Design of an electricity consumption measurement system for Non Intrusive Load Monitoring

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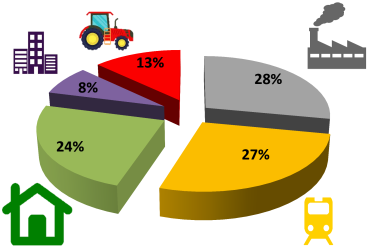
Outline

Global context

- Contribution of the residential sector to 24% of the electricity consumption in the world.
- Population growth
- Growing number of Home Electrical Appliances (HEAs) and wide diversity

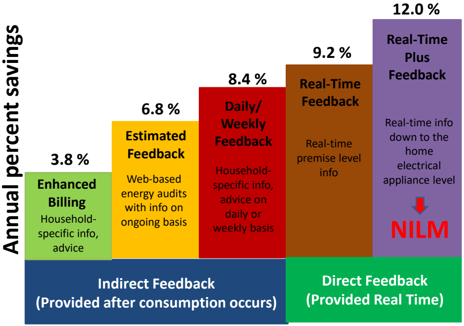


Source: International Energy Agency, Energy balance of the world, accessed July 2011.

⇒ Consequences on electricity bills and environment

Solution

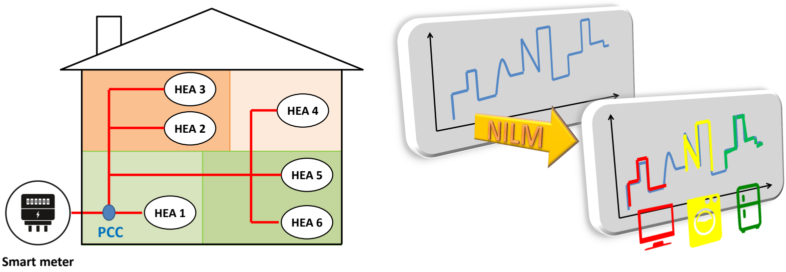
- Real-time information down to the HEA level relayed back to the consumers



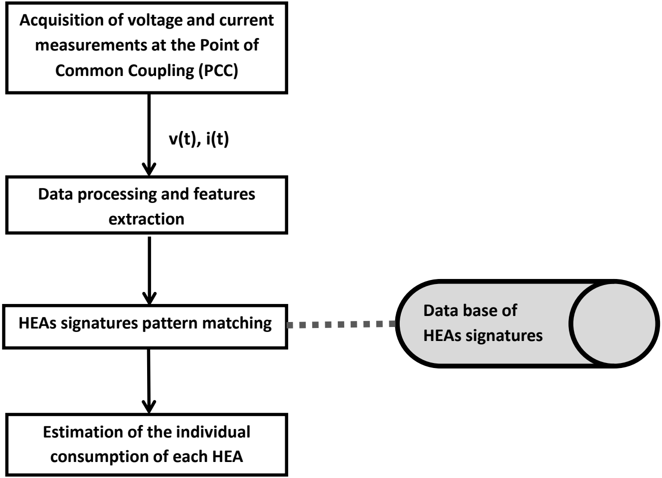
Source: American Council for an Energy Efficient Economy (ACEEE) 2010

NILM goals

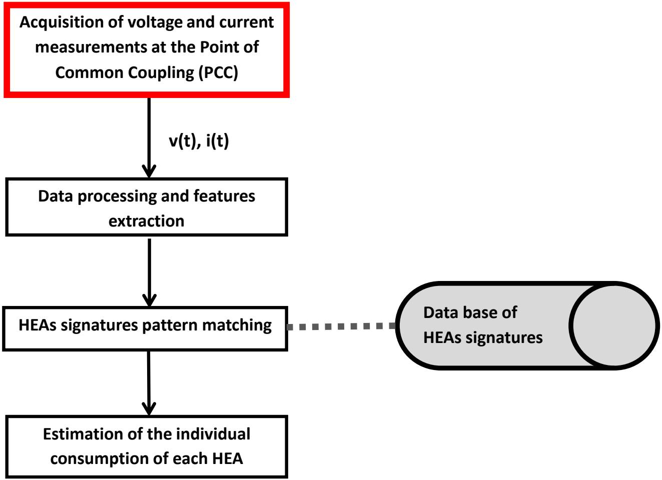
- Estimation of the individual consumption of each HEA from the load curve disaggregation by acquiring voltage and current measurements at the Point of Common Coupling (PCC).



Supervized NILM methods



Supervized NILM methods

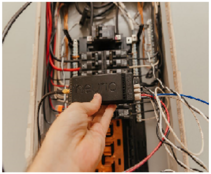


Problematic

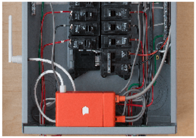
Design and development of a low cost and and easy to install metering unit for real-time current and voltage acquisition of individual HEA and whole houses

Industrial marketed products

TED 5000



Neurio



Sense Home Energy

Eyedro

Industrial marketed products

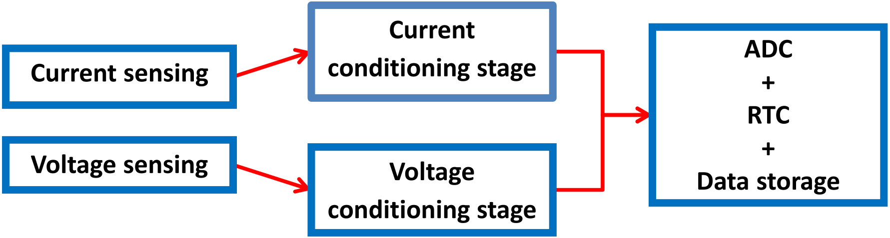
	TED 5000	Eyedro	Neurio	Sense Home Energy
Hardware device	MTU + CTs*		MTU + CTs	
Communication protocol (user side)	Ethernet		WLAN	
Sampling frequency	1 Hz	N/A	4 kHz	1 Hz
Price	270 €	200 €	220 €	200 €
Company	The Energy Detective (TED)	Eyedro Green Solutions	Neurio	Sense
Origine	USA	Canada		

*: Professional installation is required

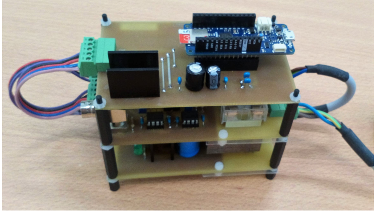
Criteria of the proposed measurement system

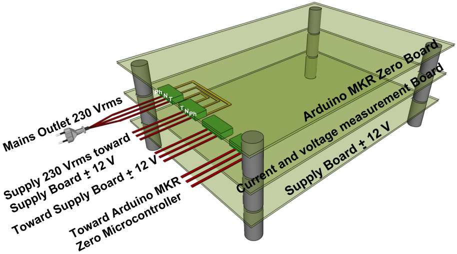
- ⇒ A low power device, cheap to produce and to deploy
- ⇒ A sampling rate that allows to extract harmonics up to the 15^{th} range (higher than 1.5 kHz according to Shannon theorem) and that supports long-time measurements
- ⇒ A good resolution
- ⇒ A low cost
- ⇒ An autonomous device with a dedicated power supply
- ⇒ An easy installation
- ⇒ A measurement capability of $\approx 6kW$ corresponding to a conventional house power contract

Data acquisition



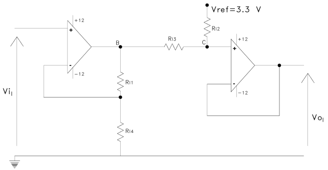
Designed prototype





- Plugging of the system into a wall outlet
- 2×12V-5VA transformer whose output is given to a bridge rectifier that converts the AC to DC, and delivers the voltage to a filter circuit
- 2 voltage regulators IC 7812 et IC 7912 to obtain an output voltage of $\pm$ 12 V
- Arduino MKR Zero microcontroller supplied with 5 V via an IC 7805 voltage regulator
- ADC microcontroller voltage range: **0-3.3 V**

Current conditioning circuit



- $V_{iI} = s.i$: voltage delivered by the ammeter
- i: load current measured in one of the domestic network phases
- s=10 mV/A: current probe sensitivity
- Non-inverting OP27 opamp circuit (R_{I4}, R_{I1}=8.25 kΩ) $\Rightarrow V_B = \left(1 + \frac{R_{I4}}{R_{I1}}\right) V_{iI}$

- Resistive voltage divider and opamp voltage follower circuit
- R_{I2}=R_{I3}=1 kΩ so that $V_{oI} = \frac{V_{ref}}{2}$ when $i = 0$ A
- When input current i_+ is negligible:

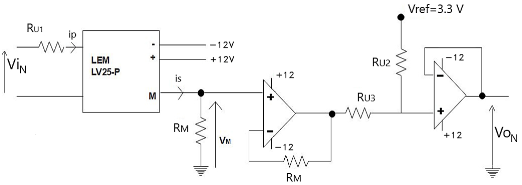
$$\frac{V_B - V_{oI}}{R_{I3}} + \frac{V_{ref} - V_{oI}}{R_{I2}} \approx 0A$$

$$V_{oI} = \frac{R_{I3}}{R_{I2} + R_{I3}} V_{ref} + \frac{R_{I2}}{R_{I2} + R_{I3}} \left(1 + \frac{R_{I1}}{R_{I4}}\right) s\, i$$

- When $V_{oI} = 3.3$ V, i_{max}=35.67 A peak value $\Rightarrow P_{max} = 230\, i_{max}/\sqrt{2} \approx 5802$ W
- Current granularity: $q_I = \frac{q_V}{s} \frac{1+R_{I3}/R_{I2}}{1+R_{I1}/R_{I4}} \approx 69$ mA

  $\Rightarrow$ Active power granularity: $q_P = \frac{q_I}{\sqrt{2}} 230 \approx 11.3$ W

Voltage conditioning circuit

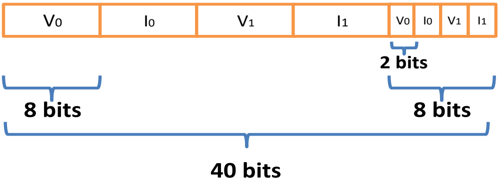


- LEM LV 25-P voltage sensor with a conversion ratio of 2.5
- Input voltage max: $V_{\mathrm{iNmax}} = 230\sqrt{2}$ V,
  Maximum primary current $\mathrm{i_{p\ max}} = 10$ mA
  $\Rightarrow R_{U1} = \frac{\mathrm{V_{ue\ max}}}{\mathrm{i_{p\ max}}} \approx 32.5$ kΩ
  $\approx$ 3 resitors in parallel of 100 kΩ
- $\mathrm{V_M} = 2.5 \frac{\mathrm{R_M}}{\mathrm{R_{U1}}} \mathrm{V_{iN}}$

- A resistive voltage divider and 2 opamp voltage follower circuits
- $\mathrm{R_{U2}} = \mathrm{R_{U3}} = 1$ kΩ so that $\mathrm{V_{oN}} = \frac{\mathrm{V_{ref}}}{2}$ when $\mathrm{V_{iN}} = 0$ V
- Voltage output:
  $\mathrm{V_{us}} = \frac{\mathrm{R_{U3}}}{\mathrm{R_{U3}+R_{U2}}} \mathrm{V_{ref}} + \frac{2.5\mathrm{R_{U2}R_M}}{\mathrm{R_M(R_{U3}+R_{U2})}} \mathrm{V_{iN}}$
- With $\mathrm{R_M} = 130\ \Omega$, $\mathrm{V_{us}} = 3.11$V

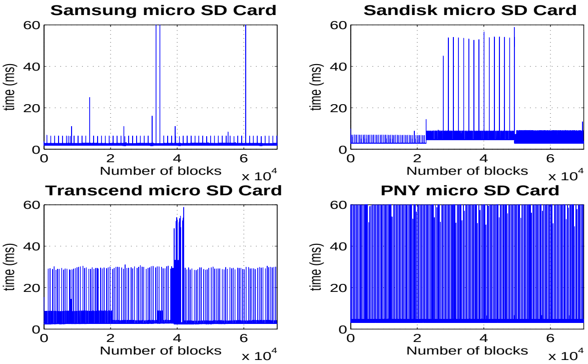
ADC, data sampling and storage

- Use of an Arduino MKR Zero microcontroller (32 bit processor SAMD21 Cortex-M0 microcontroller, 48 MHz) including ADC channels with 8/10/12 bit resolution + RTC module + micro SD card shield
- Use of two libraries to decrease the writing time into th SD card:
  - “FastADC.h” for ADC management (compatible with a 10-bit resolution)
  - “SAMDtimer.h” for timer-triggered interrupts
  - “Sd2Fat.h” for writing into the SD card
- Sampling frequency F_s=6.25 kHz
- Acquisition of voltage and current when the interrupt service is triggered by the 16-bit timer
- Use of 5 bytes to store 2 successive voltage samples (U_0 et U_1) and 2 successive current samples (I_0 et I_1)
- The SD card is used as an EEPROM composed of 512-byte blocks
- Writing into the SD card using the function *cardwriteBlock()*



SD card choice

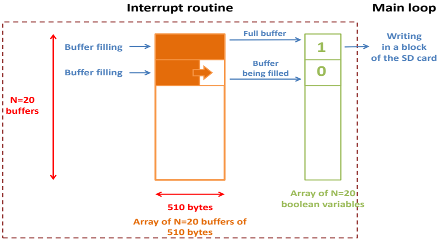
- Comparison of several SD card performances in terms of required time for successively writting 510 bytes into the SD card using the function *cardwriteblock()*



⇒ The 32 Go UHSI speed class Samsung EVO Plus SD card has the best performances. Writing speed of 20 MB/s and lifetime of 10 000 writing cycles.

CAN, échantillonnage et stockage des données

- Use of an array A_{Buffer} of N=20 buffers of 510 bytes
- One buffer can store 510×2/5=204 voltage samples and 204 current samples
- Buffers are filled one by one
- Use of an array A_{Bool} of N=20 boolean variables
- A boolean variable is set to 1 when a buffer is full, otherwise 0
- Signalization to the program main loop that the full buffer must be stored in the SD card
    - Required time to fill a buffer: 204/6250≈ 32.6 ms
    - Average writting time in a block of the SD card ≈ 4 ms ⇒ $F_{s_{max}} = \frac{204}{4.10^{-3}} = 51$ kHz



ADC, data sampling and storage

- Data acquisition during: $\frac{204 \times 32.2^{30}}{6250 \times 512}$ s $\approx$ 25.4 days (50 days using a 64 Go SD card)
- Use of the first block of the SD card to specify: the total number of acquisitions, the number of the first completed block, the date and time
- Use of two push buttons:
  - Start/stop an acquisition
  - Start/stop the transmission of the recorded data on the SD card to a PC via the USB connection cable
- Possibility to select the line or lines the user wants to transmit

Acquisitions made

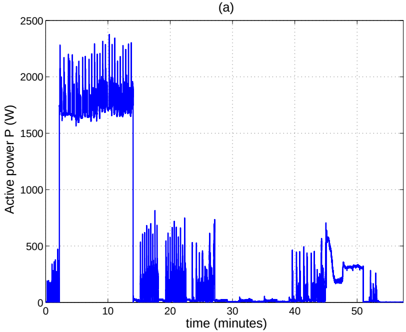
- Measure of individual HEAs' current and voltage
- Measure of a complete dwelling current and voltage
- Power consumption profile set up

$$P[n] = \frac{1}{M} \sum_{k=n-M+1}^{n} v[k]i[k]$$

$M = F_e/F = \frac{6250}{50} = 125$: number of samples per period,
$F = 50$ Hz: utility frequency

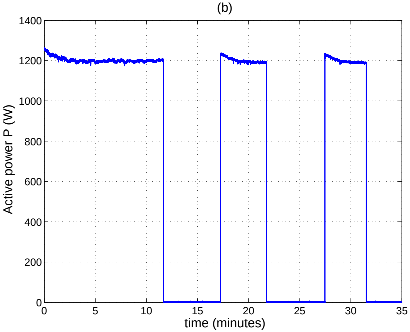
Measure of individual HEAs' current and voltage 1/2

- Washing machine power consummption profile
  - 30 °C, "Rapid" mode, spin of 800 cycles per minute
  - water heating, rinse and spinning.



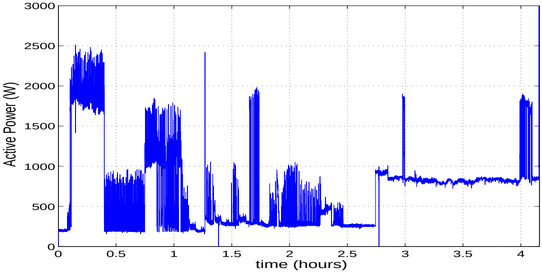
Measure of individual HEAs 'current and voltage 2/2

- Power consumption profile of an electric oven
  - 250 °C , on/off control
  - Heating phase



Measure of a house current and voltage

- 24h power consumption profile of a complete dwelling (4h extract):
  operation of a washing machine during 2h 30,
  activation of a LCD TV followed by an electrical oven
- constant power consumption of almost 250 W (baseload):
  two continuously operating wifi boxes
  standby power consumption of five cell phone chargers plugged in



Conclusion

- Design of a house electricity consumption measurement system
- Low cost acquisition system with:
  - -a dedicated **power supply**
  - -an **easy installation**,
  - -a sampling frequency of **6.25 kHz**,
  - -a storage capacity that allows **data acquisition during 25 days**.
- Use of an**Arduino MKR Zero** microcontroller (integrating a RTC and a micro SD card shield) in plus of **voltage and current sensing and conditioning stages**
- **Lossless compression system** for more storage into the SD card

Prospectives

- WLAN communication with a server
- Sampling frequency increase
  (**Dilemma**: $\nearrow \mathrm{F_s}$: $\searrow$ duration of acquisition)
- Resolution increase
- Packaging improvement
- Evaluation of the compression system
  (compression rate/computational complexity)
- Real-time energy management

Thank you for your attention.