Ph.D. in Information Engineering

HIPPOCRATICA CIVITAS STUDIUM SALERNI

Bidirectional Metering Advancements and Applications to Demand Response Resource Management

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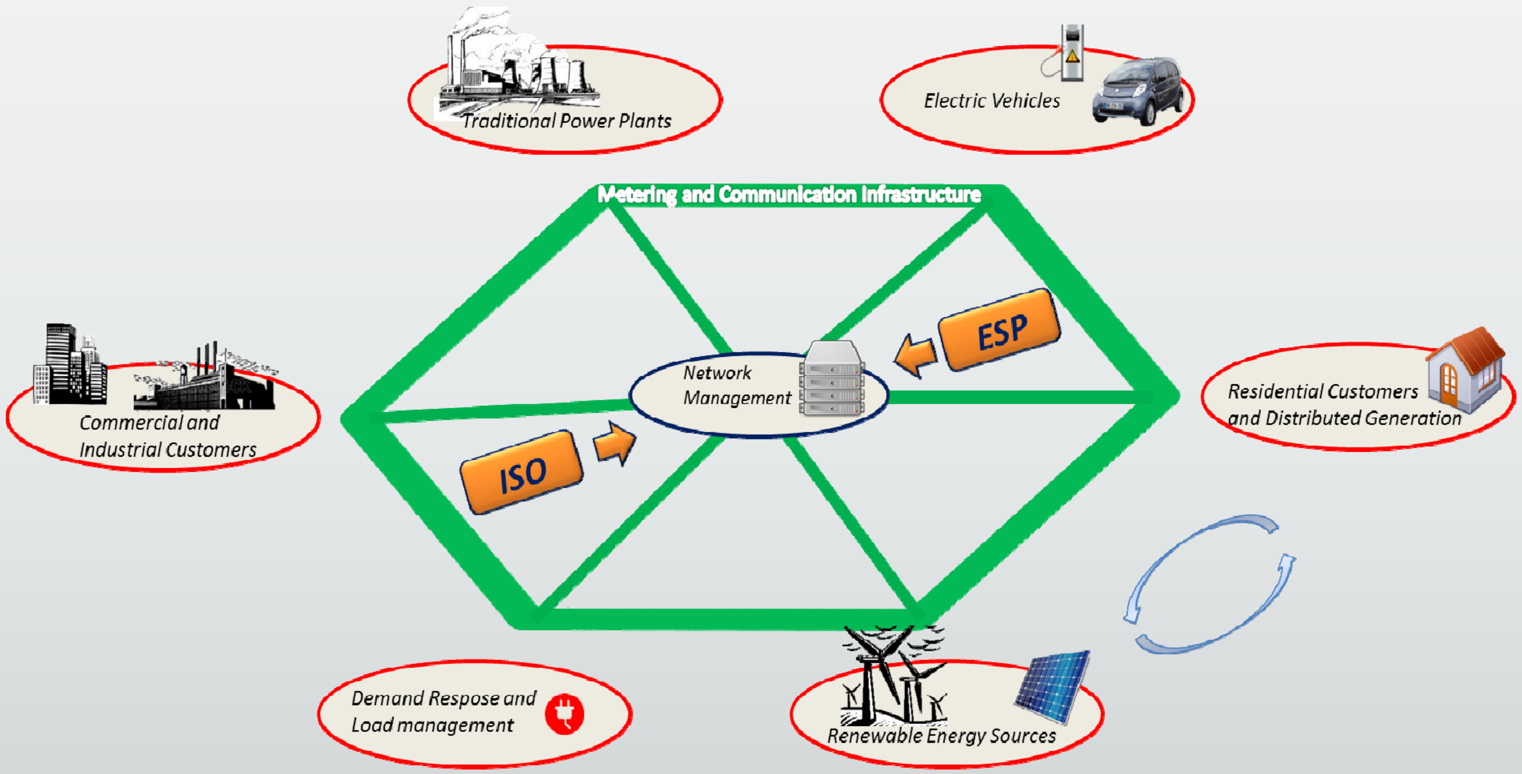
The Smart Grid

"A Smart Grid uses digital technology to improve reliability, security and efficiency (both economic and energetic) of the electric system, from large generation through the delivery systems to electricity customers and a growing number of distributed generation and storage resources."

The Smart Grid (SG):

- Accommodates all power supplies and loads
- Implements pervasive system automation
- Ensures best possible power quality
- Reduces the need for inefficient peak generators
- Favors active user participation



Technical challenges

There is still the lack of, and need to develop:

- *A monitoring, communication and command infrastructure*
- Common standards to ensure interoperability of all grid devices
- Comprehensive grid models and system operator tools
- Cyber-security and customers' data protection
- *Robust operational models that integrate new grid resources*
- *Cost-benefit and life cycle models for new grid devices and applications*
- Policy coordination

Role of Measurements in the SG scenario

"To measure is to know." [Lord Kelvin]

Automatic control of the Grid is completely meaningless without a reliable picture of the state of the grid itself.

A pervasive monitoring infrastructure, made of advanced sensors, acquisition and communication devices, must be put in place.

The metering infrastructure should:

- *Make real-time accurate measurements*
- *Measure Power Quality*
- *Collect the measurements from the sensing nodes and provide them to the system operator*
- *Provide measurements with the highest degree of reliability*
- *Be interoperable*

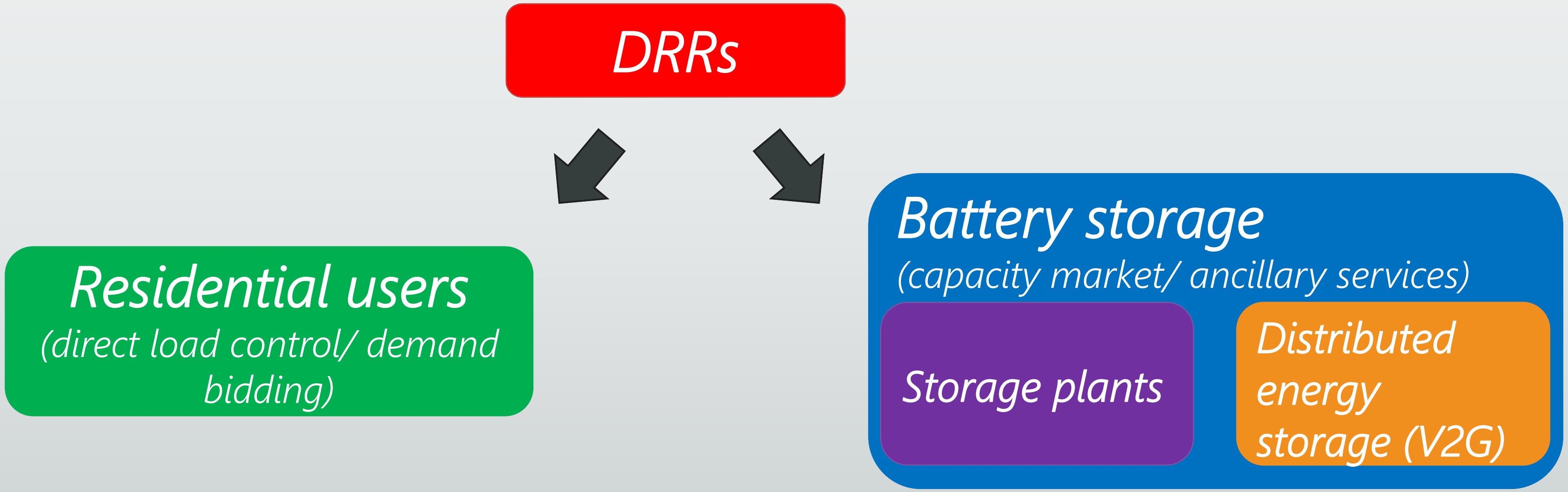
Demand Response Resources (DRRs)

Demand Response include all intentional modifications in electricity consumptions.

There are different ways to realize that:

- *reduction of consumptions*
- *load shifting*
- *reliance on onsite generation*

In this work, 2 different categories of DRRs are considered:



DRRs

Residential users

(direct load control/ demand bidding)

Battery storage

(capacity market/ ancillary services)

Storage plants

Distributed energy storage (V2G)

Aim of the work

- *Realization of a microcontroller-based measurement device to implement the **Smart Meter** integrated into the AMI and the monitoring device onboard the batteries.*
- *Develop the **metering and communication infrastructure** and the management strategy to implement DR programs*
- *Develop **measurement techniques** for monitoring of **battery storage** resources*
- *Develop a **system-level model for battery** service allocation **with consideration of battery health***
- ***Application** of the implemented model and techniques **to V2G management***

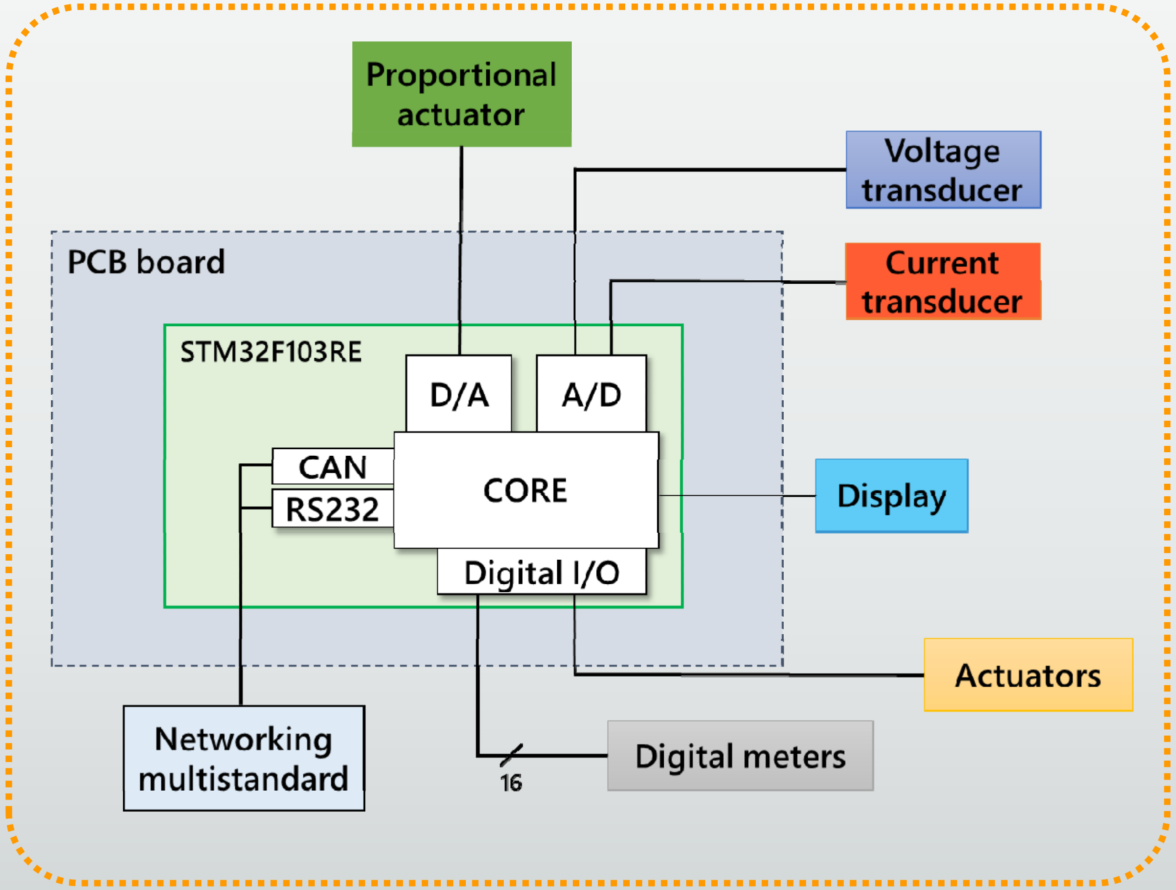
Outline

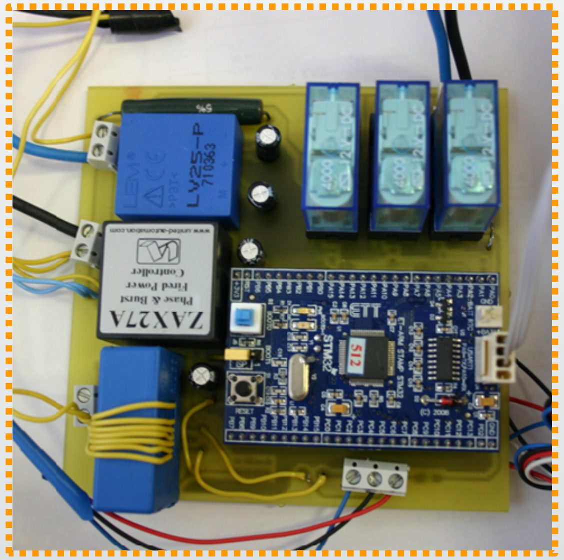
- Bidirectional smart meter for DR applications
    - Implemented Smart Meter
    - Sensing devices
    - Advanced metering infrastructure (AMI)
    - Power measurement issues
    - Metrological characterization
    - Demand Response management
- Battery measurement techniques and degradation model
- Application: V2G management strategy

Implemented Smart Meter

The realized Smart Meter is a microcontroller-based measurement device to be installed into customers' premises.

- Based on a ARM M3 microcontroller
- Voltage and current sampled at 10 kHz
- Interfaced with gas and hot water meters

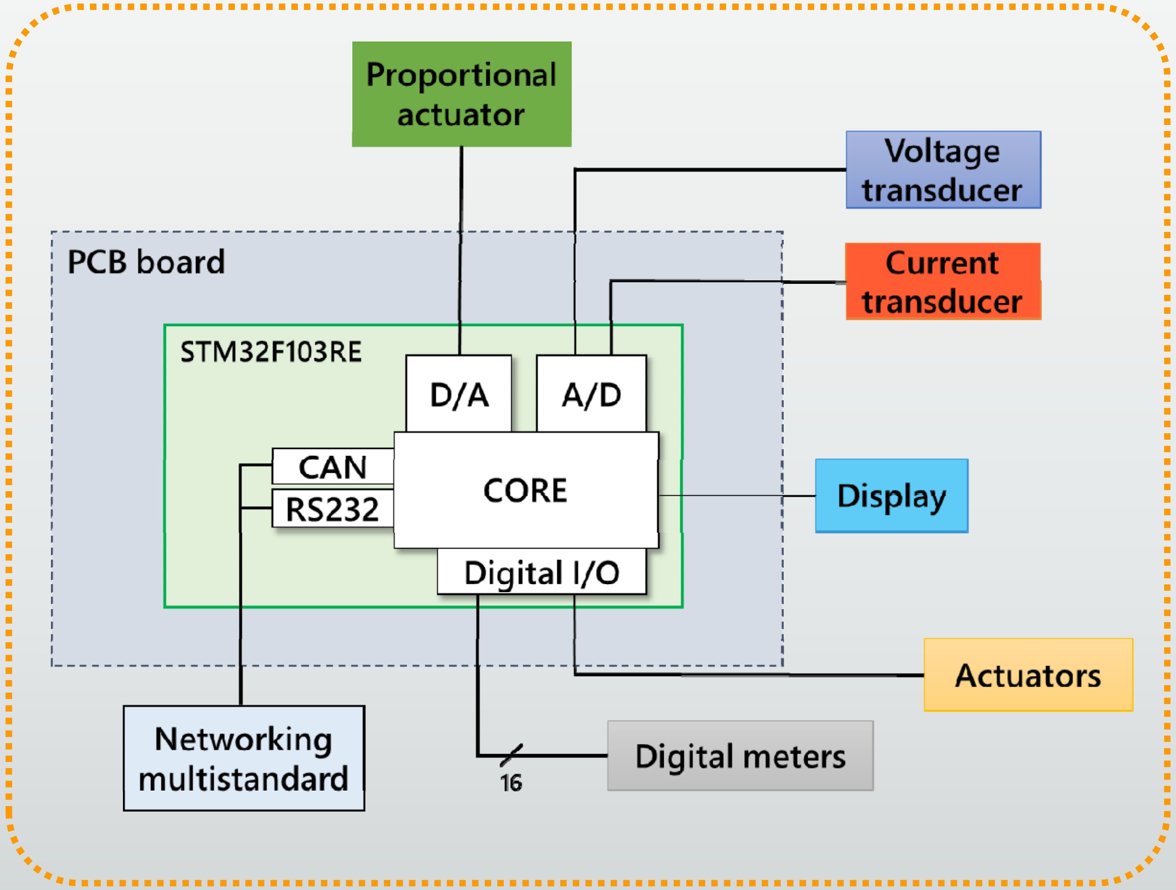


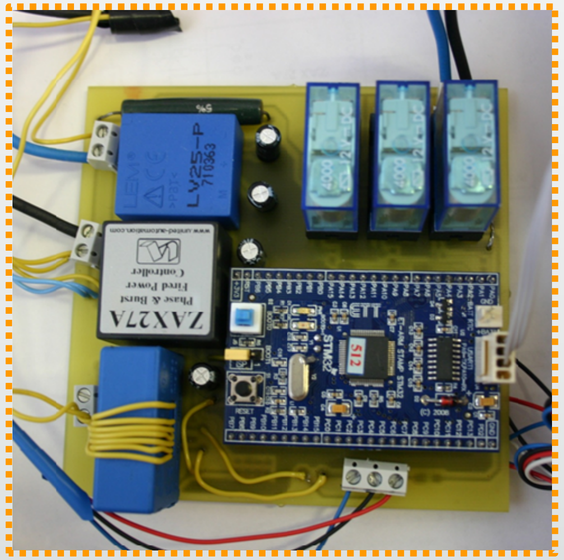


Implemented Smart Meter

The realized Smart Meter is a microcontroller-based measurement device to be installed into customers' premises.

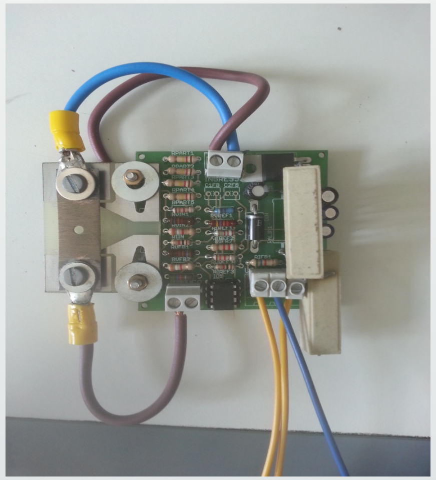
- Wide range of communication interfaces (CAN, RS232,Bluetooth, Wi-Fi)
- Binary and proportional actuators enable participation in DR programs



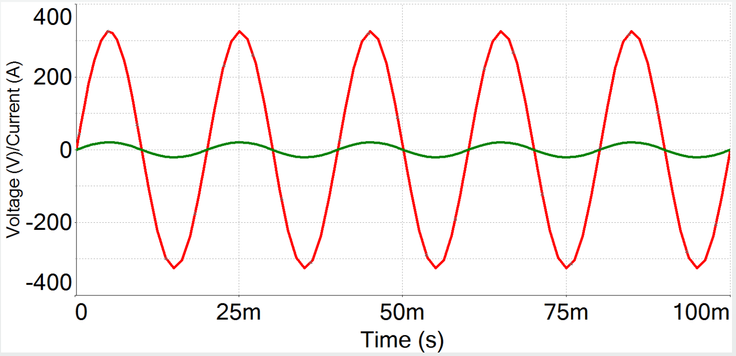


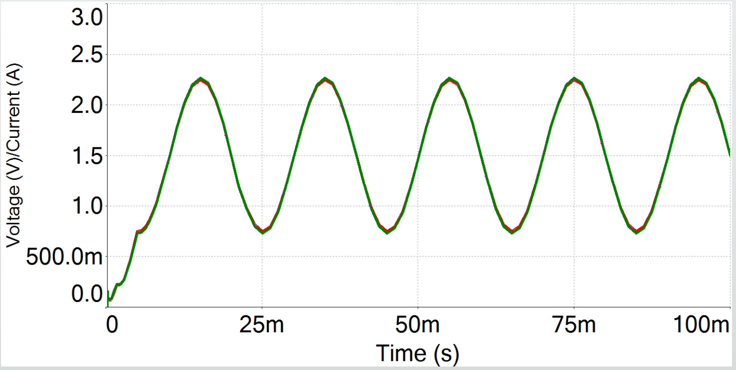
Sensing devices

To be able to measure input signals with a wide input range, a novel voltage and current transducer was developed.



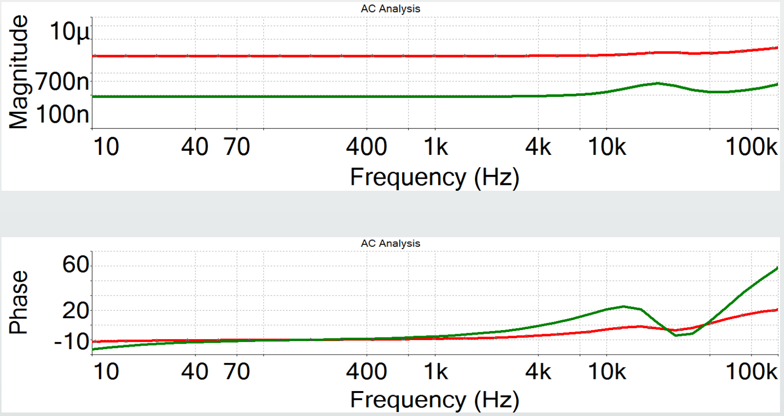
Input





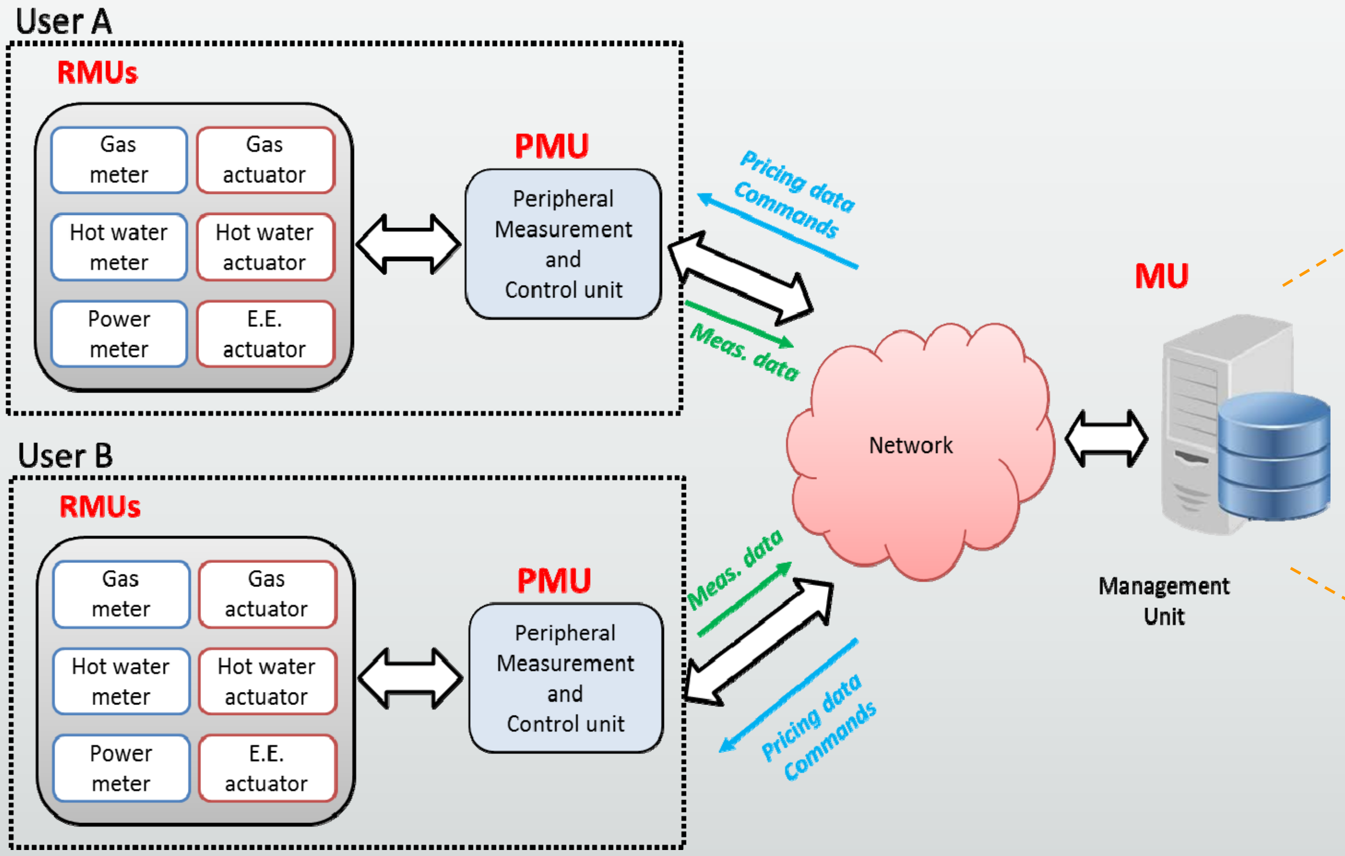
Output

Frequency response



Advanced Metering Infrastructure (AMI)

To unfold its full potential, Smart Metering requires an Advanced Metering Infrastructure (AMI) for full-scale bi-directional data communication to be in place.

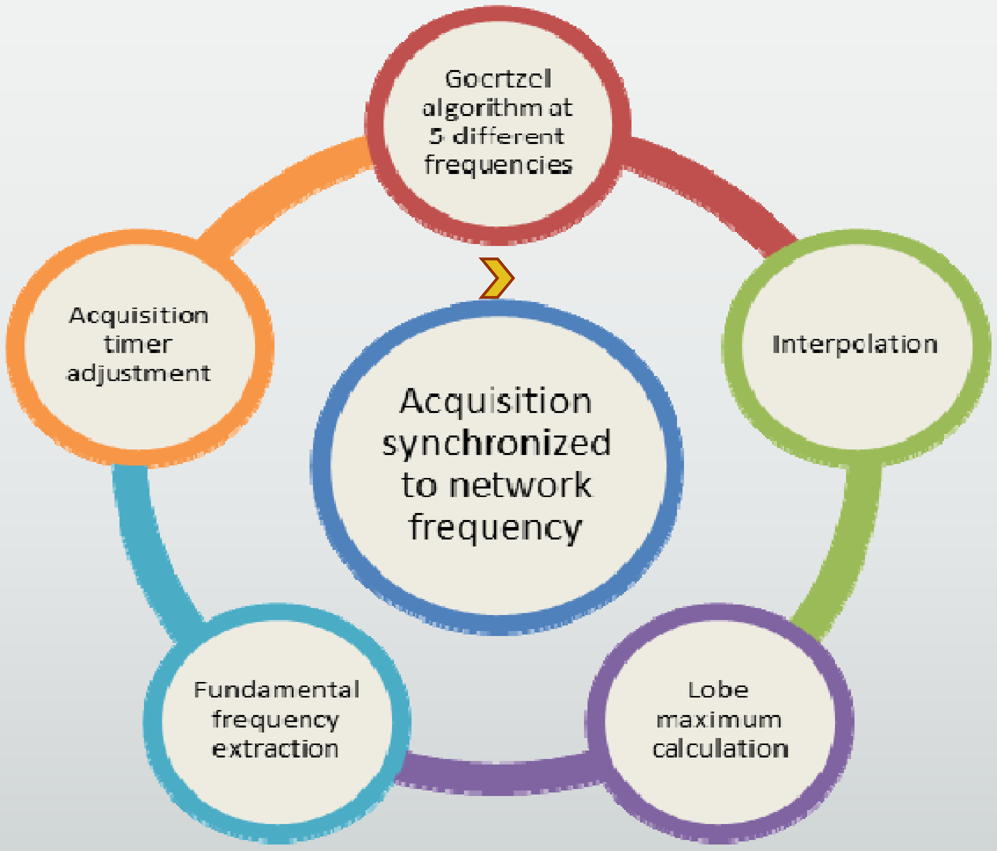


Potenza Attiva Massima [W]	1533
Potenza Reattiva Massima [var]	583
Energia Attiva [Wh]	383
Energia Reattiva [varh]	424

Power Measurement Issues

Ideally, voltage and current waveforms on the grid should be sinusoidal at 50 Hz frequency.

In reality low frequency fluctuations may occur and offset power and energy measurements.


Acquisition synchronized to network frequency

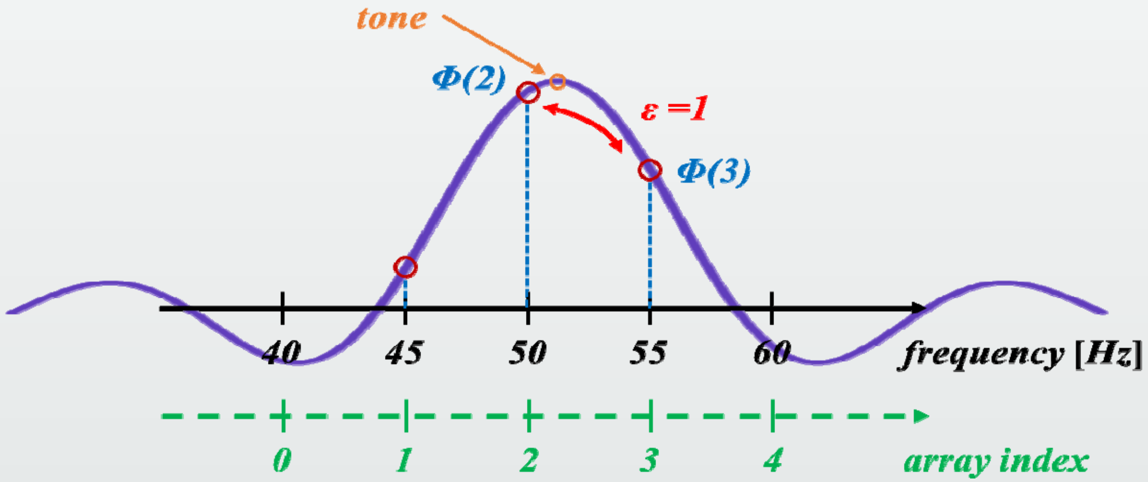
Goertzel algorithm at 5 different frequencies

Interpolation

Lobe maximum calculation

Fundamental frequency extraction

Acquisition timer adjustment



$$\varepsilon = \begin{cases} 1 & if \quad \Phi[\mathrm{maxIndex}+1] \geq \Phi[\mathrm{maxIndex}-1] \\ -1 & if \quad \Phi[\mathrm{maxIndex}+1] \leq \Phi[\mathrm{maxIndex}-1] \end{cases}$$

➡ $\varepsilon = 1$

$$\alpha = \frac{\Phi[\mathrm{maxIndex}+\varepsilon]}{\Phi[\mathrm{maxIndex}]} \qquad \delta = \varepsilon \frac{\alpha}{\alpha+1}$$

$$tone = \min Freq + (\mathrm{maxIndex}+\delta)\Delta f$$

Power Measurement Issues

Ideally, voltage and current waveforms on the grid should be sinusoidal at 50 Hz frequency.

In reality low frequency fluctuations may occur and offset power and energy measurements.

Goertzel algorithm

Goertzel filter output

$$y_m(n) = \sum_{r=0}^{N-1} x(r)\, e^{j2\pi m\,(n-r)/N} = \sum_{r=0}^{N-1} x(r)\, W_N^{-m(n-r)}$$

Recursive computation

$$y_m(n) = W_N^{-m}\; y(n-1) + x(n)$$

for n=N filter output equals

the DFT coefficient

$$X(m) = y_m(N)$$

```
//N-> Number of samples
//k-> Normalized frequency

ReCoeff = 2.0*cos(2.0*pi*k/N);
ImCoeff = sin(2.0*pi*k/N);
a = 0.0;
b = 0.0;

for (n=0; n<N; n++)
 {              PartOut= x(n) + ReCoeff*a - b;
         b = a;
         a = PartOut;
 }
ResRe = 0.5*ReCoeff*a - b;
ResIm = ImCoeff*a;
```

Power Measurement Issues

Ideally, voltage and current waveforms on the grid should be sinusoidal at 50 Hz frequency.

In reality low frequency fluctuations may occur and offset power and energy measurements.

The sign of active and non-active power is retrieved using Goertzel on the determined fundamental.

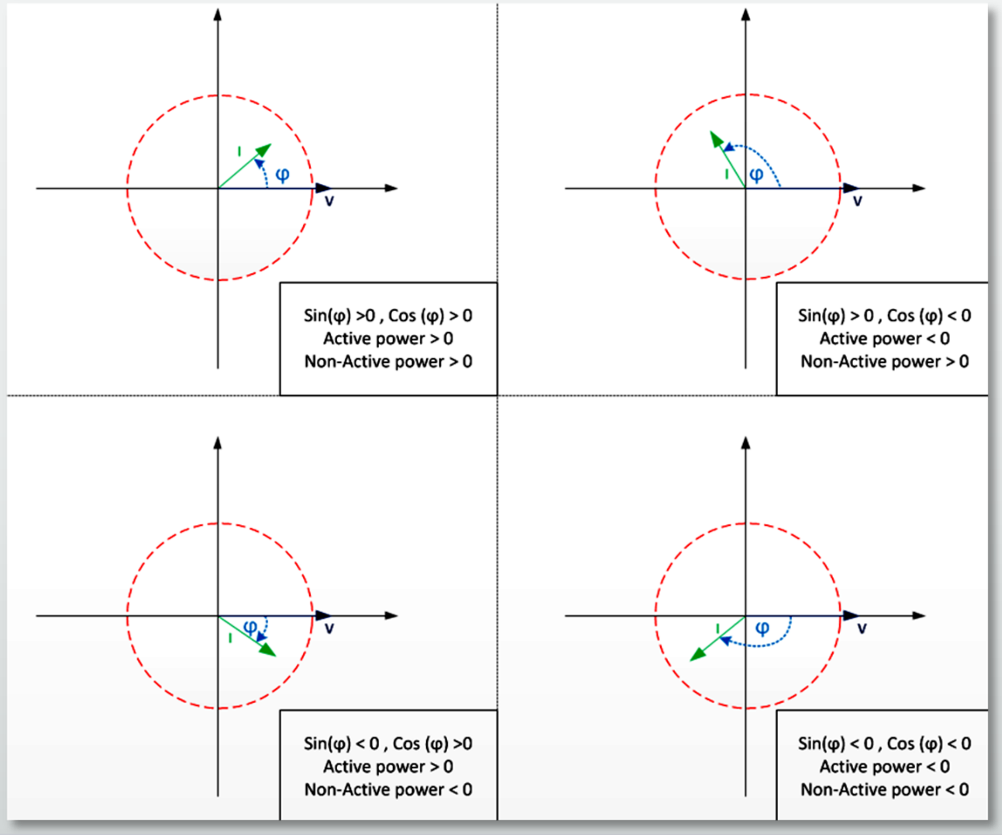
Once in the frequency domain:

$$V(k) = \mathrm{Re}_V + j\,\mathrm{Im}_V = V_0\, e^{j\alpha} = V_0\,[\cos(\alpha) + j\sin(\alpha)]$$

$$I(k) = \mathrm{Re}_I + j\,\mathrm{Im}_I = I_0\, e^{j\beta} = I_0\,[\cos(\beta) + j\sin(\beta)]$$

$$\mathrm{Re}_V\,\mathrm{Re}_I + \mathrm{Im}_V\,\mathrm{Im}_I = V_0 I_0 \cos(\alpha - \beta) = V_0 I_0 \cos(\varphi)$$

$$\mathrm{Re}_V\,\mathrm{Im}_I - \mathrm{Im}_V\,\mathrm{Re}_I = V_0 I_0 \sin(\alpha - \beta) = V_0 I_0 \sin(\varphi)$$



Power Measurement Issues

Ideally, voltage and current waveforms on the grid should be sinusoidal at 50 Hz frequency.

Due to the diffusion of nonlinear loads and power electronics waveforms in the grid show:

- *Harmonic and inter-harmonic distortion*
- *Dips and swells*

Relevant Power Quality indices must be monitored

Relevant PQ indices

- $V_{RMS}^2 = \frac{1}{N}\sum_{k=0}^{N-1} v_k^2$
- $ITHD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1}\cdot 100 \quad (\%)$
- $I_{RMS}^2 = \frac{1}{N}\sum_{k=0}^{N-1} i_k^2$
- $VTHD = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1}\cdot 100 \quad (\%)$

Need for new power metrics different from the ones used in sinusoidal conditions.

Fryze power metric

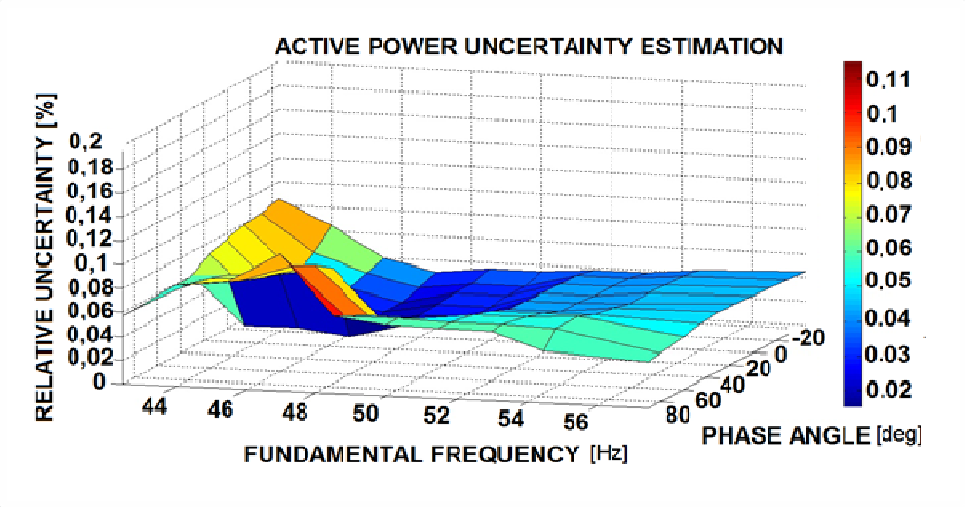
$$P = \frac{1}{kT}\int_{\tau}^{\tau+kT} vi\, dt$$

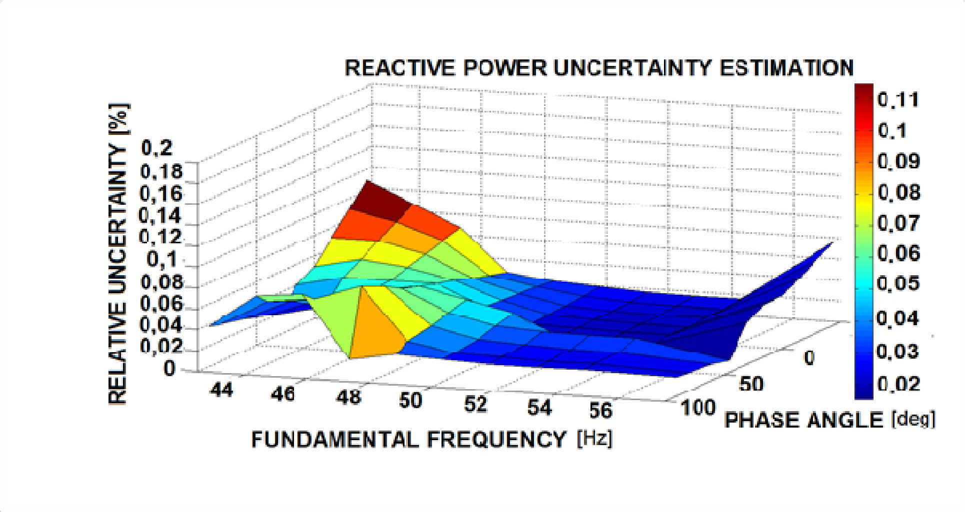
$$S = V\,I$$

$$N = \sqrt{S^2 - P^2}$$

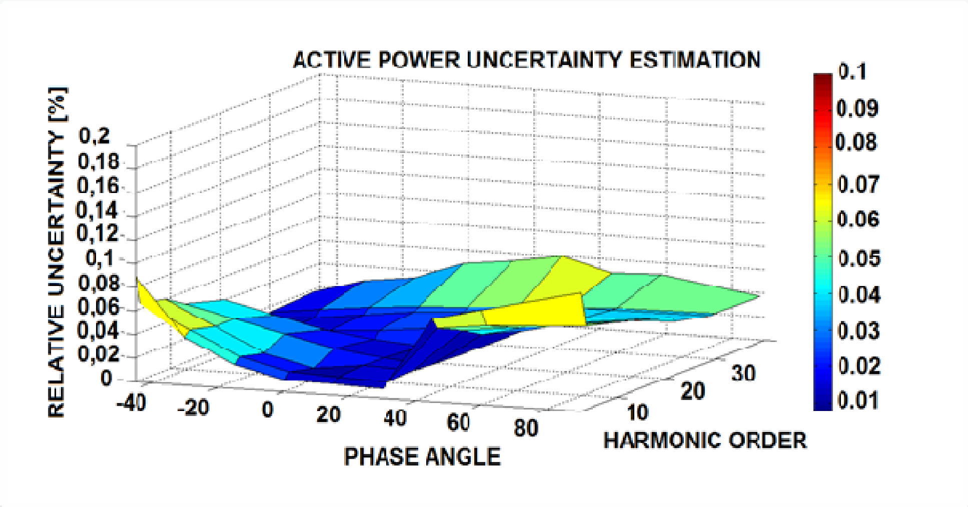
Dynamic characterization

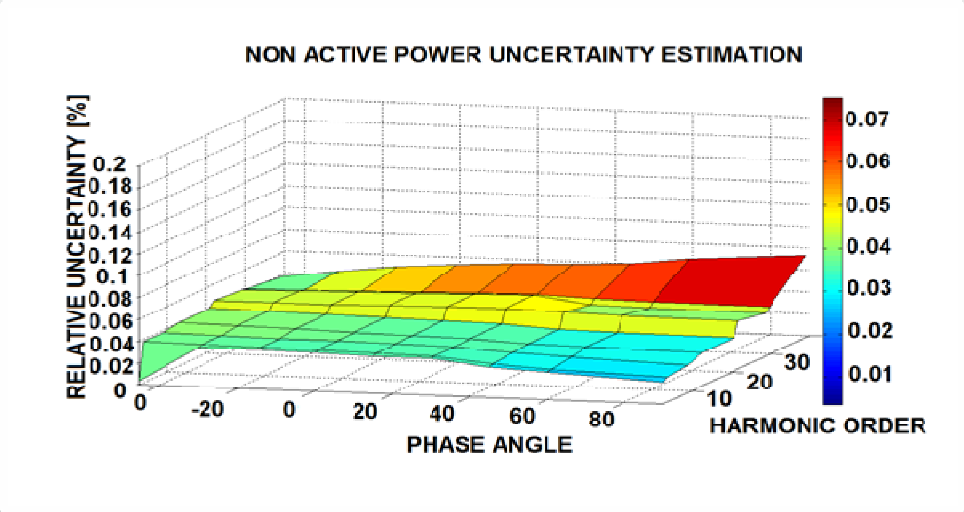
Sinusoidal characterization



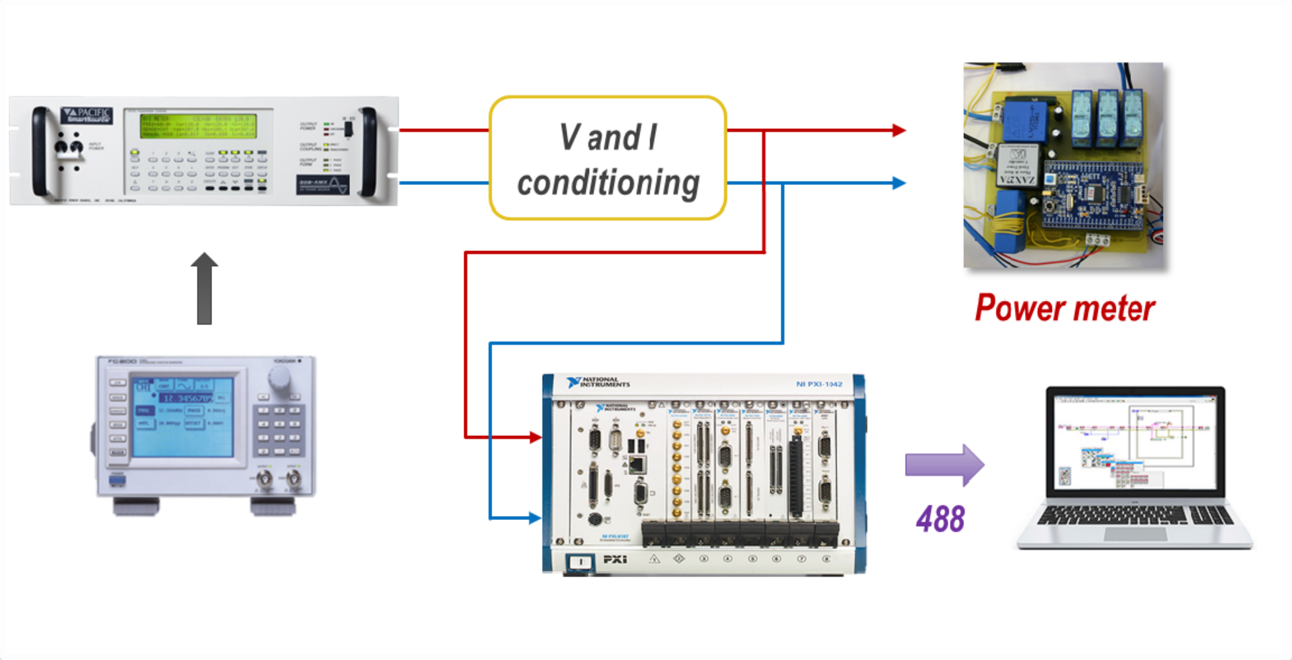


Non-sinusoidal characterization





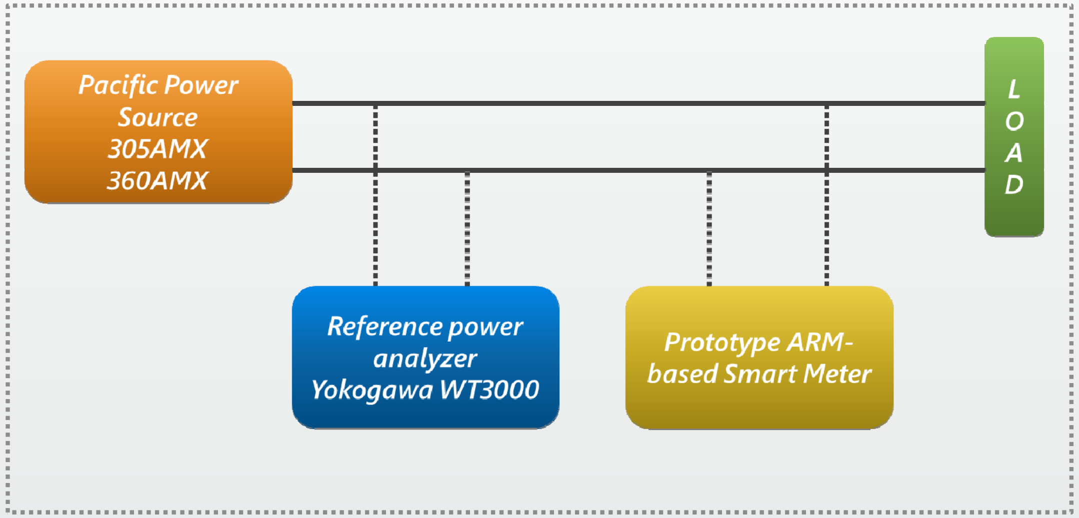
Dynamic characterization



Quantity	Uncertainty (sin. test)	Uncertainty (non-sin. test)	Units
Voltage (r.m.s.)	0.03	0.04	[%]
Current (r.m.s.)	0.03	0.04	[%]
Frequency	0.67	0.67	[mHz]
Active Power	0.043	0.061	[%]
Apparent Power	0.13	0.15	[%]
PF (conventional)	0.002	0.002	[p.u.]
Non Active Power	0.6	0.62	[%]
Voltage THD	----	0.072	[%]
Current THD	----	0.07	[%]

Metrological characterization: OIML

For the characterization test signals defined in the standard OIML-R46 are used.

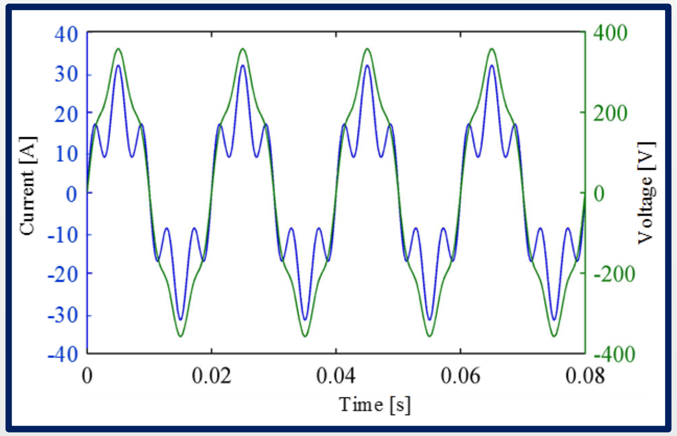


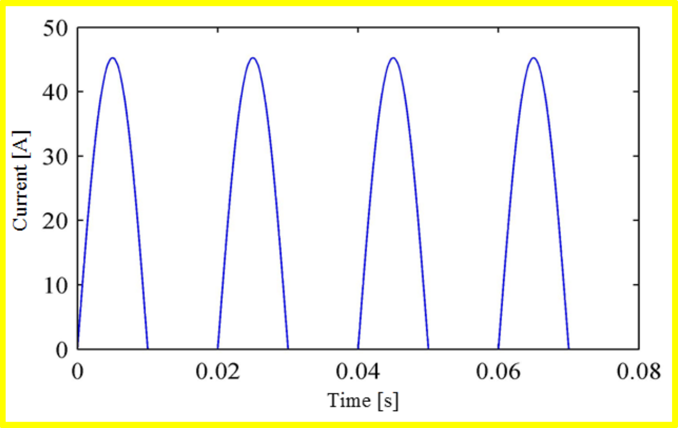
Pacific Power Source 305AMX 360AMX

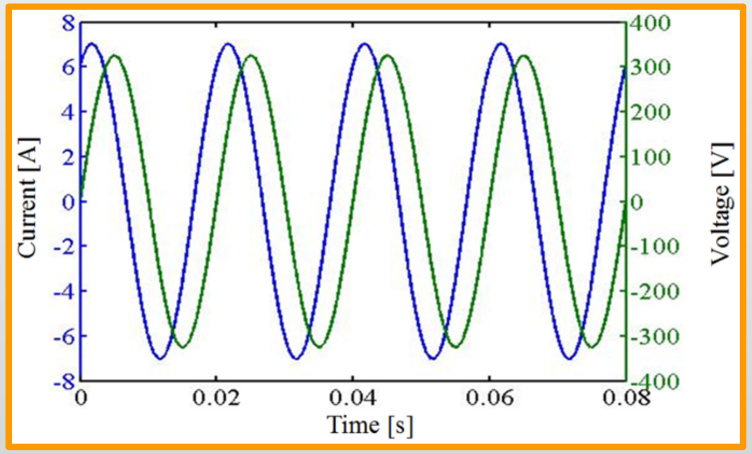
LOAD

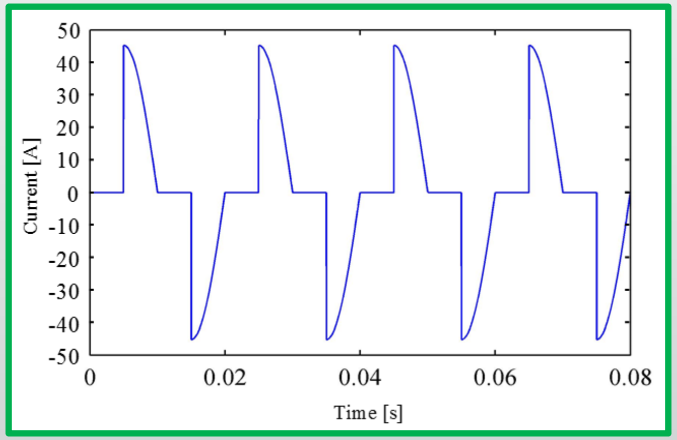
Reference power analyzer Yokogawa WT3000

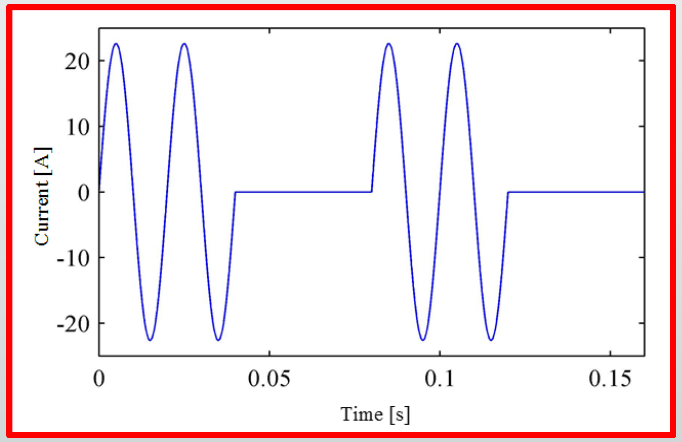
Prototype ARM-based Smart Meter











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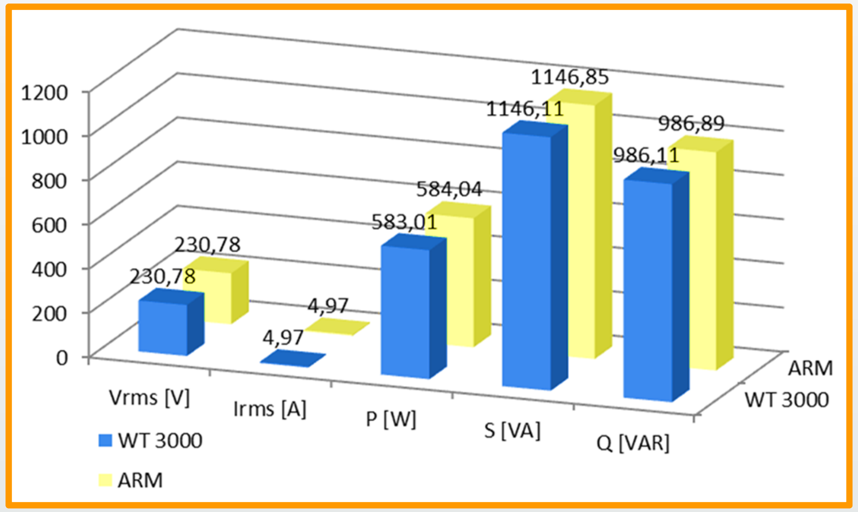
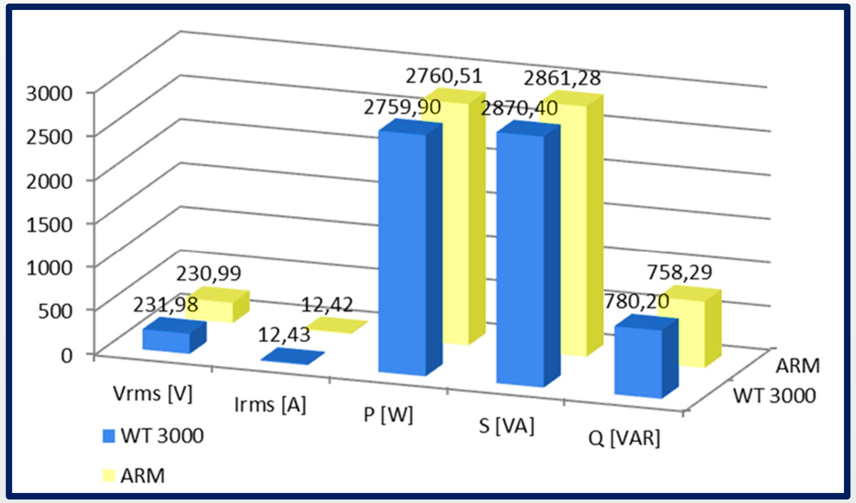
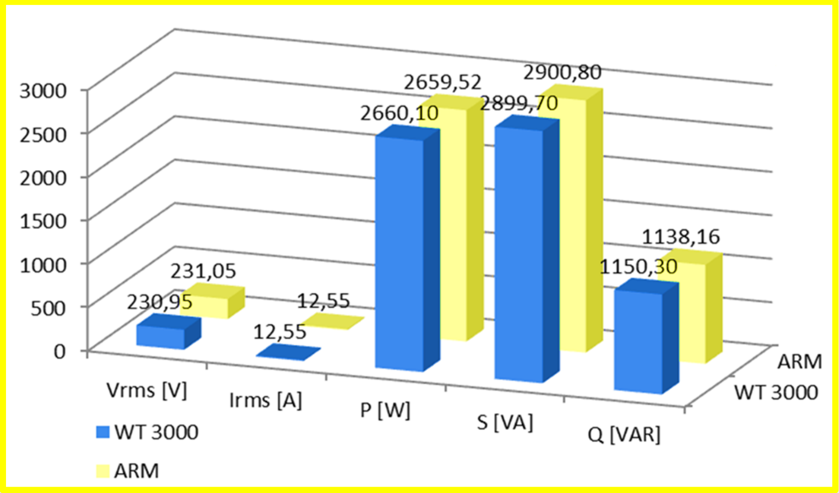
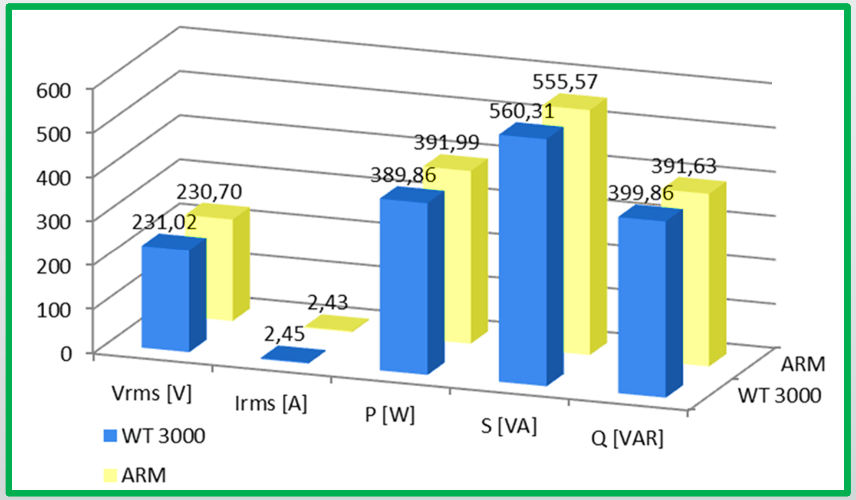
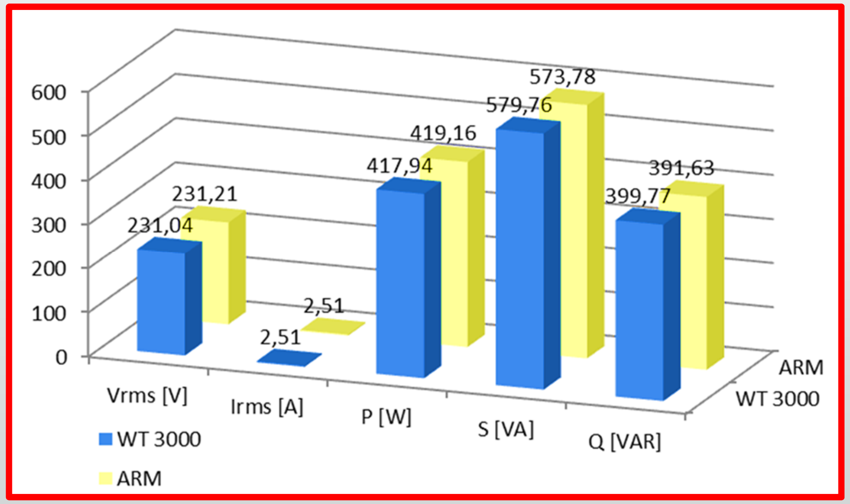










The meter is compliant to class C requirements

D class for laboratory use, A class worst

Metrological characterization: OIML

For the characterization test signals defined in the standard OIML-R46 are used.

Test case	Disturbance	Max possible error shift [%] per meter class			
		A	B	C	D
1	Sinusoidal signals	±2.0	±1.0	±0.5	±0.2
2	Harmonic component in the current and voltage circuits	±3.0	±1.8	±1.0	---
3	DC and even harmonic in the a.c. current circuit	±8.0	±4.0	±2.0	---
4	Odd harmonic in the a.c. current circuit	±8.0	±4.0	±2.0	---
5	Sub-harmonic in the a.c. current circuit	±8.0	±4.0	±2.0	---

Quantity	Max error [%]				
	Test case 1	*Test case 2*	*Test case 3*	*Test case 4*	*Test case 5*
Voltage (r.m.s.)	0.02	0.24	0.04	0.14	0.07
Current (r.m.s.)	0.02	0.08	0.02	0.41	0.18
Active Power	0.18	0.02	0.02	0.55	0.29
Apparent Power	0.06	0.14	0.02	0.46	0.88
Non Active Power	0.08	2.81	1.06	2.06	2.04

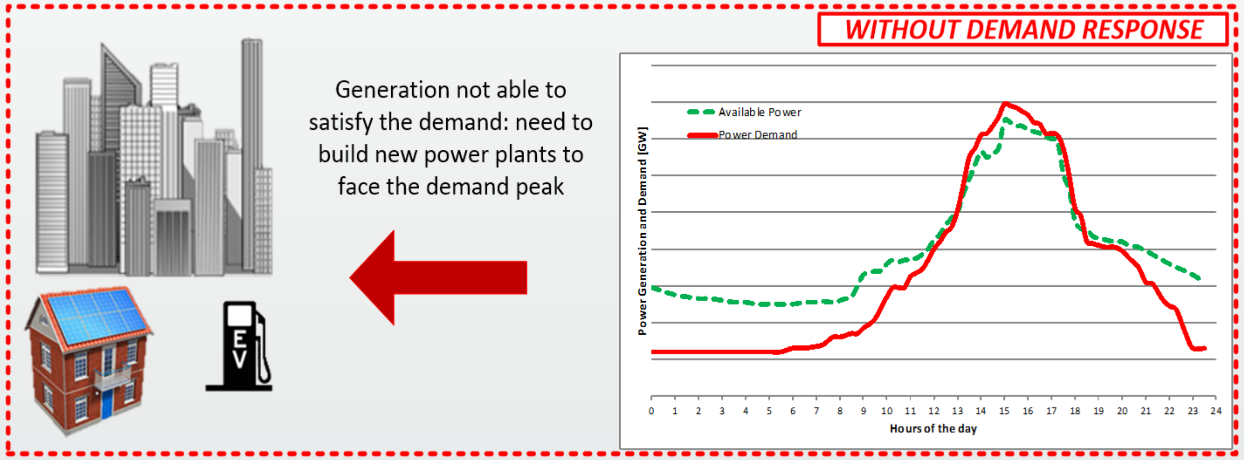
The meter is compliant to

class C requirements

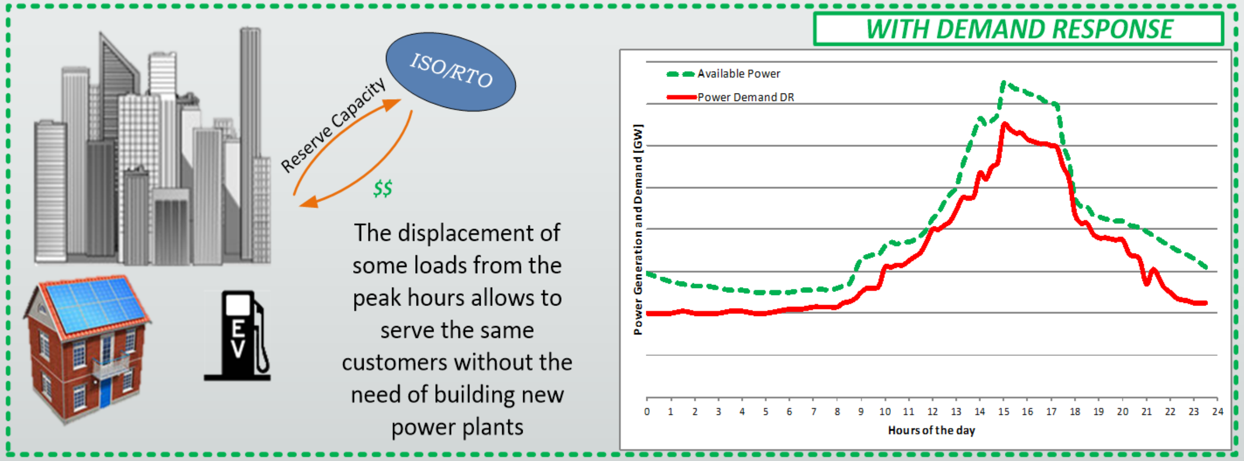
D class for laboratory use, A class worst

Demand Response management

The application of Demand Response programs to residential customers entails performing load curtailments and, possibly, for the customer to recover the curtailed energy at a different time.

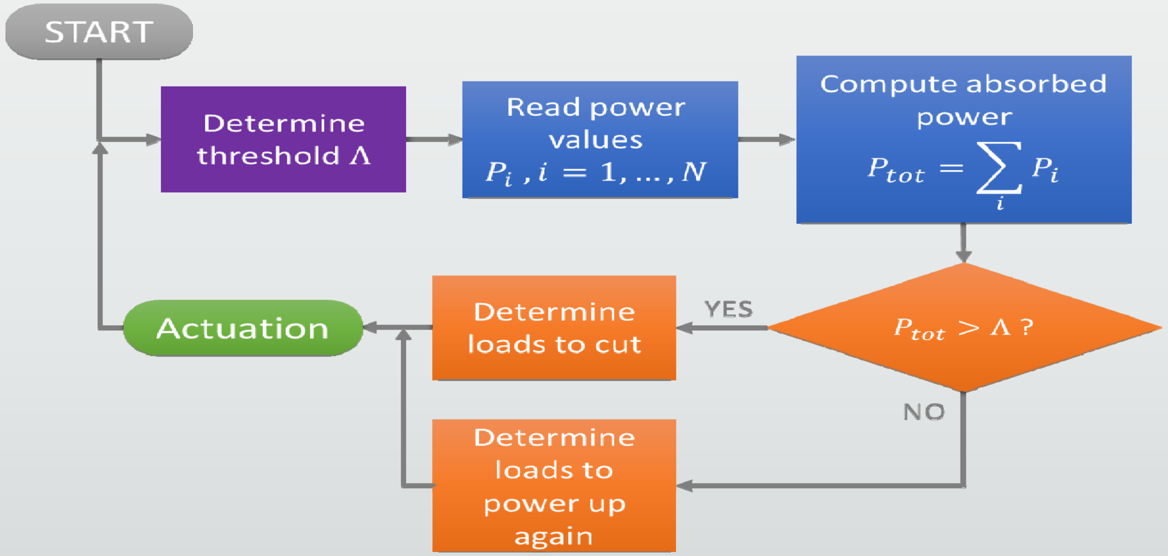


Generation not able to satisfy the demand: need to build new power plants to face the demand peak



The displacement of some loads from the peak hours allows to serve the same customers without the need of building new power plants

The implemented algorithm performs load curtailment in response to the electricity price signal.



START

Determine threshold Λ

Read power values $P_i\ , i = 1, \dots, N$

Compute absorbed power $P_{tot} = \sum_i P_i$

$P_{tot} > \Lambda$?

YES

Determine loads to cut

NO

Determine loads to power up again

Actuation

Demand Response management

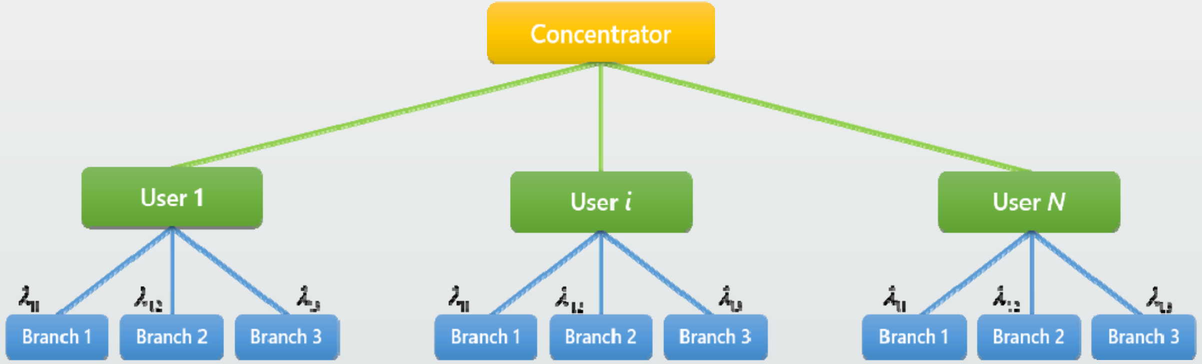
The application of Demand Response programs to residential customers entails performing load curtailments and, possibly, for the customer to recover the curtailed energy at a different time.

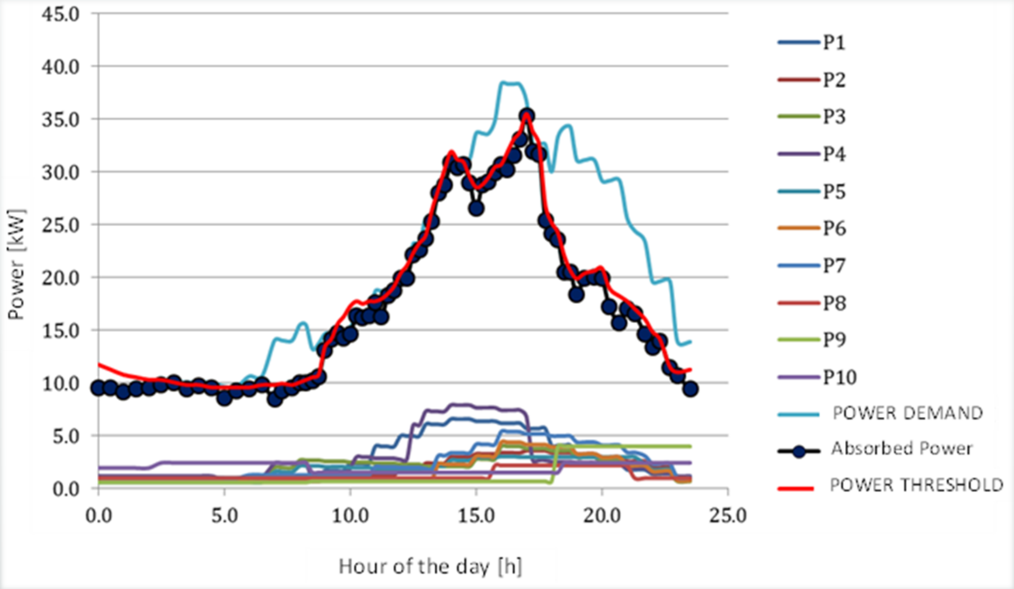
Total absorbed power $P_{TOT}(t) = \sum_{i=1}^{N} \sum_{j=1}^{M} \sigma_{ij} P_{ij}(t)$

Cost function to minimize

$$\Psi(\bar{\sigma},t) = \Lambda - P_{TOT}(t) = \Lambda - \sum_{i=1}^{N} \sum_{j=1}^{M} \sigma_{ij} P_{ij}(t)$$

$$\Psi(\bar{\sigma},t) \geq 0 \qquad \min[\Psi(\bar{\sigma},t)]$$





Load prioritization $\sigma_{ij} \leq \sigma_{lk} \quad if \quad \lambda_{ij} \leq \lambda_{lk}$

Outline

- Bidirectional smart meter for DR applications
- Battery measurement techniques and degradation model
    - Grid-oriented storage
    - Grid support via battery storage
    - Measurement issues with batteries
    - Implemented technique for parameter estimation
    - Implemented technique for health estimation
    - System-level battery degradation model
- Application: V2G management strategy

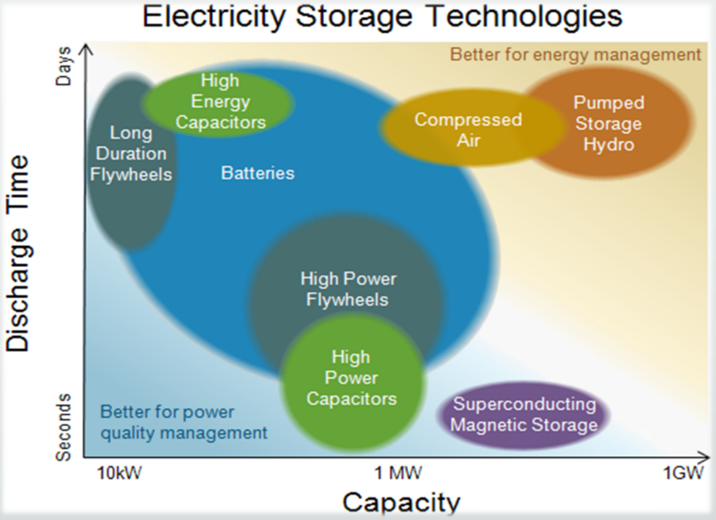
Grid-oriented Storage

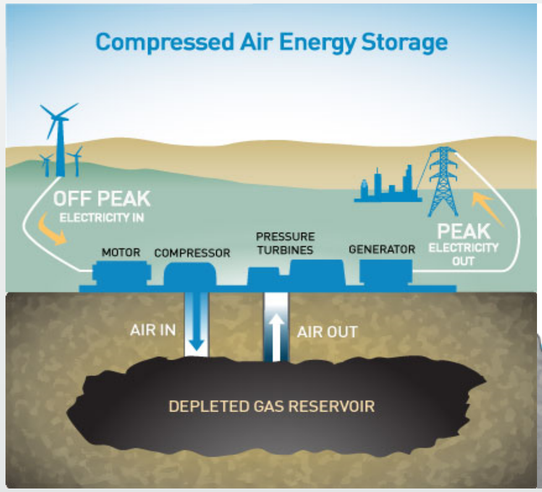
A Smart grid should be able to integrate multiple energy sources and dynamically adapt to fluctuations in loads and sources.

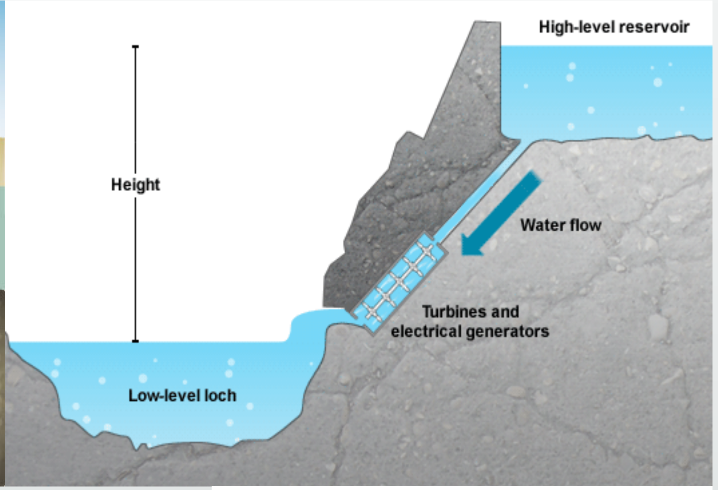
Energy Storage Systems (ESSs) allow for decoupling production and usage times.

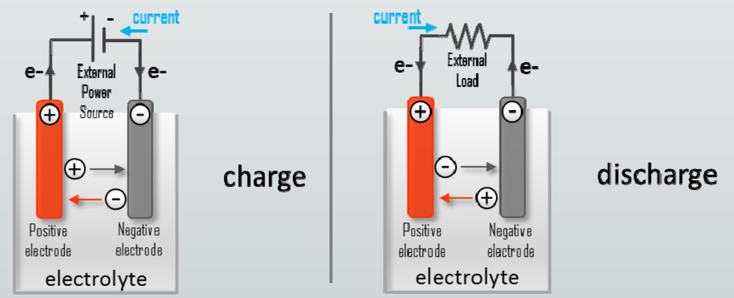
Different solutions for electricity storage:

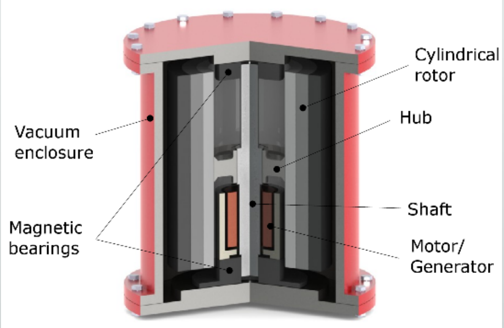
- Compressed air
- Pumped-storage hydroelectricity
- Flywheel
- Batteries (storage plants and ancillary distributed storage)











Grid support via battery storage

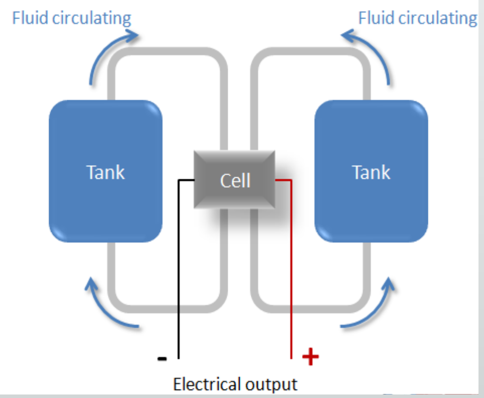
Compared to other storage technologies, batteries guarantee much **shorter response times** and **high efficiency**.

Organized in centralized **storage plants**, or as **Distributed Energy Resources**, batteries are employed for:

- *peak shaving and shifting*
- *ancillary services provision (i.e., frequency regulation)*
- *ease penetration and use for renewable resources*
- *emergency supply (i.e., when in load shedding condition)*
- *energy reserve for off-grid devices (i.e., electric vehicles)*

Newest and most promising battery technologies include:

- *Li-ion*
- *Flow batteries*
- *Liquid metal*



Measurement issues with batteries

From a system-level point of view, to effectively integrate battery storage in the grid two measures are needed

How much energy is stored in the battery ➡ *State of Charge*

Max energy that can be stored: degradation of the battery ➡ *State of Health*

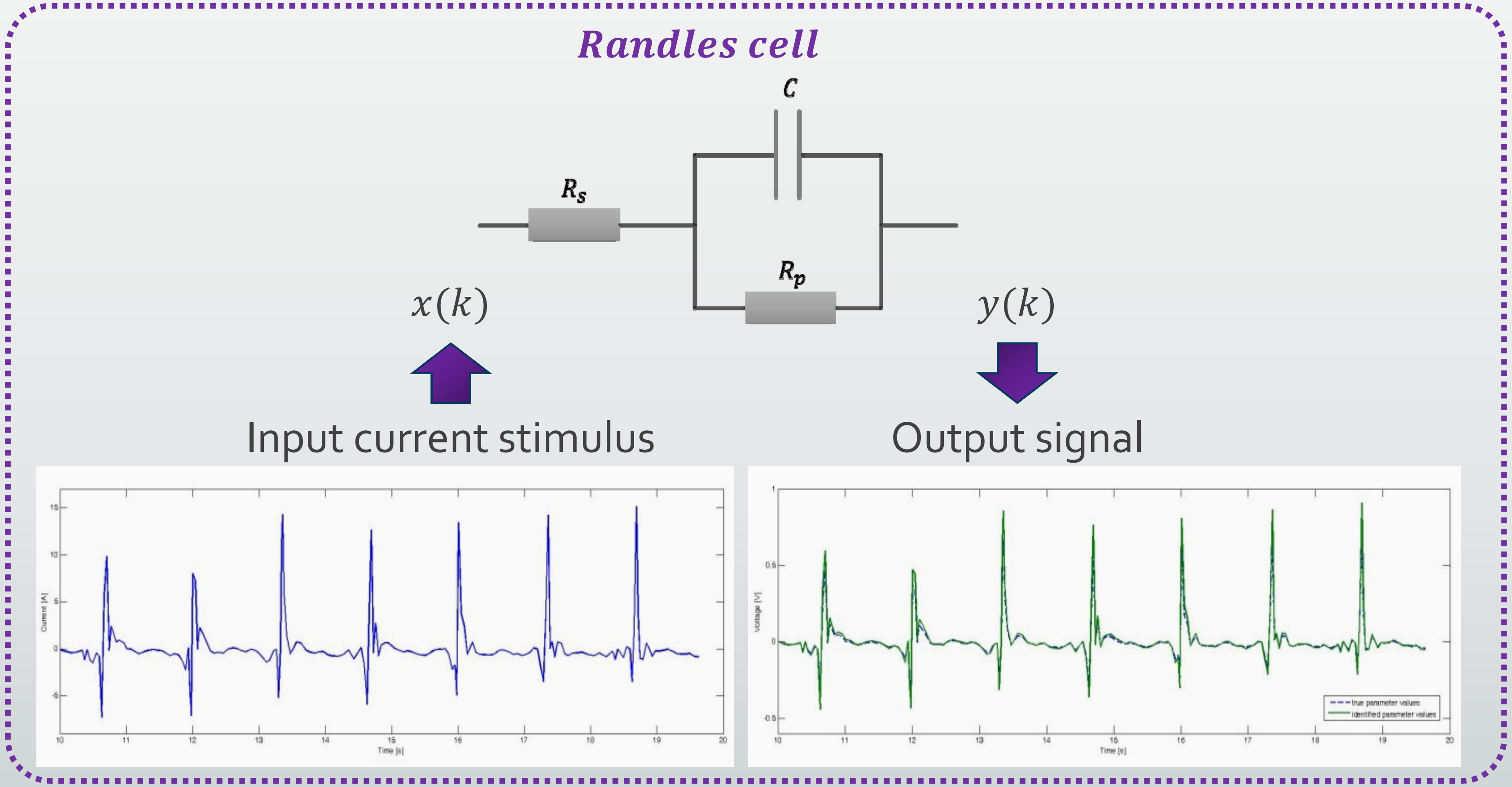
The work focuses on measurements for battery degradation:

- A fast technique for battery equivalent-circuit parameters estimation
- An online technique for estimation of battery State of Health

Battery testing: parameter estimation

For their analysis and integration into electrical system, batteries can be represented as an equivalent circuit.

The values of the parameters determines battery electrical behavior and can be used to estimate degradation.



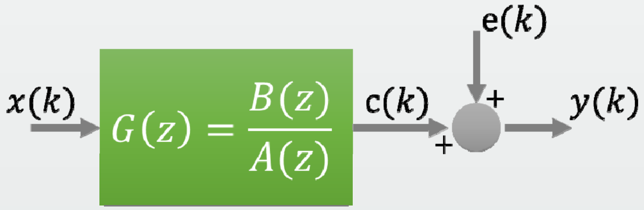
State of art measuring values of parameters characteristics of an electrochemical process is the Electrochemical Impedance Spectroscopy (EIS).

The implemented technique is fast and suitable for online monitoring.

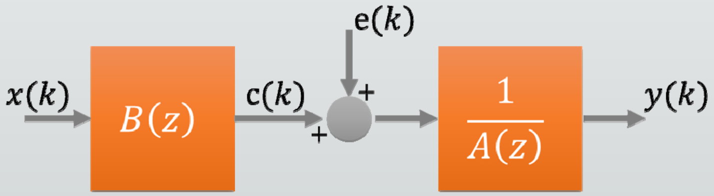
Battery testing: parameter estimation

2 system models adopted in the estimation

Output Error Model



ARX Model



For the assumed battery model

$$G(z) = \frac{a_1 + a_2 z^{-1}}{1 + a_0 z^{-1}}$$

$$R_s = \frac{(a_1 - a_2)}{(1 - a_0)}$$

$$R_P = 2\frac{(a_2 - a_0 a_1)}{(1 - a_0^2)}$$

$$C = \frac{T}{4}\frac{(1 - a_0)^2}{(a_2 - a_0 a_1)}$$

T sampling period

Results

Ni-MH

OUTPUT ERROR MODEL

Parameter\Noise	*0 %*	*0.2%*	*0.5%*	*1%*	*2%*	*5%*
Rs [mΩ]	1.000	1.000	0.999	0.999	0.999	0.997
Rs_error [%]	6.8e-4	0.025	-0.099	-0.043	-0.072	-0.26
Rp [Ω]	0.648	0.638	0.637	0.637	0.637	0.638
Rp_error [%]	-1.1e-6	-0.003	-0.014	-0.032	-0.077	0.039
C [F]	43.68	43.67	43.67	43.68	43.67	43.66
C_error [%]	2.1e-6	-0.006	-0.023	0.019	-0.026	-0.033

ARX MODEL

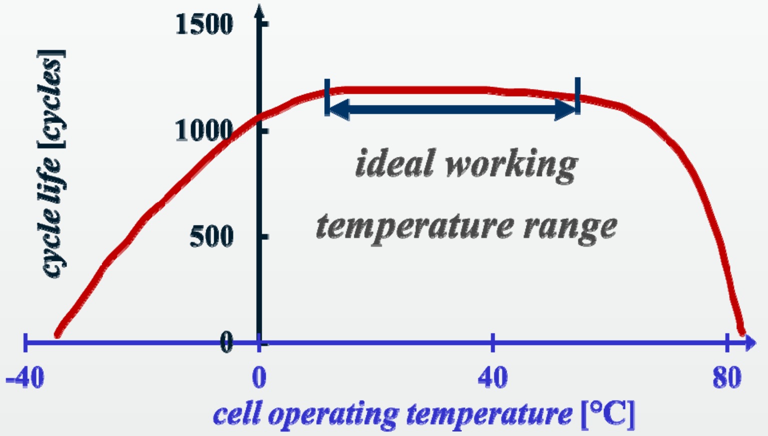
Parameter\Noise	*0 %*	*0.2%*	*0.5%*	*1%*	*2%*	*5%*
Rs [mΩ]	1.000	0.999	0.998	0.999	0.981	0.8833
Rs_error [%]	6.8e-4	-0.030	-0.23	-0.089	-1.9	-12
Rp [Ω]	0.638	0.631	0.595	0.498	0.301	0.084
Rp_error [%]	-1.1e-6	-1.1	-6.7	-22	-53	-87
C [F]	43.68	43.67	43.64	43.50	43.22	40.93
C_error [%]	2.1e-6	-0.009	-0.089	-0.40	-1.03	-6.3

ARX execution time on different microcontrollers

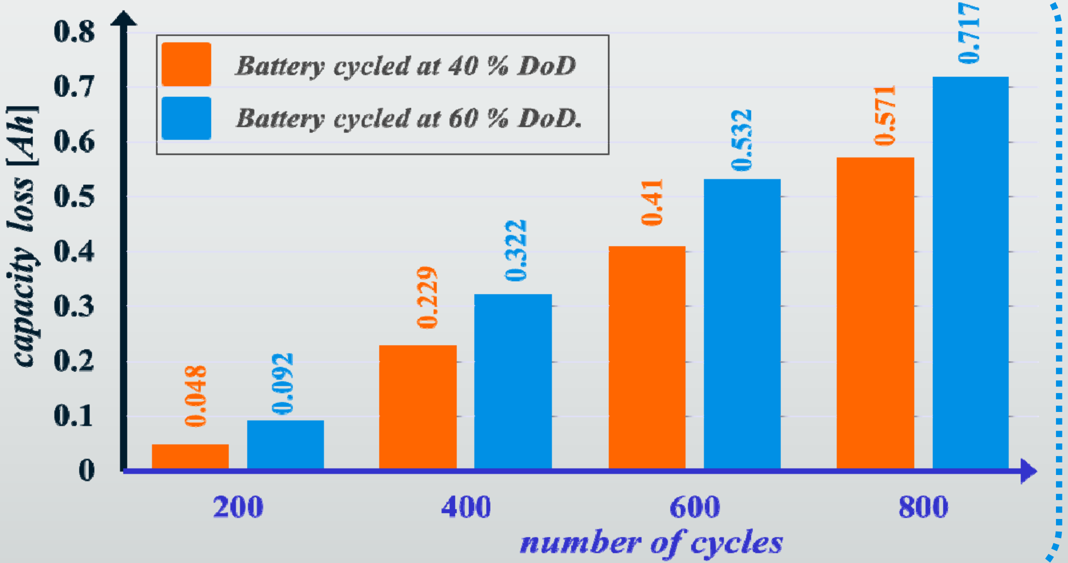
Exec time (ms)	*64 samples*	*128 samples*	*256 samples*
ARM – M3	18.76	36.36	63.57
ARM – M4	5.5	10.3	18.98

Factors influencing battery health

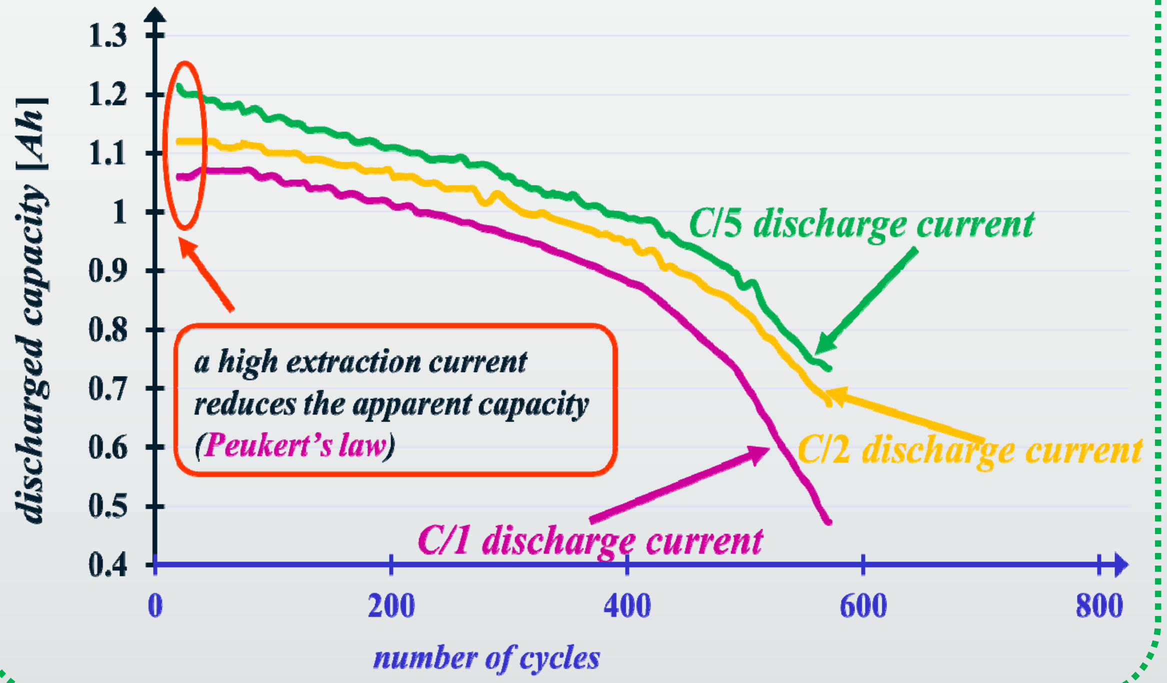
Temperature



Depth of Discharge



Discharge current



a high extraction current reduces the apparent capacity (Peukert's law)

Battery testing: health estimation

The State of Health (ξ) expresses the available fraction of storage capacity, with values in [0,1].

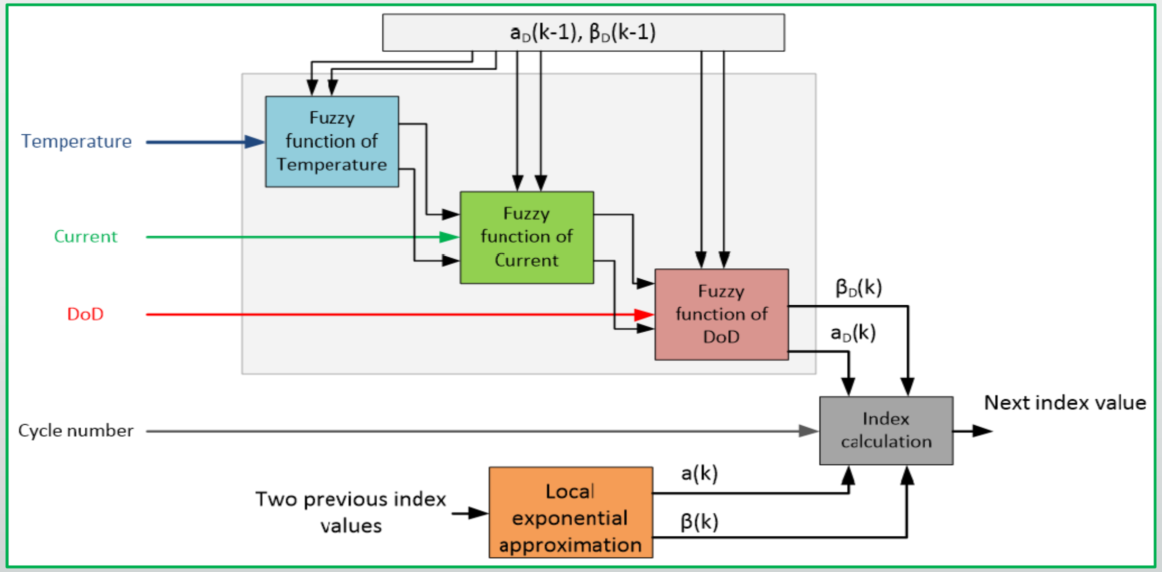
Fuzzy logic system

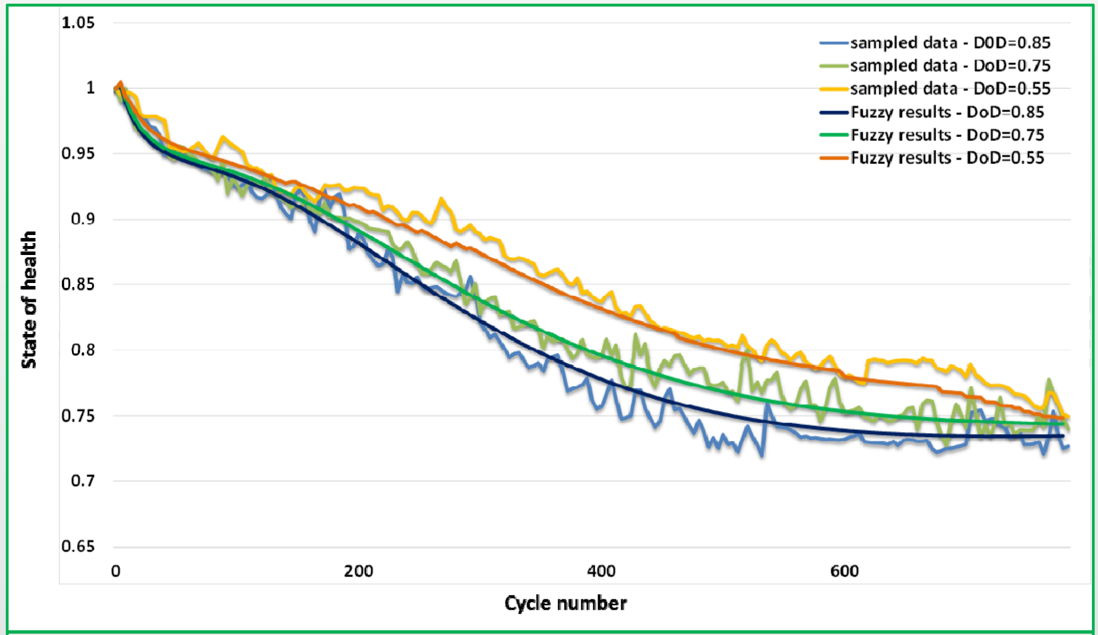
- *Exponential data approximation*

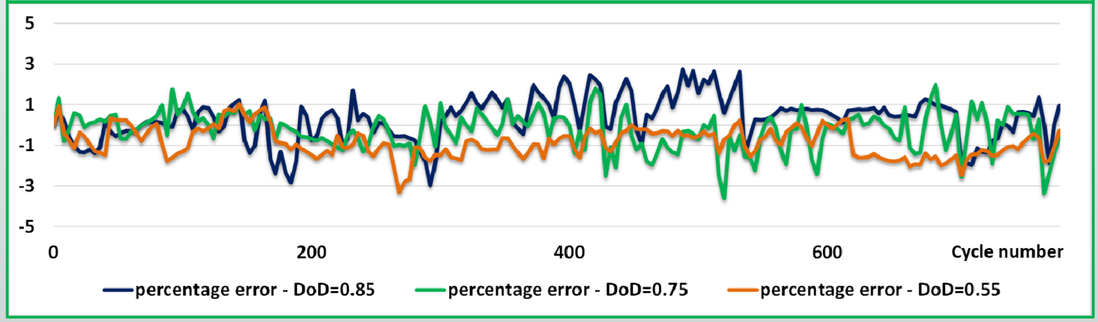
$$\xi_{fit} = a_0 + a_1 e^{-\left(\frac{n}{d_1}\right)^{\beta 1}} + a_2 e^{-\left(\frac{n}{d_2}\right)^{\beta 2}}$$

$$\xi_{fit} = a e^{-\beta n}$$

- *Fuzzy algorithm*



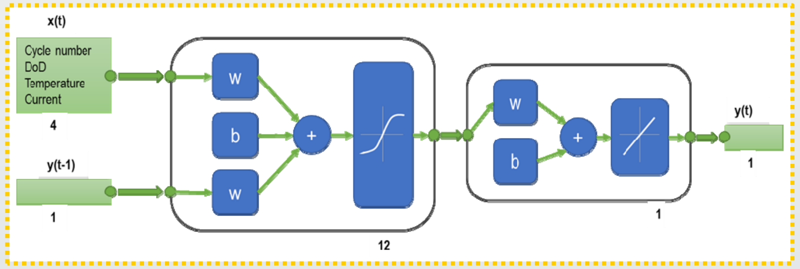


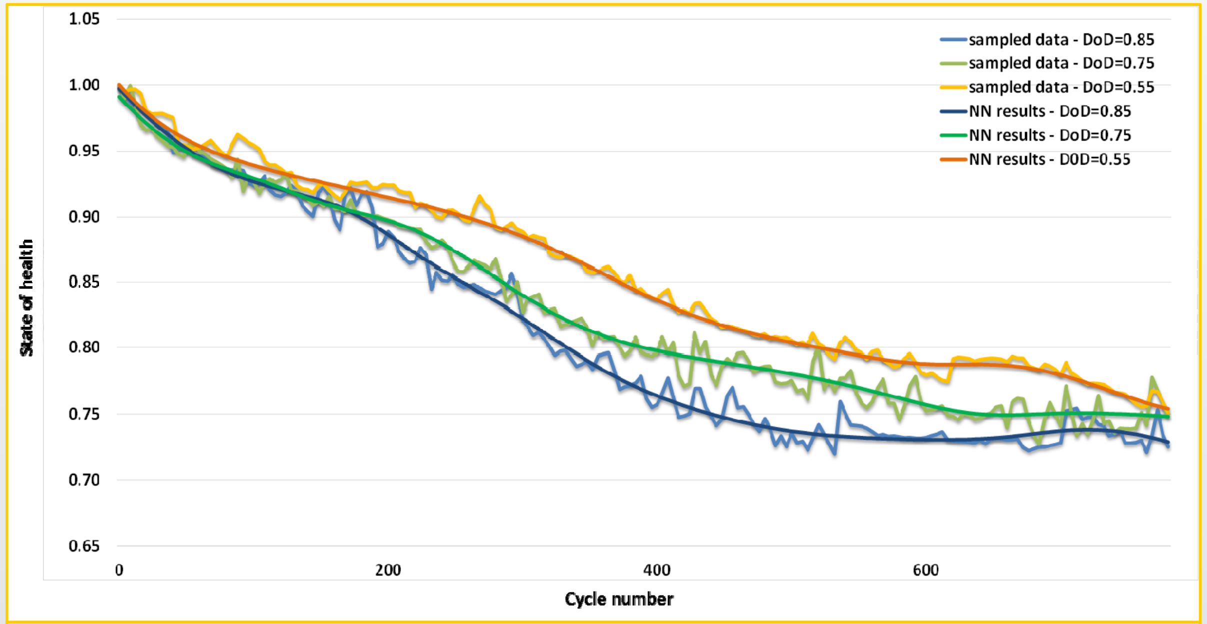


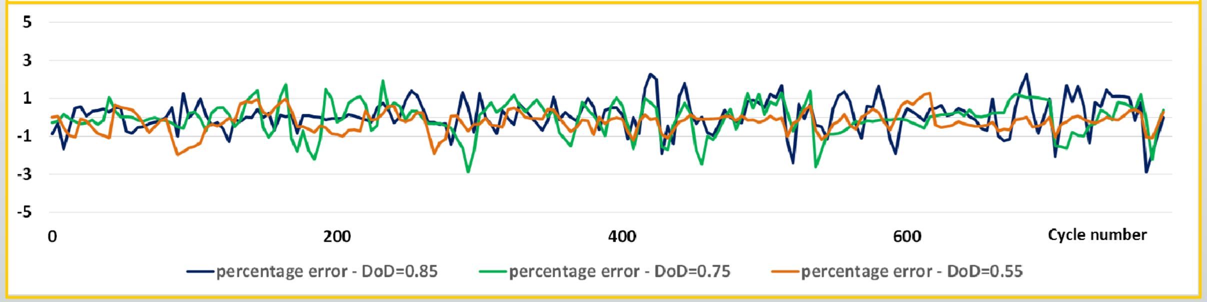
Battery testing: health estimation

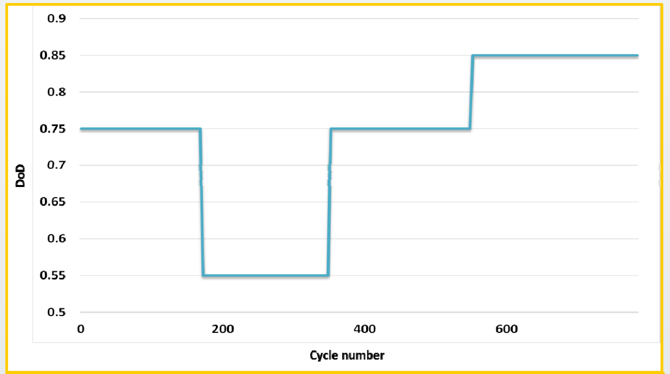
The State of Health (ξ) expresses the available fraction of storage capacity, with values in [0,1].

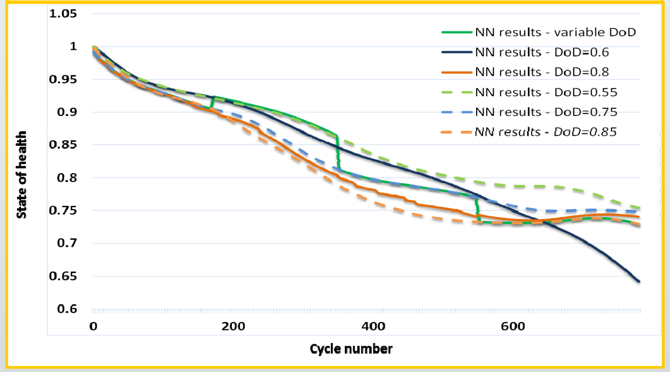
Neural network system





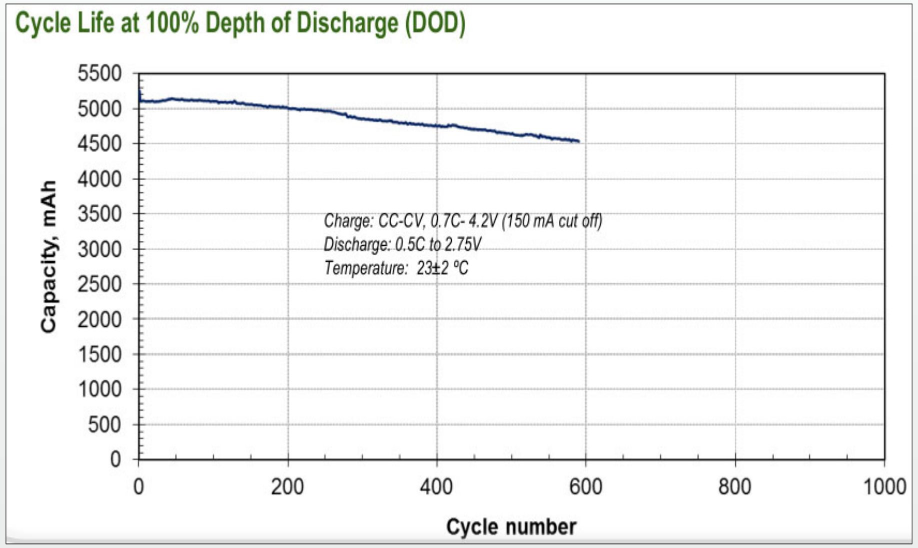






Battery degradation model - 1

Available experimental data generally relates battery capacity decay to number of cycles.



Provision of services to the grid *does not involve full cycles*.

Given known battery testing conditions, battery decay can be related to the energy throughput (energy flowing in/out of the battery)

$$\Delta E = 2V_{nom} c_0 \xi$$

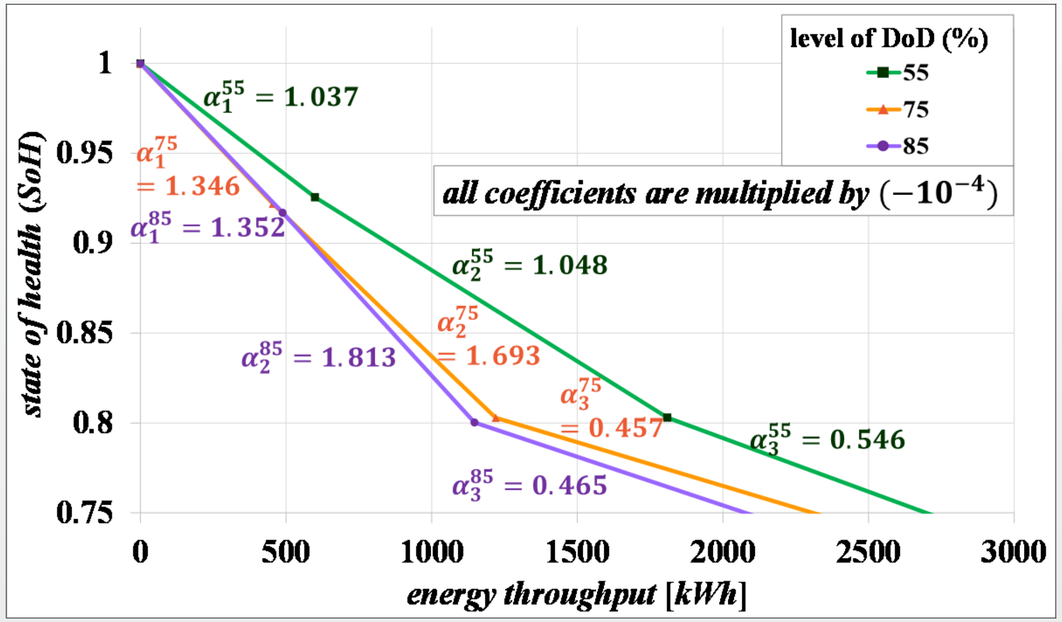
The total energy throughput the battery has been subject to until the *n-th* cycle is:

$$\Delta E_{TOT}(n) = \sum_{i=1}^{n} 2V_{nom} c_0 \xi(i)$$

Battery degradation model - 2

Decay coefficients link State of Health (ξ) to energy throughput.

They depend on the *depth of discharge* and are retrieved using a piecewise approximation of capacity decay experimental data.



$$\Delta\xi_k(\xi_k,\chi_k,T_k,i_k) = w(T_k,i_k)\,\alpha(\chi_k,\xi_k)\,\Delta E_k$$

Factors such as current and temperature are considered through a weighting function.

$$w(T_k,i_k) = \gamma_T (T_k - 25)^2 + \gamma_C \left(\frac{i_k}{I_n}\right)^{0.05}$$

Total decay for N batteries in H hours of operation is:

$$\Delta\xi^{TOT} = \sum_{h=1}^{H} \sum_{k=1}^{N} u_{h,k}\,\Delta\xi_{h,k}$$

Battery degradation model - summary

Total decay for N vehicles in H hours of operation is:

$$\Delta\xi^{TOT} = \sum_{h=1}^{H}\sum_{k=1}^{N} u_{h,k}\,\Delta\xi_{h,k}$$

where:

$$\Delta\xi_k(\xi_k,\chi_k,T_k,i_k) = w(T_k,i_k)\,\alpha(\chi_k,\xi_k)\,\Delta E_k$$

$$w(T_k,i_k) = \gamma_T(T_k-25)^2 + \gamma_C\left(\frac{i_k}{I_n}\right)^{0.05}$$

with:

ξ_k → state of health of *k-th* battery

χ_k → state of charge of *k-th* battery

c_0 → battery capacity

V_{nom} → battery nominal voltage

under constraint:

$$E_{aval}^{\uparrow} = c_0 V_{nom}\,\xi_k\,\chi_k \le \Delta E_{req}^{\uparrow}$$

$$E_{aval}^{\downarrow} = c_0 V_{nom}\,\xi_k(1-\chi_k) \le \Delta E_{req}^{\downarrow}$$

$$0.1 \le \chi_k \le 0.9$$

$$i_k \le I_{batt}^{MAX}$$

$$\chi_{k,H} = \chi_{k,H}^{DESIRED}$$

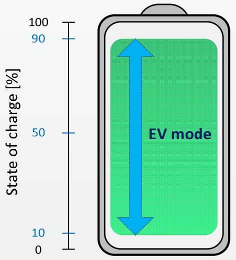
Outline

- Bidirectional smart meter for DR applications
- Battery measurement techniques and degradation model
- Application: V2G management strategy
    - Battery Vehicles (BVs) and V2G
    - V2G management
    - Implemented V2G management strategy
    - Case study for V2G strategy evaluation
    - Case study: results

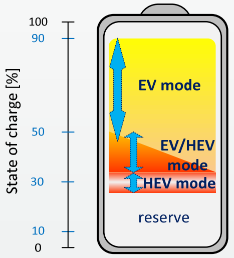
Battery Vehicles and V2G

Battery Vehicles (BVs) represent a sustainable mean of transportation.

- All Electric Vehicles (**AEV**s)
- Plug-in Hybrid Electric Vehicles (**PHEV**s)



All Electric Vehicle



Plug-in Hybrid Electric Vehicle

Battery system requirements

Key aspects	**HEV**	**PHEV**	**AEV**
High power	●	●	
High energy		●	●
Adaptability to different usage scenarios		●	
Rechargeable from the grid		●	●
Fast recharge time			●
Operational modes	CS	AEV,CD,CS, Engine priority	AEV
Cost	Medium/Low	Medium/High	High

*Charging a relevant number of vehicles at the same time in peak hours represents an **unbearable stress** for the power grid.*

The BVs, however, represent not only a load but also a **resource**:

- **Dispatchable load** ➡ ***Smart charging***
- **Distributed Energy Resource** ➡ ***Vehicle-to-Grid (V2G)***

Suitable measurement devices and management models are needed.

V2G management

To be able to affect the power grid the vehicles need to be grouped in **sizable aggregations.**

The fleet of thousands of tens of thousands BVs acts on the power grid and electricity market as a *single entity*:

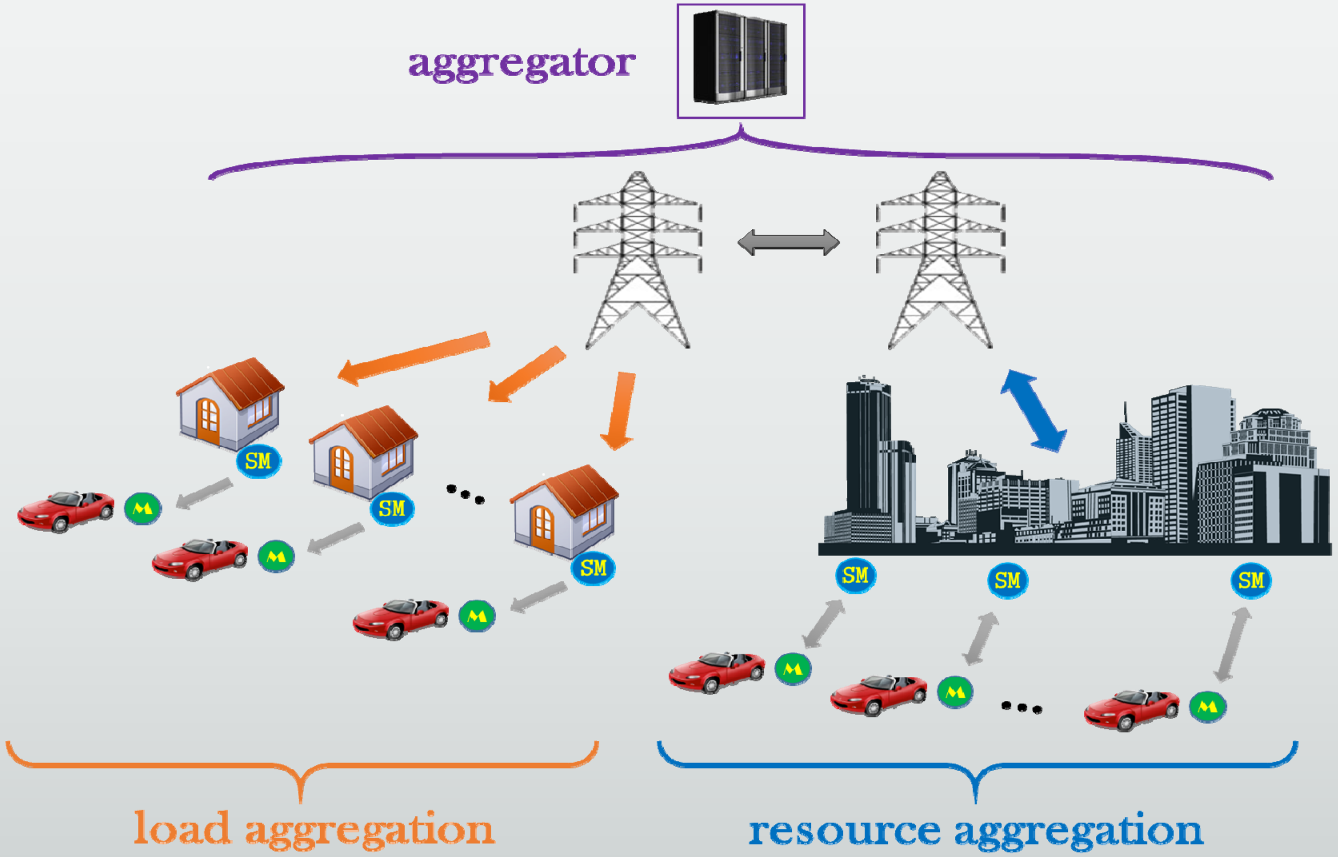
- as a ***load***, it represents the total capacity of batteries
- acting as a relevant-size ***Distributed Energy Resource***, can provide *regulation services*, paid independently of actual provision of service. Energy supply involves additional payment.

The aggregation has ***higher negotiating power***, allowing for better deals and for some of the savings to be passed to vehicles' owners.

V2G management

Pivotal is then the role of the ***aggregator***:

- it represents the interface of the fleet to the electricity market and the power grid
- manages the fleet.



In the assumed business model the *aggregator* is responsible for acquisition and maintenance of the batteries.

↓

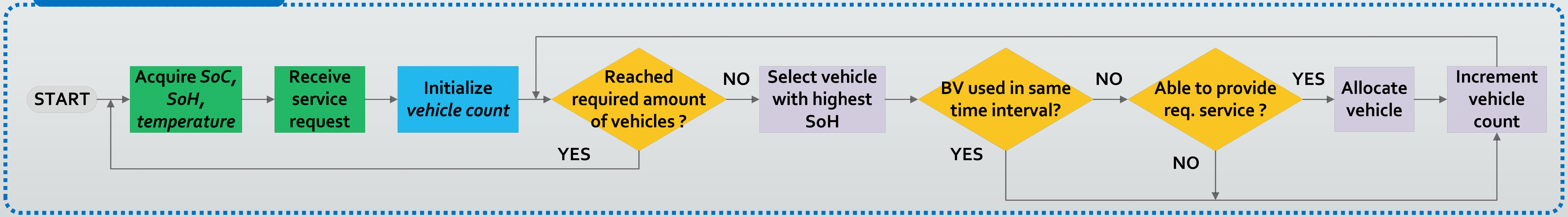
Strategy to allocate the services among the BVs so to *maximize the life of the batteries* (value of its assets).

Implemented V2G management strategy

Basic assumptions :

- Each battery, upon connection to the grid, is identified univocally (SIM card based identification)
- Each battery embeds a meter able to measure the *state of charge* and the *state of health*, communicated to the aggregator upon connection to the grid
- The aggregator receives a *raise/lower capacity* signal (service request) from the system operator, which involves provision or acceptance of a specified amount of energy

Block scheme



START

Acquire *SoC, SoH, temperature*

Receive service request

Initialize *vehicle count*

Reached required amount of vehicles ?

NO

YES

Select vehicle with highest SoH

BV used in same time interval?

NO

YES

Able to provide req. service ?

YES

NO

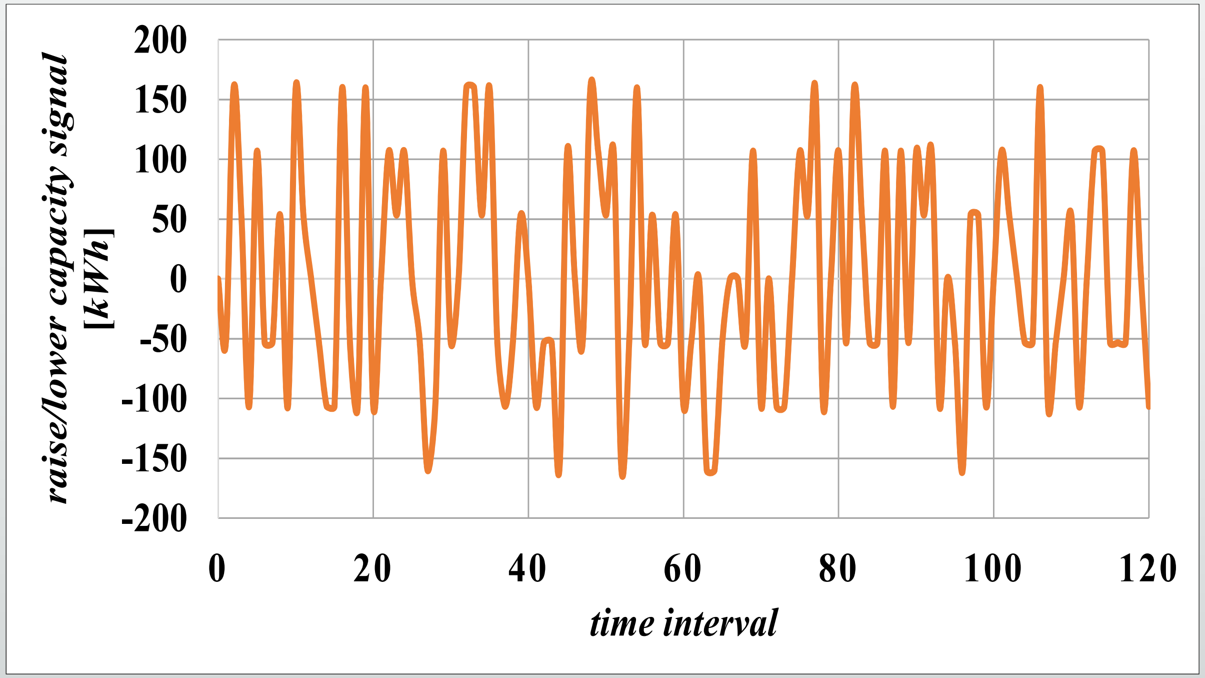
Allocate vehicle

Increment vehicle count

Implemented V2G management strategy

- The allocation of vehicles is performed every 5 minutes long time interval
- Charge and discharge take place at a fixed current level (10 A)
- All vehicles have the same battery, composed of 600 Tenergy 18650 cells

- The considered *rise/lower capacity signal* is a zero-average arbitrary profile, scaled by the minimum number of vehicles to be involved in service provision each time interval (*base unit*)
- Strategy guarantees final *state of charge* equal to the one upon connection



V2G strategy evaluation: case study

To evaluate the implemented strategy, the improvement in battery life in a FIFO V2G management strategy where only the *state of charge* is assumed as state variable.

Name	Configuration		
	number of vehicles (N)	base unit	distribution
28800-80g	N= 28800	N/80	Gaussian
28800-80u	N= 28800	N/80	Uniform
19200-80g	N= 19200	N/80	Gaussian
19200-80u	N= 19200	N/80	Uniform
19200-40g	N= 19200	N/40	Gaussian
19200-40u	N= 19200	N/40	Uniform
11520-80g	N= 11520	N/80	Gaussian
11520-80u	N= 11520	N/80	Uniform
11520-40g	N= 11520	N/40	Gaussian
11520-40u	N= 11520	N/40	Uniform
960-80g	N= 960	N/80	Gaussian
960-80u	N= 960	N/80	Uniform
480-80g	N= 480	N/80	Gaussian
480-80u	N= 480	N/80	Uniform

- Simulations are conducted with initial state of charge and state of health randomly generated.
- To evaluate the effect of the number of vehicles and *base unit*, several configurations are adopted.
- *100 simulation run are considered for each configuration.*

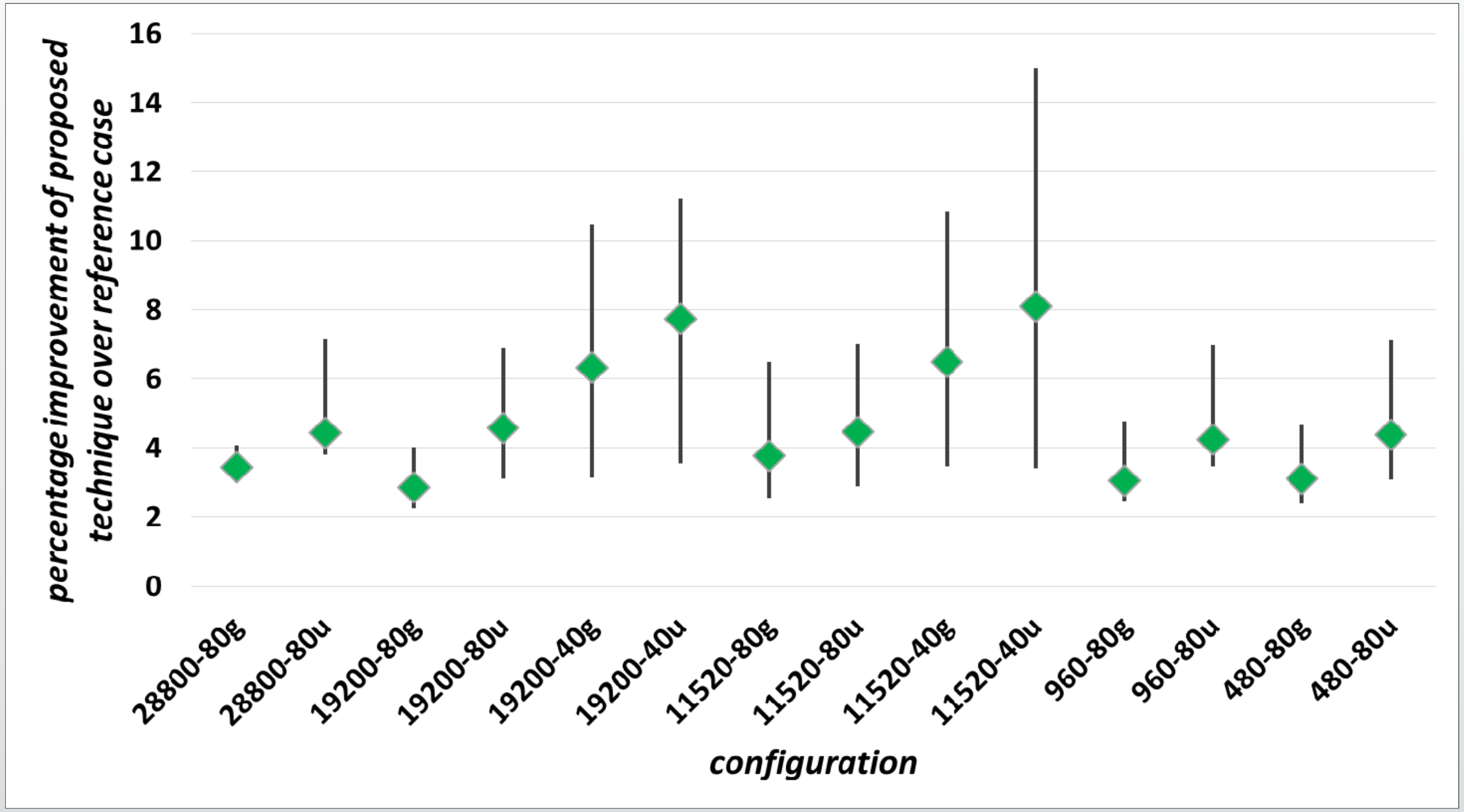
Case study: results

Results show there is an increase in battery lifetime of the order of 3% to 8%.

Considering:

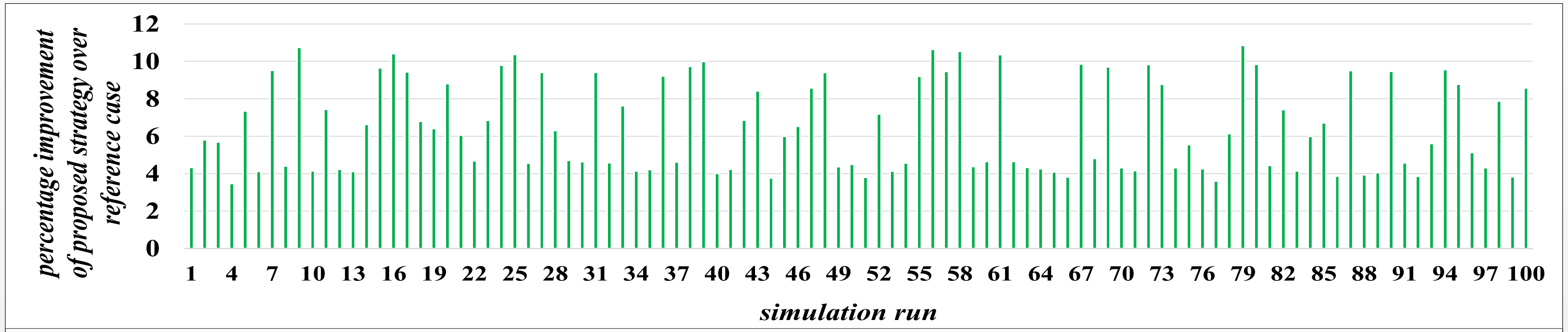
- *Estimated battery life of 3000 cycles*
- *Worst case scenario of 2 full cycles per day*

An increment of 5% means ***extra 75 days of operation***

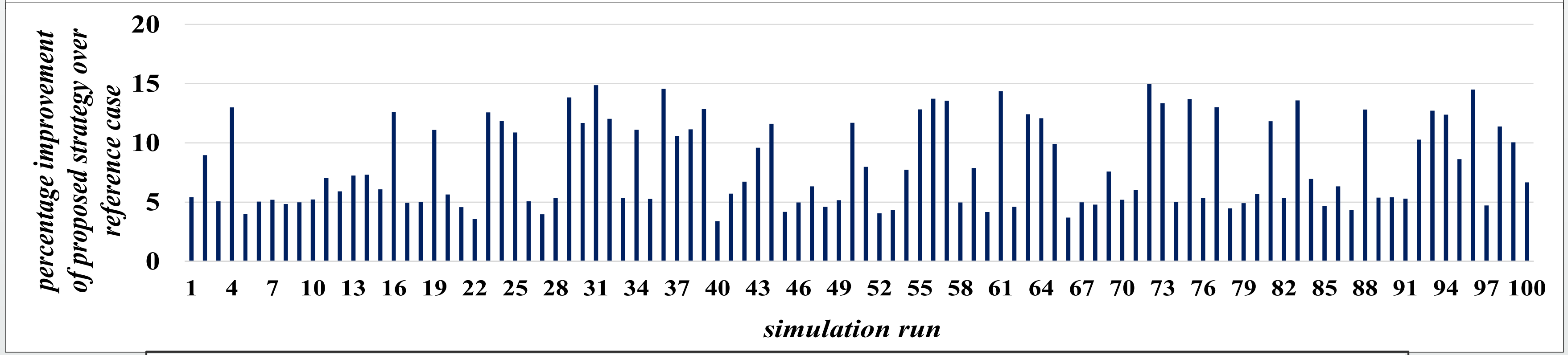


Case study: results

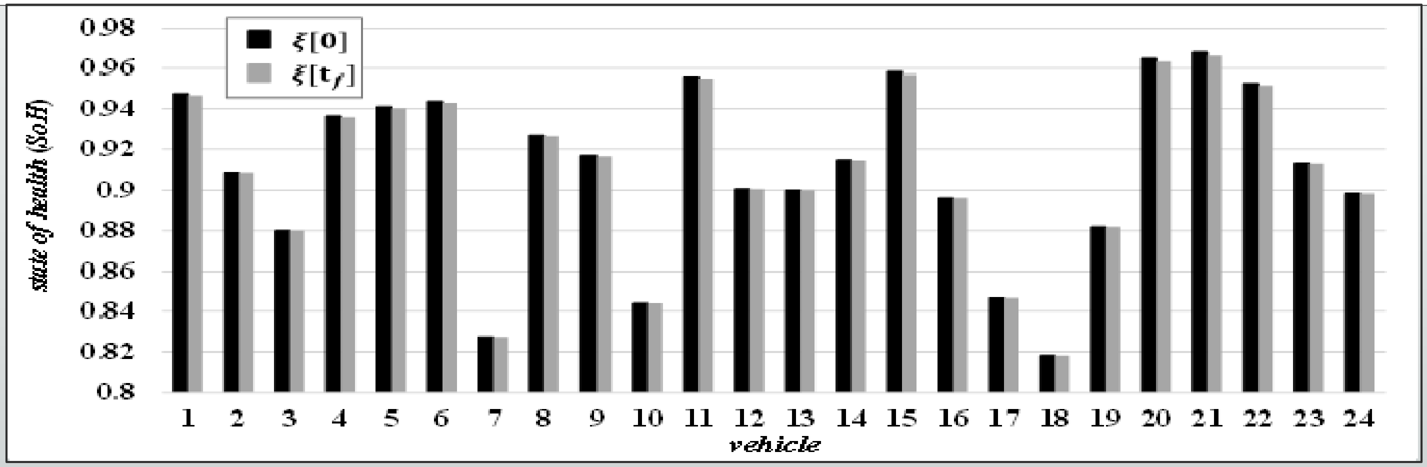
- *Results for 100 tests in 11520-40g configuration*



- *Results for 100 tests in 11520-40u configuration*



- *Sample of computed state of health for subset of vehicles in 11520-40g configuration*



Conclusions

- ✓ A **Smart Meter** for installment in low voltage distribution network has been developed.

  Its main characteristics are: good measurement performances (class C), low cost, real-time operation, presence of actuators to implement DR programs, ability to integrate into an AMI architecture.

- ✓ A **metering architecture for monitoring and DR management** for the developed SM has been realized.

- ✓ Online **measurement techniques** to estimate **battery** parameters and state of health have been developed. *Implemented on a SM, can be used together with the developed system-level degradation model to manage aggregations of batteries in provision of services to the grid.*

- ✓ An application for the developed measurement techniques and model is represented by the implemented **strategy to manage aggregations of BVs**.

Open issues

- Development of communication protocols and communication frontends to guarantee interoperability between different metering networks
- Development of distributed architectures for real time grid management
- Integration of prognostics algorithms with implemented battery monitoring techniques

Appendix: conversion efficiency in V2G

Stating the efficiency of the V2G approach is difficult since there still is no unanimous standard regarding charging stations and plugs, type of connection (mono-phase or three-phase), voltages. It is even debated whether to put the inverter on the car or on the charging station.

- Considering a charge/discharge efficiency of around 85% for Li-Ion batteries
- With rather conservative converter efficiency of 93%

⬇

Total efficiency of storing and recovering energy with V2G is of around 74%.

However, vehicles can sell energy to the grid when it is expensive and recover it back at cheaper rates.

In some cases, as with low-load conditions and with renewables, BVs help in grid operations

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