles in different days, drifting of voltage patterns along different seasons, correlations among voltages and powers

Effect of local load on voltage



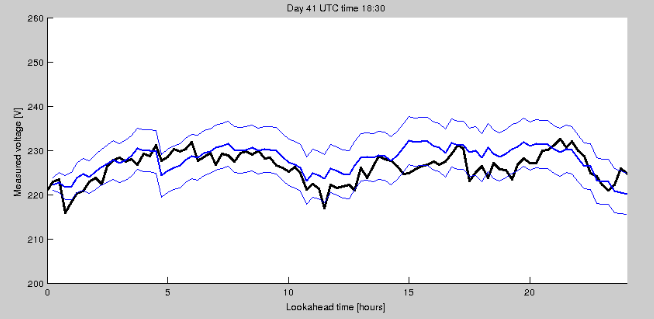
Each kW causes a voltage drop of about 2.1V

Voltage forecast



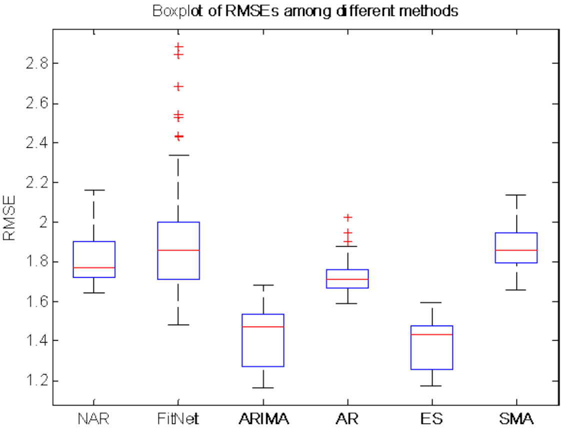
Exponential smoothing after 5 days of training.

Voltage forecast



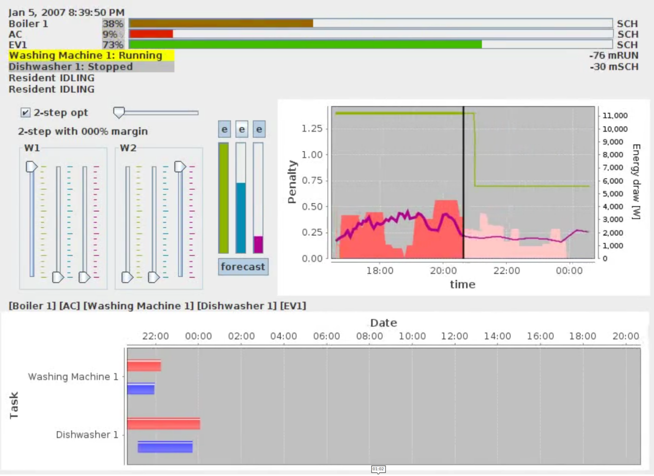
Exponential smoothing after 5 days of training.

Other forecast techniques



Exponential smoothing, despite simple, is the most effective.

A full featured HH simulation tool



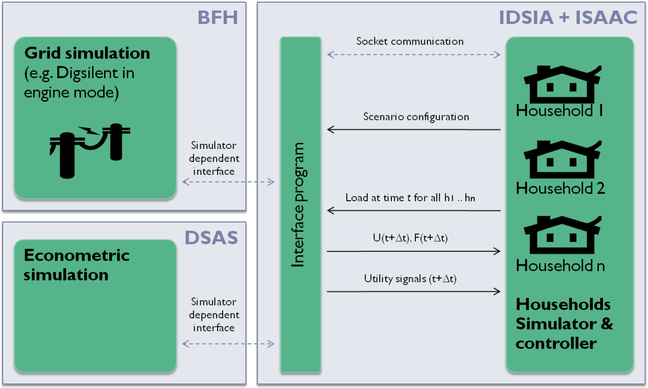
Jan 5, 2007 8:39:50 PM
Boiler 1 38% SCH
AC 9% SCH
EV1 73% SCH
Washing Machine 1: Running -76 mRUN
Dishwasher 1: Stopped -30 mSCH
Resident IDLING
Resident IDLING

☑ 2-step opt

2-step with 000% margin

[Boiler 1] [AC] [Washing Machine 1] [Dishwasher 1] [EV1]

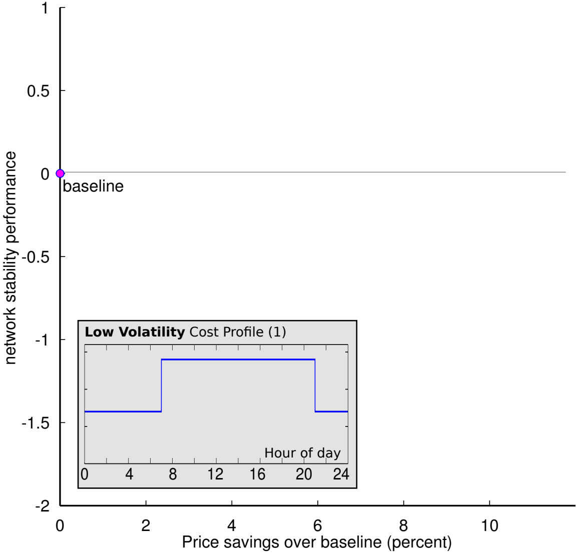
Architecture of simulations



Simulation step of 10 seconds, control step of 15 minutes.

Simulation tests - LV network

120 Households connected to a single MV-LV transformer.



Simulation tests - LV network

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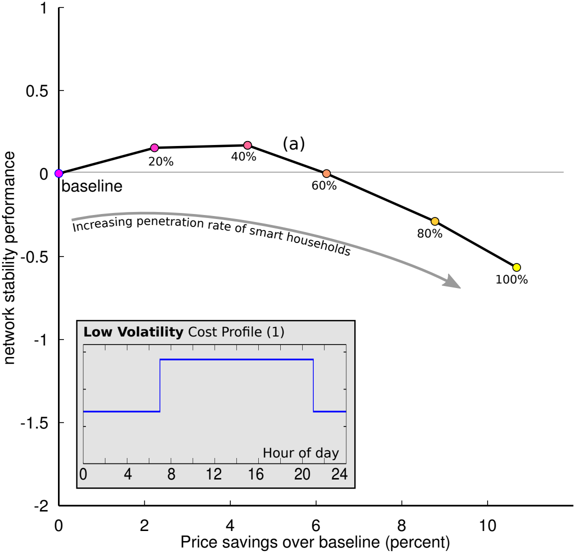

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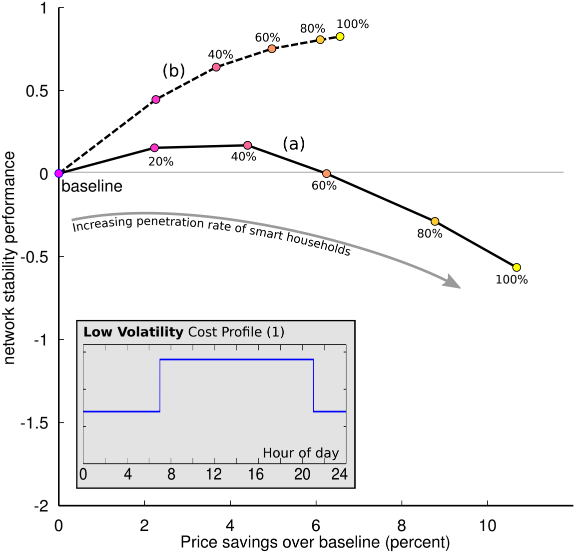

Simulation tests - LV network

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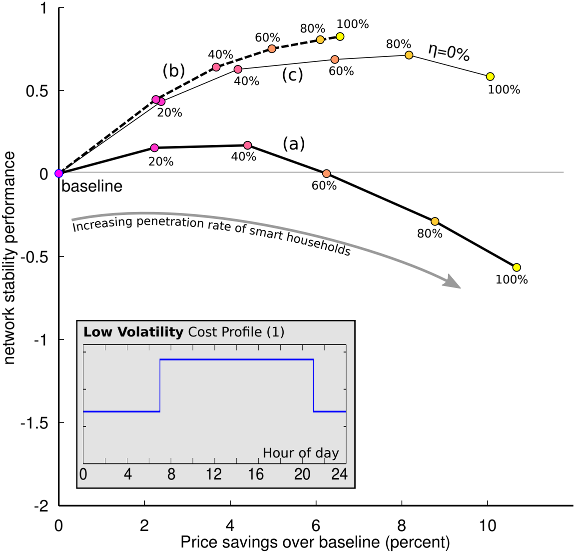
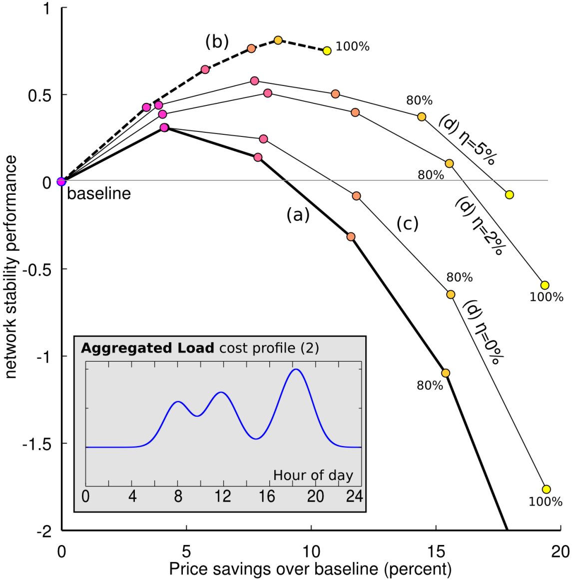
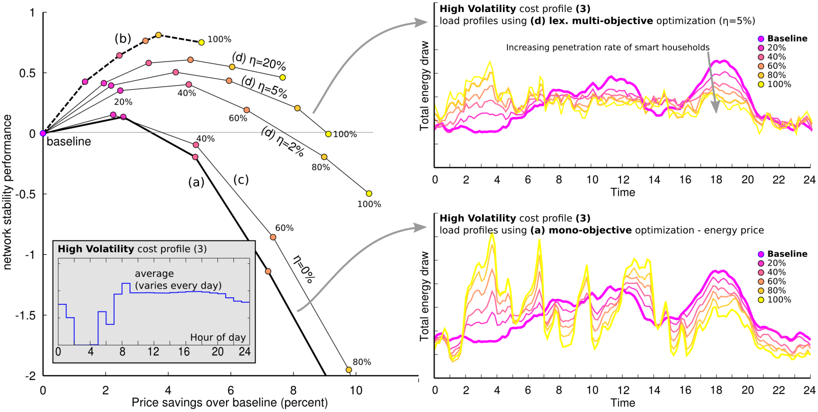


Results



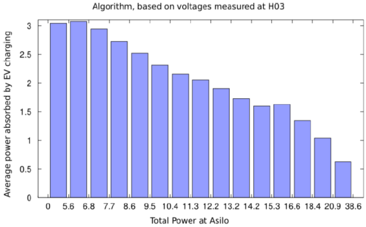
1
0.5
0
-0.5
-1
-1.5
-2
network stability performance
0
5
10
15
20
Price savings over baseline (percent)
(b)
100%
80%
(d) η=5%
80%
(d) η=2%
100%
baseline
(a)
(c)
80%
(d) η=0%
80%
100%
Aggregated Load cost profile (2)
Hour of day
0
4
8
12
16
20
24

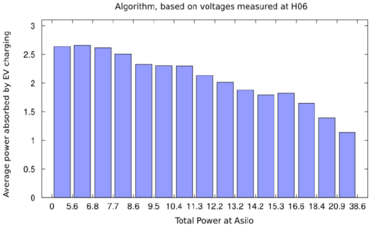
Results

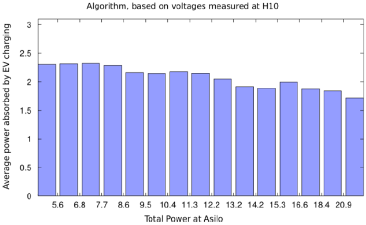


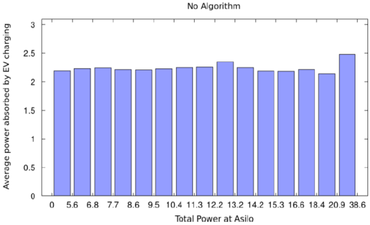
network stability performance
Price savings over baseline (percent)
1
0.5
0
-0.5
-1
-1.5
-2
0
2
4
6
8
10
(b)
100%
(d) η=20%
(d) η=5%
(d) η=2%
20%
40%
60%
80%
100%
baseline
(a)
(c)
η=0%
High Volatility cost profile (3)
average
(varies every day)
Hour of day
0 4 8 12 16 20 24
High Volatility cost profile **(3)**
load profiles using **(d) lex. multi-objective** optimization (η=5%)
Increasing penetration rate of smart households
Total energy draw
Time
0 2 4 6 8 10 12 14 16 18 20 22 24
Baseline
20%
40%
60%
80%
100%
High Volatility cost profile **(3)**
load profiles using **(a) mono-objective** optimization - energy price
Total energy draw
Time
0 2 4 6 8 10 12 14 16 18 20 22 24
Baseline
20%
40%
60%
80%
100%

Results

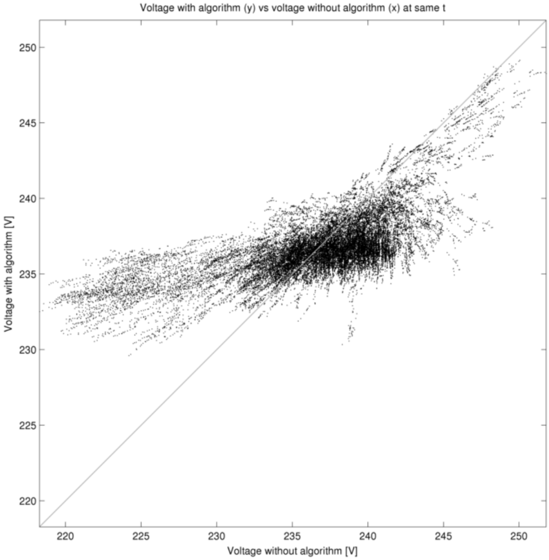

Algorithm, based on voltages measured at H03
Average power absorbed by EV charging
0
0.5
1
1.5
2
2.5
3
0 5.6 6.8 7.7 8.6 9.5 10.4 11.3 12.2 13.2 14.2 15.3 16.6 18.4 20.9 38.6
Total Power at Asilo


Algorithm, based on voltages measured at H06
Average power absorbed by EV charging
0
0.5
1
1.5
2
2.5
3
0 5.6 6.8 7.7 8.6 9.5 10.4 11.3 12.2 13.2 14.2 15.3 16.6 18.4 20.9 38.6
Total Power at Asilo

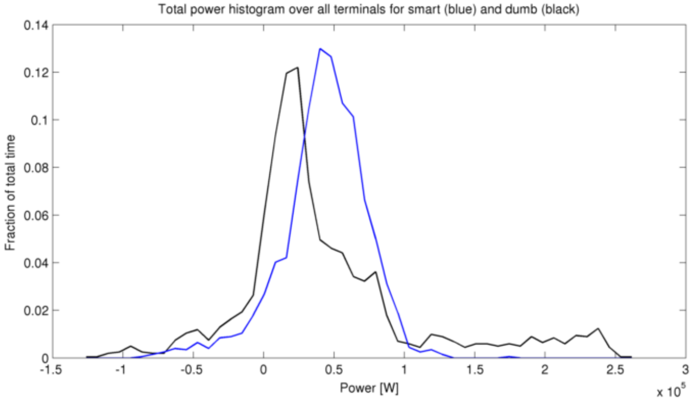

Algorithm, based on voltages measured at H10
Average power absorbed by EV charging
0
0.5
1
1.5
2
2.5
3
5.6 6.8 7.7 8.6 9.5 10.4 11.3 12.2 13.2 14.2 15.3 16.6 18.4 20.9
Total Power at Asilo


No Algorithm
Average power absorbed by EV charging
0
0.5
1
1.5
2
2.5
3
0 5.6 6.8 7.7 8.6 9.5 10.4 11.3 12.2 13.2 14.2 15.3 16.6 18.4 20.9 38.6
Total Power at Asilo

Voltage comparison

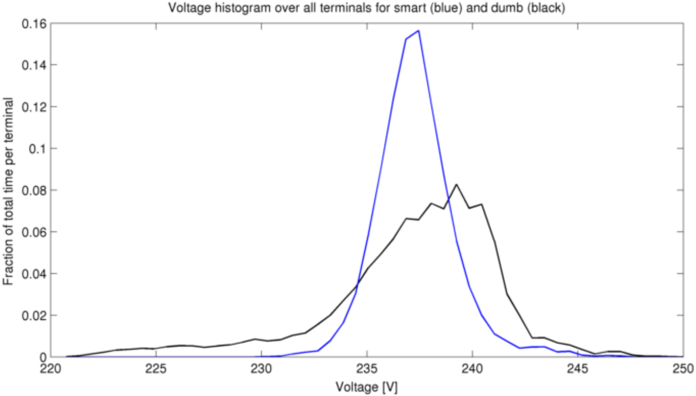


Power histogram - summer



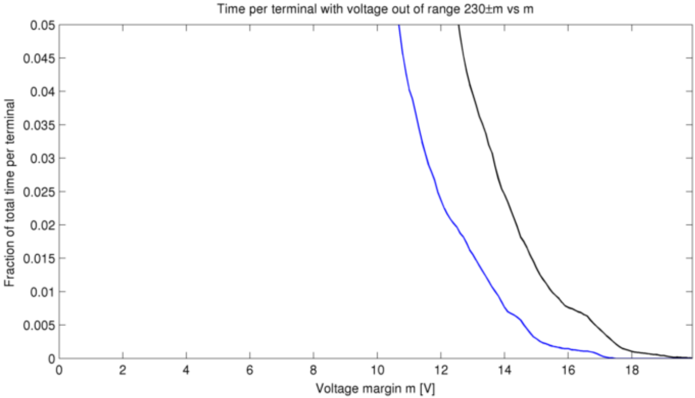
No more very high peaks.

Voltage histogram - summer



More stable voltage.

Voltage violations - summer

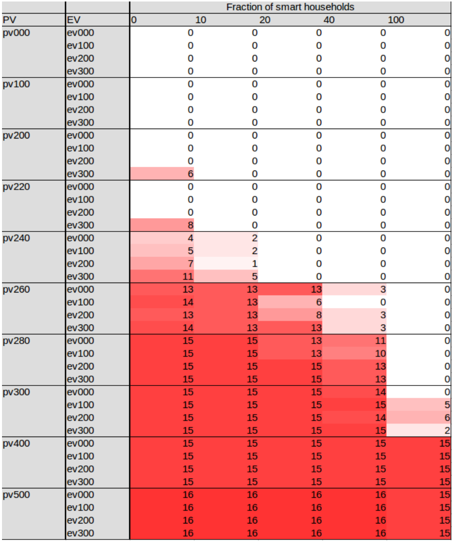


More stable voltage.

IEC 50160 power quality

Averaged over 10 minutes, voltage at a terminal is outside the interval 230 ± 23 V for more than 5% of the time during a week result in a **violation**.

In the simulations, no violations happen up to pv200, ev200



		Fraction of smart households				
PV	EV	0	10	20	40	100
pv000	ev000	0	0	0	0	0
	ev100	0	0	0	0	0
	ev200	0	0	0	0	0
	ev300	0	0	0	0	0
pv100	ev000	0	0	0	0	0
	ev100	0	0	0	0	0
	ev200	0	0	0	0	0
	ev300	0	0	0	0	0
pv200	ev000	0	0	0	0	0
	ev100	0	0	0	0	0
	ev200	0	0	0	0	0
	ev300	6	0	0	0	0
pv220	ev000	0	0	0	0	0
	ev100	0	0	0	0	0
	ev200	0	0	0	0	0
	ev300	8	0	0	0	0
pv240	ev000	4	2	0	0	0
	ev100	5	2	0	0	0
	ev200	7	1	0	0	0
	ev300	11	5	0	0	0
pv260	ev000	13	13	13	3	0
	ev100	14	13	6	0	0
	ev200	13	13	8	3	0
	ev300	14	13	13	3	0
pv280	ev000	15	15	13	11	0
	ev100	15	15	13	10	0
	ev200	15	15	15	13	0
	ev300	15	15	15	13	0
pv300	ev000	15	15	15	14	0
	ev100	15	15	15	15	5
	ev200	15	15	15	14	6
	ev300	15	15	15	15	2
pv400	ev000	15	15	15	15	15
	ev100	15	15	15	15	15
	ev200	15	15	15	15	15
	ev300	15	15	15	15	15
pv500	ev000	16	16	16	16	15
	ev100	16	16	16	16	15
	ev200	16	16	16	16	15
	ev300	16	16	16	16	15

Is centralized control needed?

Current trend to enable Smart Grid is pervasive ICT.

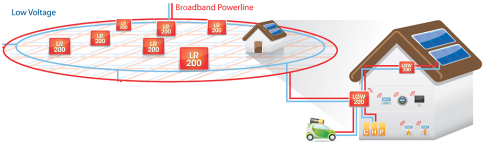
Quoting from Galli et. al (2011):
"The brute force solution of polling all the sensors can become the true bottleneck for the sheer problem of collecting all the data in a timely way" and also, "Delivering messages to Smart Grid terminals through many relays will produce a broadcast storm if protocols to support this function are not designed judiciously".

To what extent communication (i.e., synchronization among terminals) helps?

Inter-agent communication

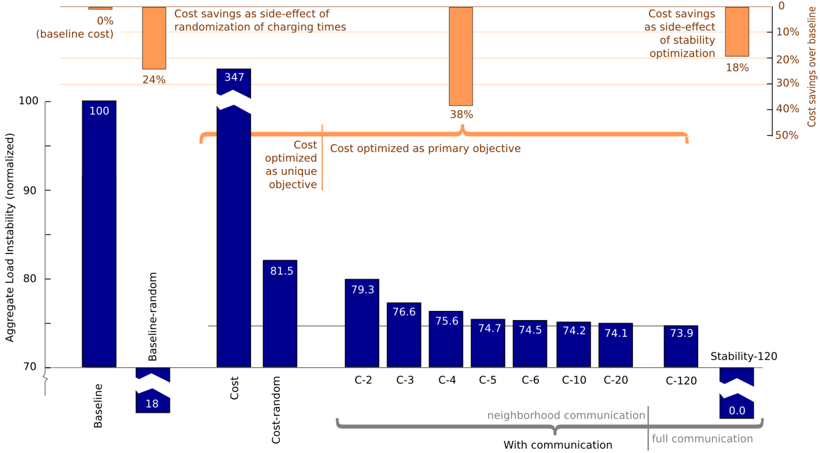
We intend to assess the added value of sharing information among households as an alternative to voltage prediction.

We define as *Neighbourhood* a set of households that can communicate among them (via wireless or PLC).



Every time a control algorithm completes the optimization, it broadcasts the expected load to its neighbours. In average 50 times a day (about 10kB/day) way below current standards, e.g. narrow-band PLC 21.4 kbps (`www.prime-alliance.org`).

Benefits of communication



Conclusions and future work

Some insights:

- Massive and reliable data collection is essential
- Local information can be exploited to guide the controllers to achieve a common goal
- Decentralized approach is reliable and has a strong potential
- Cost and Network stability should be concerned as separate objectives (market does not self-regulate)
- Communication can improve results up to a limited extent

Future work:

- Integration of local forecasts and partial communication
- Extend models and algorithms to manage stochastic information

References

Thank you

M. Salani, A. Giusti, G. Di Caro, A. Rizzoli, L. Gambardella *Lexicographic Multi-objective Optimization for the Unit Commitment Problem and Economic Dispatch in a Microgrid*. Proc. of IEEE-PES International Conference on Smart GridTechnology (ISGT), 2011.

Kriett, P.O., Salani, M. *Optimal control of a residential microgrid*. (2012). Energy 42(1):321-330.

Giusti, A, Salani, M., Di Caro, G.A, Rizzoli, AE., Gambardella, L.M., *Restricted Neighborhood Communication Improves Decentralized Demand-Side Load Management*, Smart Grid, IEEE Transactions on , vol.5, no.1, pp.92,101, Jan. 2014

Deterministic model for EV Charging

symbol	par/var	description
V	par	Set of electric vehicle jobs indexed by v
Ei_v	par	SOC at time r_v for EV v
Et_v	par	Target SOC at due date of EV v
r_v	par	Release date (relative time step) of EV v
d_v	par	Due date (relative time step) of EV v
F_v^t	par	Self discharge rate of EV v
$\eta_v^c \leq 1$	par	Efficiency rate for charging EV v
$\eta_v^d \geq 1$	par	Inverse of efficiency rate for discharging EV v
E_v^{LB}	par	Energy lower band limit for EV v
E_v^{UB}	par	Energy upper band limit for EV v
E_v^d	par	Derating limit for EV v
MP_v^c	par	Max power that can be drawn for charging EV v
mP_v^c	par	Min power at full derating for charging EV v
MP_v^d	par	Max power that can be released discharging EV v
Pc_v^t	var	Power drawn for charging EV v at time step t
Pd_v^t	var	Power released discharging EV v at time step t
P_v^t	var	Overall power exchange for EV v at time step t
Ev_v^t	var	Energy stored in EV v at time step t

Table : EV jobs

Deterministic model for EV Charging

$$\min \bar{z}_s = \sum_{t \in T} s_t \cdot P^t \cdot \Delta t \tag{5}$$

$$s.t. \qquad z_c = \sum_{t \in T} c_t \cdot P^t \cdot \Delta t \tag{6}$$

$$z_c \leq (1+\eta) \cdot z_c^* \tag{7}$$

$$Ev_v^{rv} = \begin{array}{l} +(Pc_v^{rv} \cdot \eta_v^c \cdot \Delta t) \\ -(Pd_v^{rv} \cdot \eta_v^d \cdot \Delta t) \\ -(F_v \cdot \Delta t) + Ei_v \end{array} \qquad \forall v \in V \tag{8}$$

$$Ev_v^t = \begin{array}{l} +(Pc_v^t \cdot \eta_v^c \cdot \Delta t) \\ -(Pd_v^t \cdot \eta_v^d \cdot \Delta t) \\ -(F_v \cdot \Delta t) + Ev_v^{t-1} \end{array} \qquad \begin{array}{c} \forall v \in V, \\ \forall t \in T \mid r_v < t \leq d_v \end{array} \tag{9}$$

$$E_v^{LB} \leq Ev_v^t \leq E_v^{UB} \qquad \begin{array}{c} \forall v \in V, \\ \forall t \in T \mid r_v \leq t \leq d_v \end{array} \tag{10}$$

$$Ev_v^{d_v} \geq Et_v \qquad \forall v \in V \tag{11}$$

$$z_v^t \geq Ev_v^t - E_v^d \qquad \forall v \in V, \forall t \in T \tag{12}$$

$$Pc_v^t \leq \frac{z_v^t}{E_v^{UB} - E_v^d} \cdot mP_v^c + \left(1 - \frac{z_v^t}{E_v^{UB} - E_v^d}\right) \cdot MP_v^c \qquad \forall v \in V, \forall t \in T \tag{13}$$

$$Pd_v^t \leq MP_v^d \qquad \forall v \in V, \forall t \in T \tag{14}$$

$$P_v^t = Pc_v^t - Pd_v^t \qquad \forall v \in V, \forall t \in T \tag{15}$$

$$P_v^t = 0 \qquad \begin{array}{c} \forall v \in V, \\ \forall t \in T \mid t < r_v, t > d_v \end{array} \tag{16}$$

$$P^t = \sum_{v \in V} P_v^t \qquad \forall t \in T \tag{17}$$