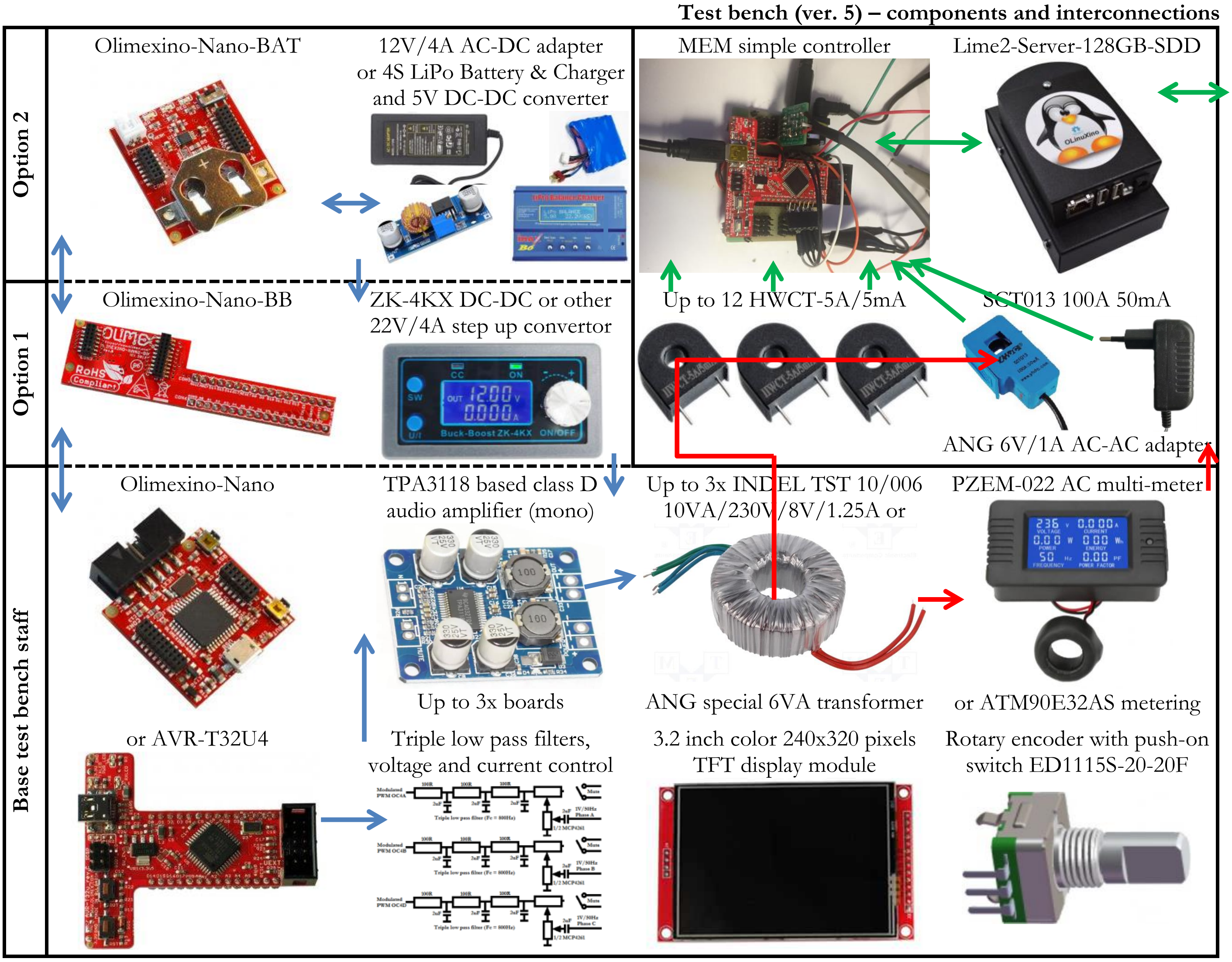
MEM system test bench – 5th version planning and development

After measuring of some transformers parameters and waiting for a special ANG transformer production the test bench software was extended in following directions. PWM outputs of timer 4 were increased to 3x for implementing of 3-phase voltage and current source. In case of using it as a single phase 2x PWM outputs were used for separate voltage and current generating with controllable phase difference in the range [-π, +π]. In 3-phase variant voltage and current for each phase will be generated by a single transformer without phase difference between them. The user interface was added and tested with rotary encoder with push-on switch ED1115S-20-20F (Code for Rotary Encoder with interrupts), 16x2 character LCD with I²C interface (LiquidCrystal I2C library for Arduino) and 3.2" 240x320 pixels TFT display with SPI interface. In case of TFT display Arduino Ucglib color graphics library was used for low memory footprint. For better level control of voltages and currents digital potentiometer of Microchip MCP4261 was added and Arduino library available from https://github.com/dreamcat4/Mcp4261 was used. After all above staff the sketch uses 92% flash and 34% RAM of Atmega32u4 memories resources and some of them will be freed after application optimization.

Test bench (ver. 5) – components and interconnections



It is planned none monolithic design in the latest test bench (ver. 5). MCU controller staff and power supply components will be mounted in a single plastic box produced by 3D printing. Transformers and probably audio amplifiers will be mounted in separate adapter like plastic boxes. All transformers will be identical with 6V (6VA w-shaped) or 8V (10VA toroidal) primary and 230V secondary coils and a special single turn current coil. Current coil load will be a copper wire with tunable length for producing currents up to 20A. In such a design the tester could be used as a single or three-phase voltage and current source with up to 3 transformer units. In case of single phase usage with at least 2 transformer units phase difference between voltage and current could be controlled.

The embedded software can be used in both single and three phase variants with 1, 2 or 3 transformer units. If test bench is used as single phase with 1 transformer unit or three-phase with 3 transformer units, phase difference between voltage and current could not be controlled. The only scenario to control phase difference between voltage and current is to use the test bench as a single phase source with at least 2 transformer units. In such a case phase A will be used as voltage source and phase B as current one.

It is planned in future if have enough memory resources in Atmega32u4 AC multi-meter to be replaced by built-in metering part based on Microchip's ATM90E32AS IC. In such a case voltage transformers will be replaced by resistive dividers. Other possible feature could be added is serial connection to tested MEM system for sending data and command for calibration.

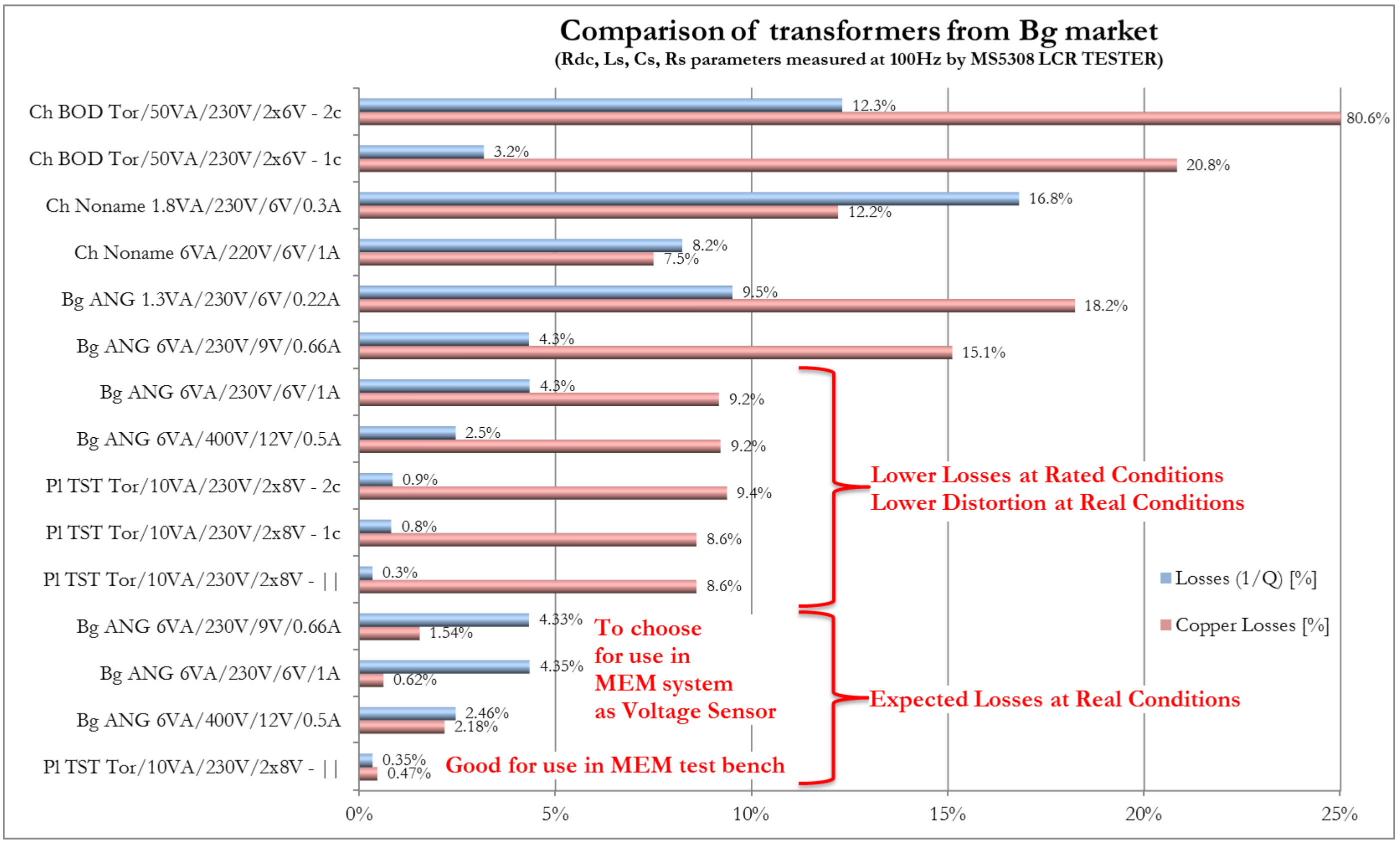
MEM system test bench – 5th version planning and development

While trying to finish 3rd test bench version (putting it in a box) a number of new problems were found (mainly amplifier excitation because of noise coming from the potentiometer). The idea to replace it with a digital one was considered and extended with the idea to add secondary even third simulation channel. In such a way the voltage and current can be simulated separately and it will be possible to implement a phase difference between both. It will also be possible in case of 3 channels to simulate 3-phase mains. The software was successfully modified and 16x2 character LCD and rotary encoder were added for parameters setup. While adding the second channel for separate current simulation Mastech MS5308 LCR tester was found and some transformers offered on Bg market was measured and compared. The difference in measured and calculated Q is not investigated. The results are shown on the next table.

Parameters of transformers from Bg market (R_{DC}, L_S, C_S and R_S parameters measured at 100Hz by MS5308 LCR tester)

	Pl TST Tor/10VA/230V/2x8V - ||	Bg ANG 6VA/400V/12V/0.5A	Bg ANG 6VA/230V/6V/1A	Bg ANG 6VA/230V/9V/0.66A	Pl TST Tor/10VA/230V/2x8V - ||	Pl TST Tor/10VA/230V/2x8V - 1c	Pl TST Tor/10VA/230V/2x8V - 2c	Bg ANG 6VA/400V/12V/0.5A	Bg ANG 6VA/230V/6V/1A	Bg ANG 6VA/230V/9V/0.66A	Bg ANG 1.3VA/230V/6V/0.22A	Ch Noname 6VA/220V/6V/1A	Ch Noname 1.8VA/230V/6V/0.3A	Ch BOD Tor/50VA/230V/2x6V - 1c	Ch BOD Tor/50VA/230V/2x6V - 2c	
DCR	0.55	2.21	0.55	2.04	0.55	1.10	1.20	2.21	0.55	2.04	5.05	0.45	2.44	0.30	1.16	Ohm
Ls	253.20	142.90	20.14	75.00	253.20	213.50	222.90	142.90	20.14	75.00	84.50	8.70	23.10	15.00	15.00	mH
Q	0.94	3.95	5.35	5.60	0.94	1.04	1.04	3.95	5.35	5.60	2.90	5.17	3.94	2.10	1.77	
Cs	9.99	17.40	125.80	33.78	9.99	11.90	11.34	17.40	125.80	33.78	29.41	291.00	109.50	170.00	169.60	uF
D	1.06	0.26	0.19	0.18	1.06	0.96	0.96	0.26	0.19	0.18	0.35	0.19	0.25	0.48	0.57	
Rs	169.34	22.70	2.31	8.38	169.34	128.60	134.30	22.70	2.31	8.38	18.31	1.05	3.70	4.46	5.34	Ohm
Rp	318.40	377.60	71.65	272.80	318.40	268.80	281.00	377.60	71.65	272.80	172.80	29.35	60.60	24.04	21.68	Ohm
XL, Q, F, Z calculation at 100Hz																
XL	159.09	89.79	12.65	47.12	159.09	134.15	140.05	89.79	12.65	47.12	53.09	5.47	14.51	9.42	9.42	Ohm
Q	289.26	40.63	23.01	23.10	289.26	121.95	116.71	40.63	23.01	23.10	10.51	12.15	5.95	31.42	8.12	
Freq	100.09	100.93	99.99	99.99	100.09	99.85	100.11	100.93	99.99	99.99	100.96	100.03	100.07	99.67	99.78	Hz
Z	159.09	89.81	12.67	47.17	159.09	134.15	140.06	89.81	12.67	47.17	53.33	5.48	14.72	9.43	9.50	Ohm
Losses calculation																
VA	0.544	0.469	0.408	0.612	10.00	5.00	5.00	6.00	6.00	6.00	1.30	6.00	1.80	25.00	25.00	VA
Vsec	8.00	6.90	6.00	9.00	8.00	8.00	8.00	12.00	6.00	9.00	6.00	6.00	6.00	6.00	6.00	Vrms
Irms	0.0680	0.0680	0.0680	0.0680	1.25	0.63	0.63	0.50	1.00	0.67	0.22	1.00	0.30	4.17	4.17	Arms
Pv[VA]	0.0025	0.0102	0.0025	0.01	0.86	0.43	0.47	0.55	0.55	0.91	0.24	0.45	0.22	5.21	20.14	VA
Pv[%]	0.47%	2.18%	0.62%	1.54%	8.59%	8.59%	9.38%	9.21%	9.17%	15.11%	18.24%	7.50%	12.20%	20.83%	80.56%	%
1/Q[%}	0.35%	2.46%	4.35%	4.33%	0.35%	0.82%	0.86%	2.46%	4.35%	4.33%	9.51%	8.23%	16.81%	3.18%	12.31%	%

The big difference for BOD coils was not investigated. The red colored columns present the extrapolated computations to real use case in MEM system test bench where the power and current are away from the rated. Comparison is shown on the next chart.



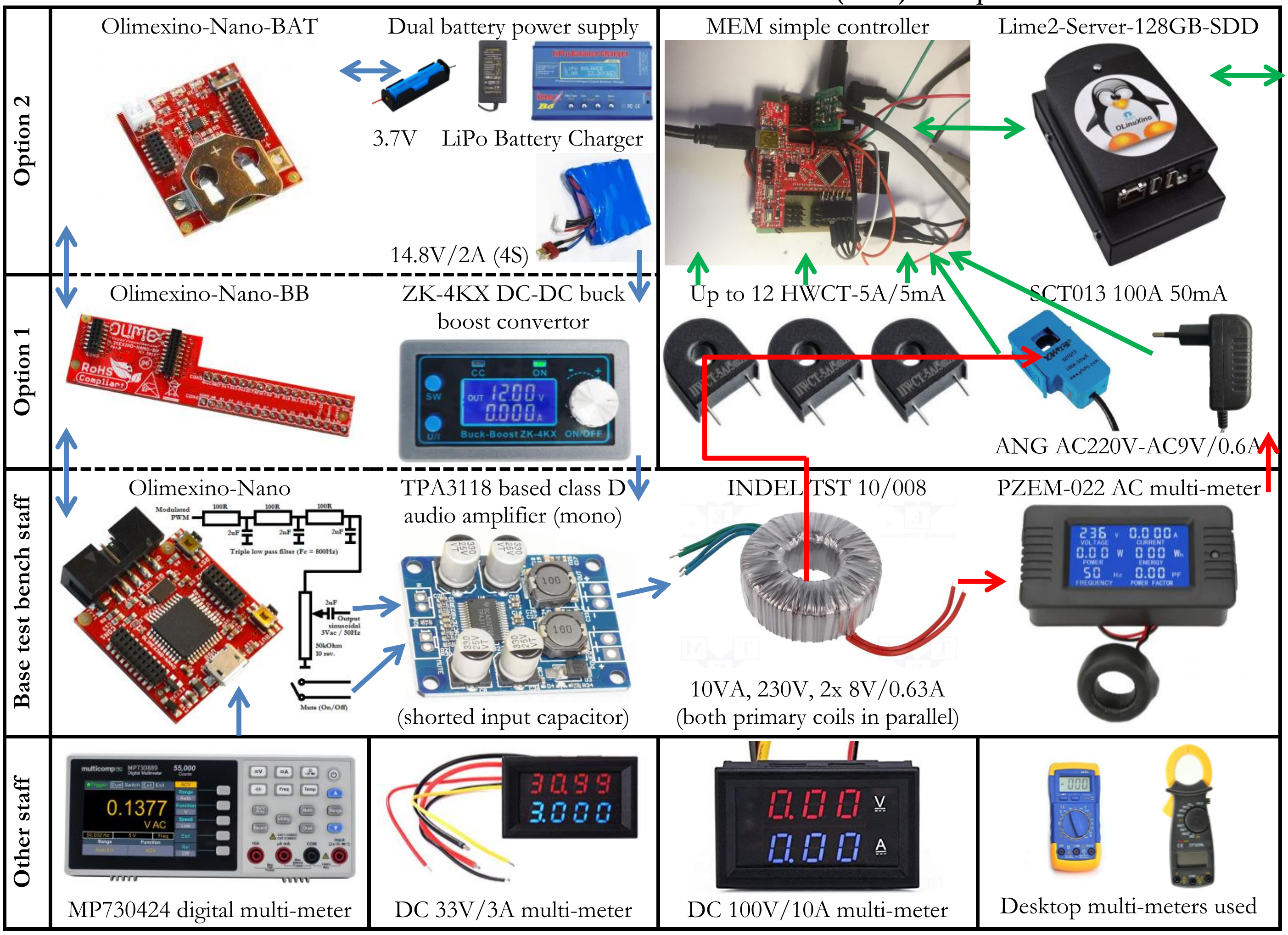
The conclusion is that the transformer TST 10/006 (toroidal, 10VA, 230Vac on a primary and 8Vac/0.63Aac on any of both secondary coils) produced by Polish company INDEL has the lowest losses but is relatively expensive. The transformers were tested in real conditions in which the secondary coil(s) are connected as a load to the 60W class D mono audio amplifier lased on TPA3118 IC. In case of TST 10/006 both secondary coils was connected in parallel because their parameters are very close to each other.

The result of the tests is that the transformer TST 10/006 has the smallest distortion of the waveform for voltages higher than 240Vac on a primary coil and is the best candidate for usage in both voltage and current simulation channels of the test bench. Three of the transformers produced by Bulgarian company ANG are good candidates for usage as voltage sensor in MEM system. Till now ANG transformer 6VA/230V/9V/0.66A was used in tests of MEM system prototype and the observation is that the distortions of the waveform for voltages higher than 240Vac are relatively small. It could be replaced without any problems by ANG transformer 6VA/230V/9V/0.66A but adapters with 6VA/400V/12V/0.5A have to be ordered as a special product and the advantages must be assessed carefully especially if the price is bigger.

MEM system and test bench – precision assessment

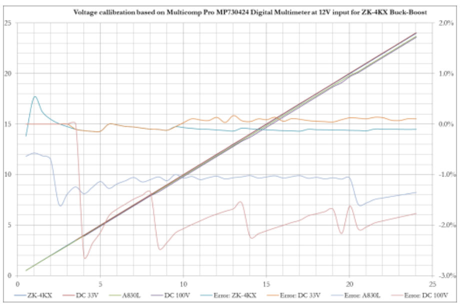
Before precision assessment some changes were made in test bench. DC-DC convertor was changed to ZK-4KX DC-DC buck boost one with precise tuning and measurement features. Peacefiare's PZEM 022 AC digital multi-meter was added for precise measurement of mains simulation (voltage, frequency, current, power and power factor). The other change is in current coil. The wire was changed with magnet wire with 3.15mm diameter and part of its length was planned for current tuning. For nonfunctional part of the current coil is used 10mm² wire. All test bench staff is planned to be mounted on two aluminum or plastic panels.

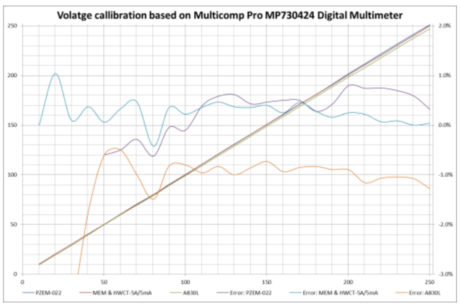
Test bench (ver. 4) – components and interconnections

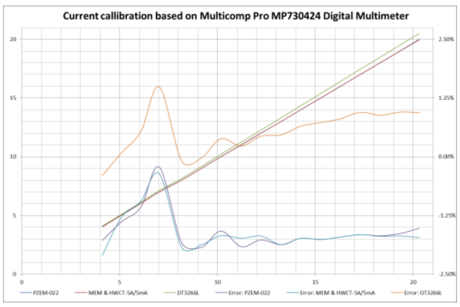


In addition to above changes it was planned to add AC measurement staff to the Olimexino-Nano firmware based on original emonLibCM library, LCD display, additional coil to the toroidal transformer (for voltage measurement) and precise LEM LTS 15-NP current transducer. In the final test bench version 4 this entire staff will substitute functionality of PZEM-022 AC multi-meter.

It was tested some calibration procedures based on class 1 Multicomp Pro MP730424 digital multi-meter. It is able to measure AC voltages precisely but the current measurement is up to 10Aac and requires high voltage. That is why the current measurement was done by using LTS 15-NP current transducer for 15A nominal AC/DC current, 0.2% accuracy and 0.1% linearity. In addition to the test bench output voltages and currents ZK-4KX convertor parameters were also measured together with some DC digital multi-meters and used desktop units A830L and DT3266L. The preliminary results are shown on pictures below.





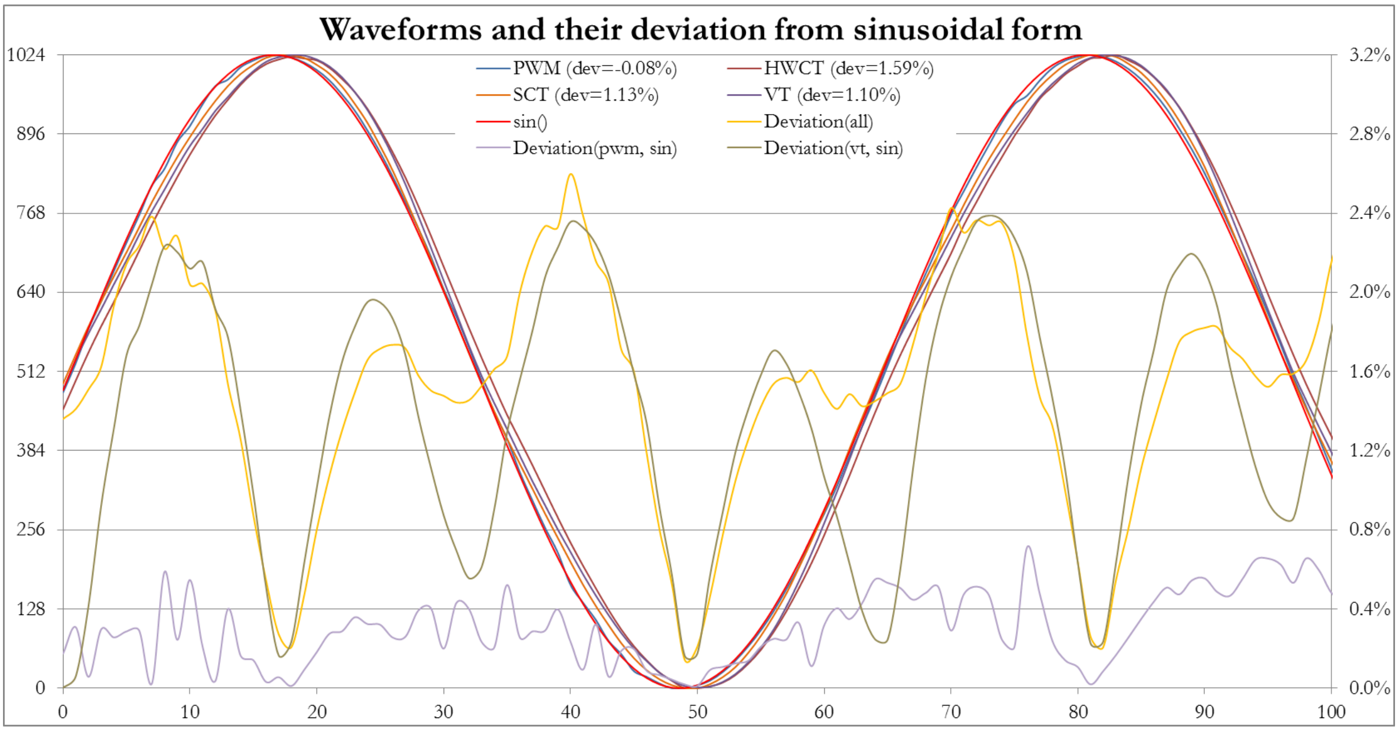


Interesting in the above measurement is that ZK-4KX convertor and DC 33V/3A panel digital multi-meter are precise in almost all range. ZK-4KX has good setup and tuning features as well. Unfortunately, PZEM-022 AC multi-meter is not precise enough so its substitution with Olimexino-Nano firmware based measurement is highly recommended.

The main conclusion from this phase is that for the final test bench and MEM system calibration other more precise and appropriate multi-meter like Megger's DCM2000P power clamp meter should be used. It is recommendable in addition to the mains true RMS parameters to measure total harmonics distortion, power, crest and distortion factors and other helpful once.

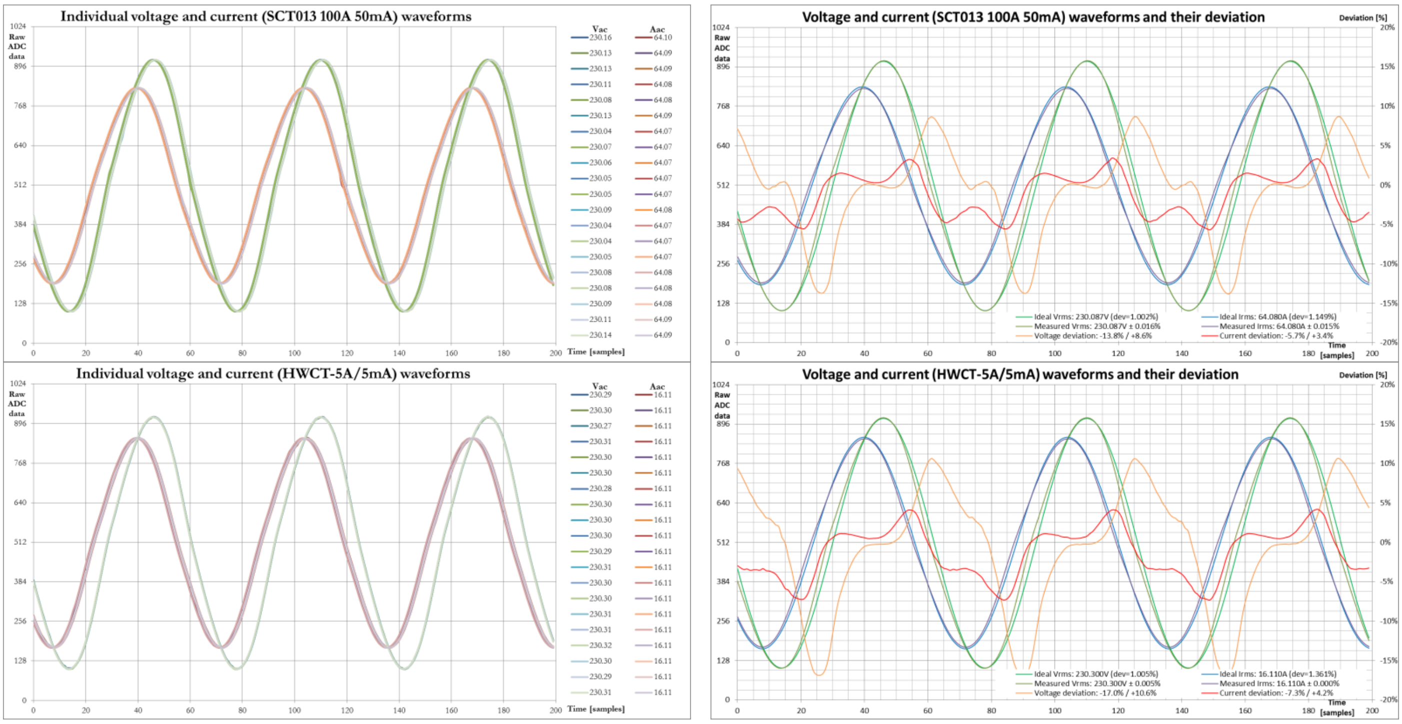
MEM system – voltage / current sensing and waveform distortion assessment

This assessment was accomplished with the help of MEM system and its test bench (ver. 3) with modified emonLibCM library (Version 2.2.2 15/9/2022) including the raw data capturing. Because of memory restriction only captured signals were measured (the voltage and a single current from the tested CT). The captured results from 20 measurement cycles were averaged and compared with the ideal sinusoidal waveform. The assessment was done off-line in Excel 2010 calculating RMS (Root Mean Square), CF (Crest Factor), PP (Peak-to-Peak) and other values. Deviation was calculated for both the waveforms ($dev_i = X_i / S_i - 1$ in %) and the total values ($dev = CF / \sqrt[2]{2} - 1$ in %). The waveforms as normalized raw data and their deviations from the sinusoidal form of the modulated PWM (the test bench generator), the voltage transformer (VT) and the current transformers (SCT013 100A 50mA and HWCT-5A/5mA) are shown on the next figure.



The total voltage and current deviations are in the interval from 1% to 1.6% while the generator's one (modulated PWM) is 0.08%. The relatively big dispersion of the signals is mainly caused by the discretization.

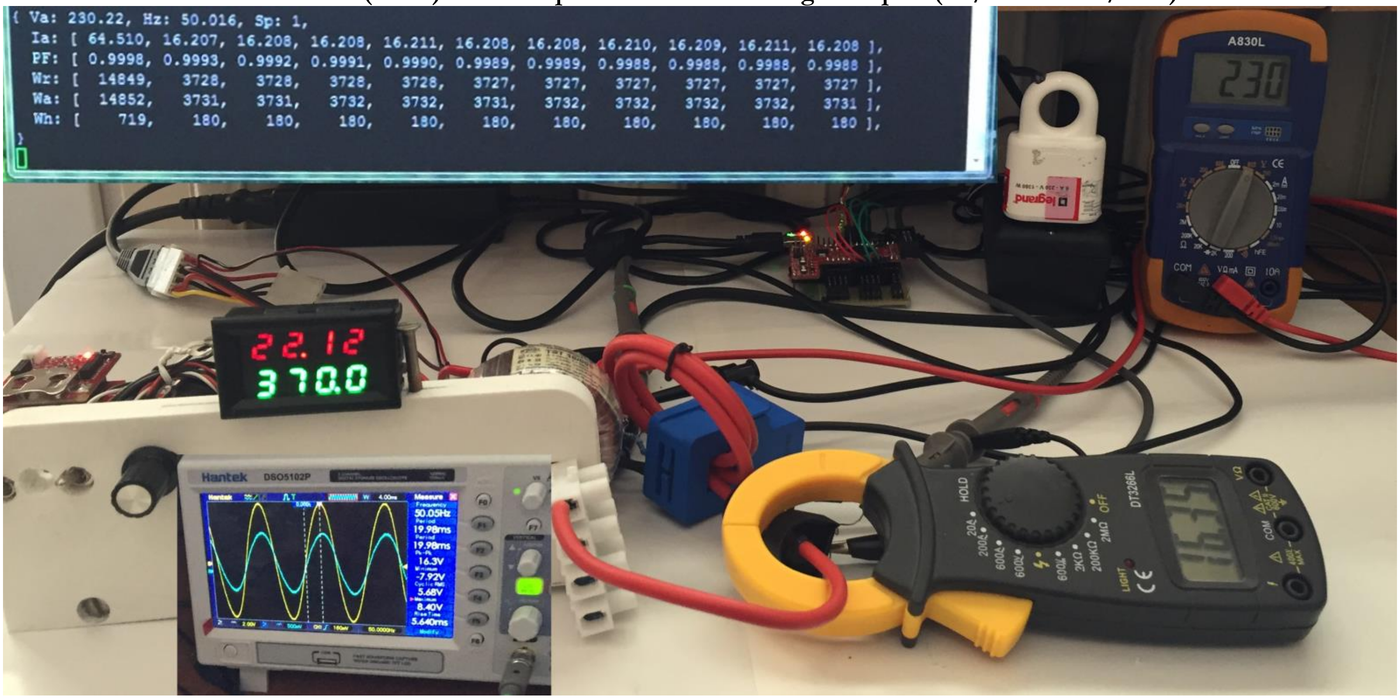
The individual and the averaged waveforms of the voltage and the currents for both SCT013 100A 50mA and HWCT-5A/5mA sensors are shown on the next figures.



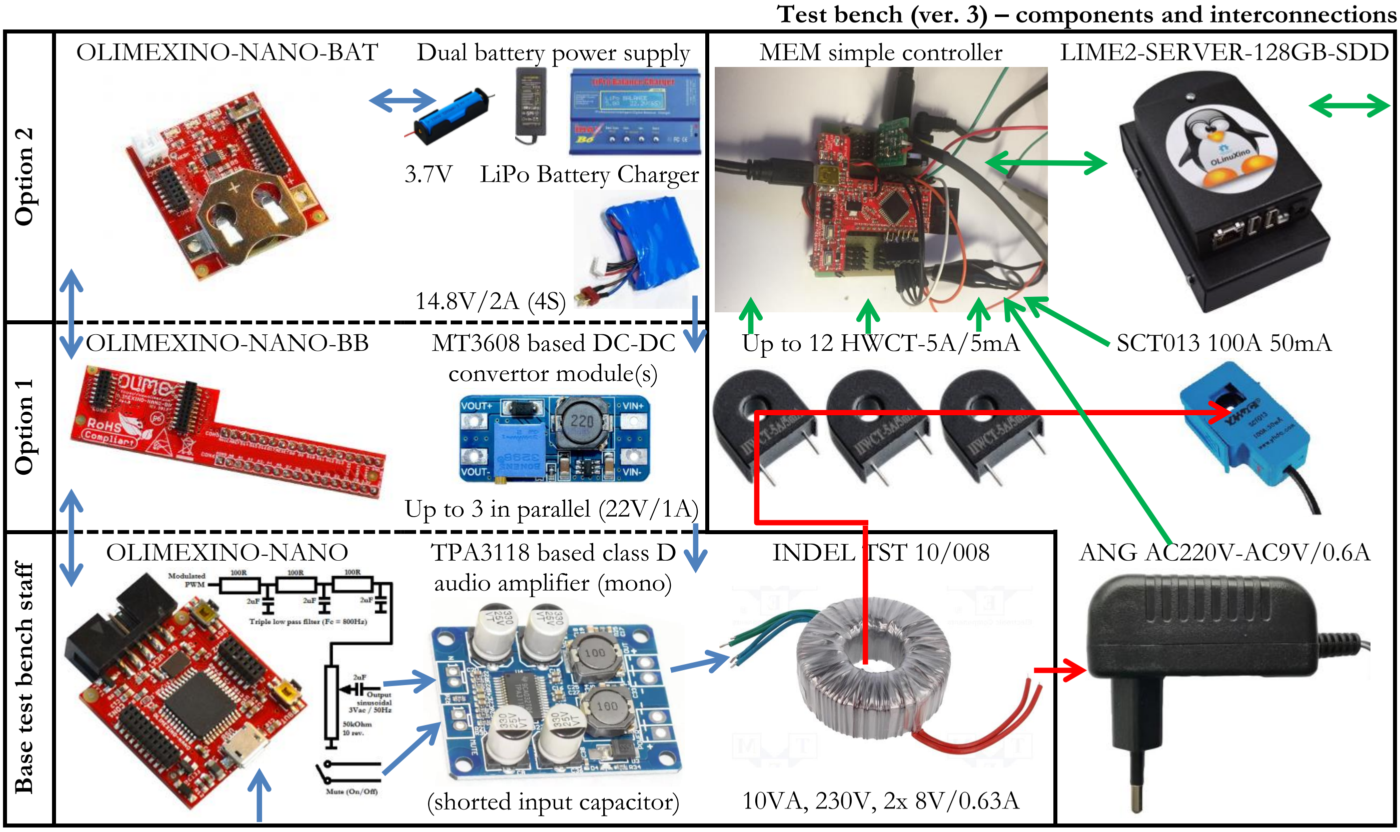
In addition to the waveform graphs calculated total RMS values and their deviations are shown. As it can be seen the latest version of the test bench grants extremely stable values for both the voltage and the currents (0.016% and less). Without matter that waveform deviations from sinusoidal form are relatively big (up to 17% at given individual points) the total deviations of the voltage and the currents are less than 1.15%.

MEM system – test scenario 3rd version final implementation

Test bench (ver. 3) – final implementation with single adapter (5V/1.5A + 12V/1.5A) instead of batteries



Test bench (ver. 3) – components and interconnections



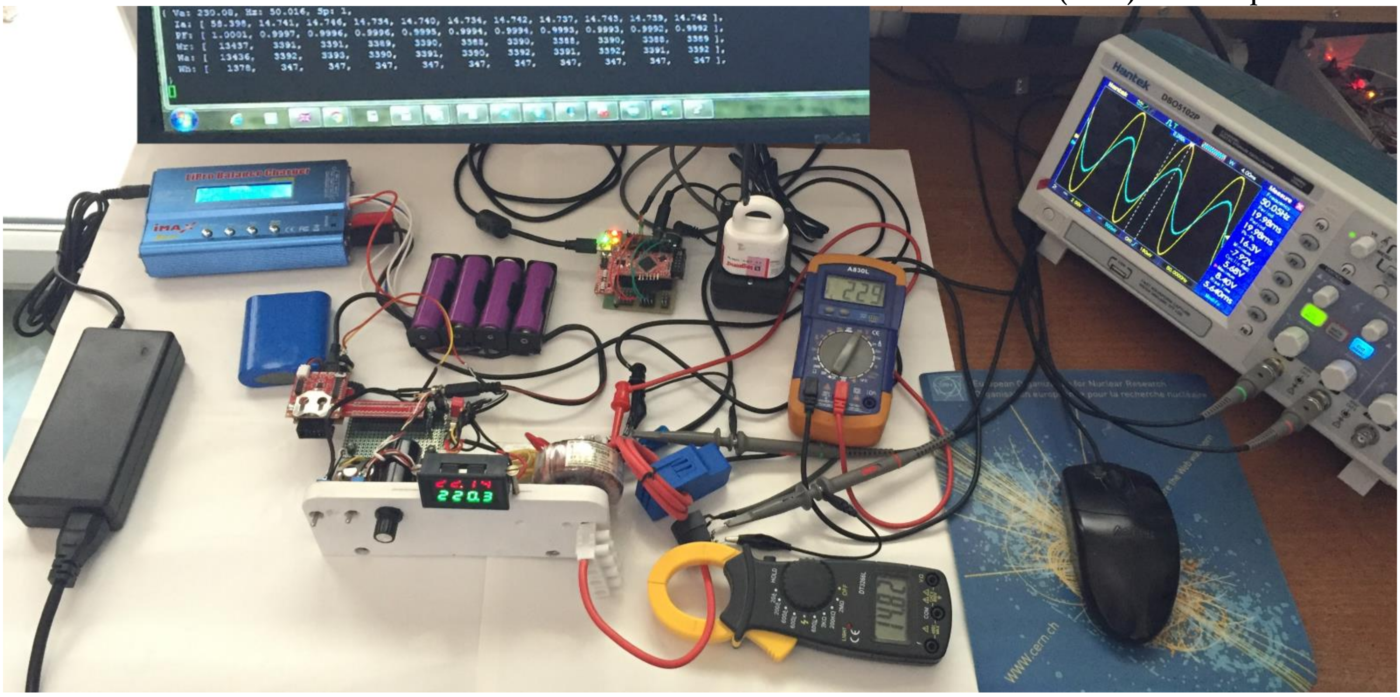
Notes about options of the final implementation:

- Dual battery supply is optional and can be replaced by external USB power supply for Olimexino-Nano and 12-15V/2A external power supply for DC-DC module(s);
- It also possible to replace the DC-DC module(s) with 20-24V/1A external power supply for the audio amplifier;
- The other option is to use dual voltage power supply (5V/1.5A & 12V/1.5A) instead of separate ones;
- The cheapest option is to use dual voltage power supply (5V/1.5A & 24V/1.5A) without DC-DC convertor.

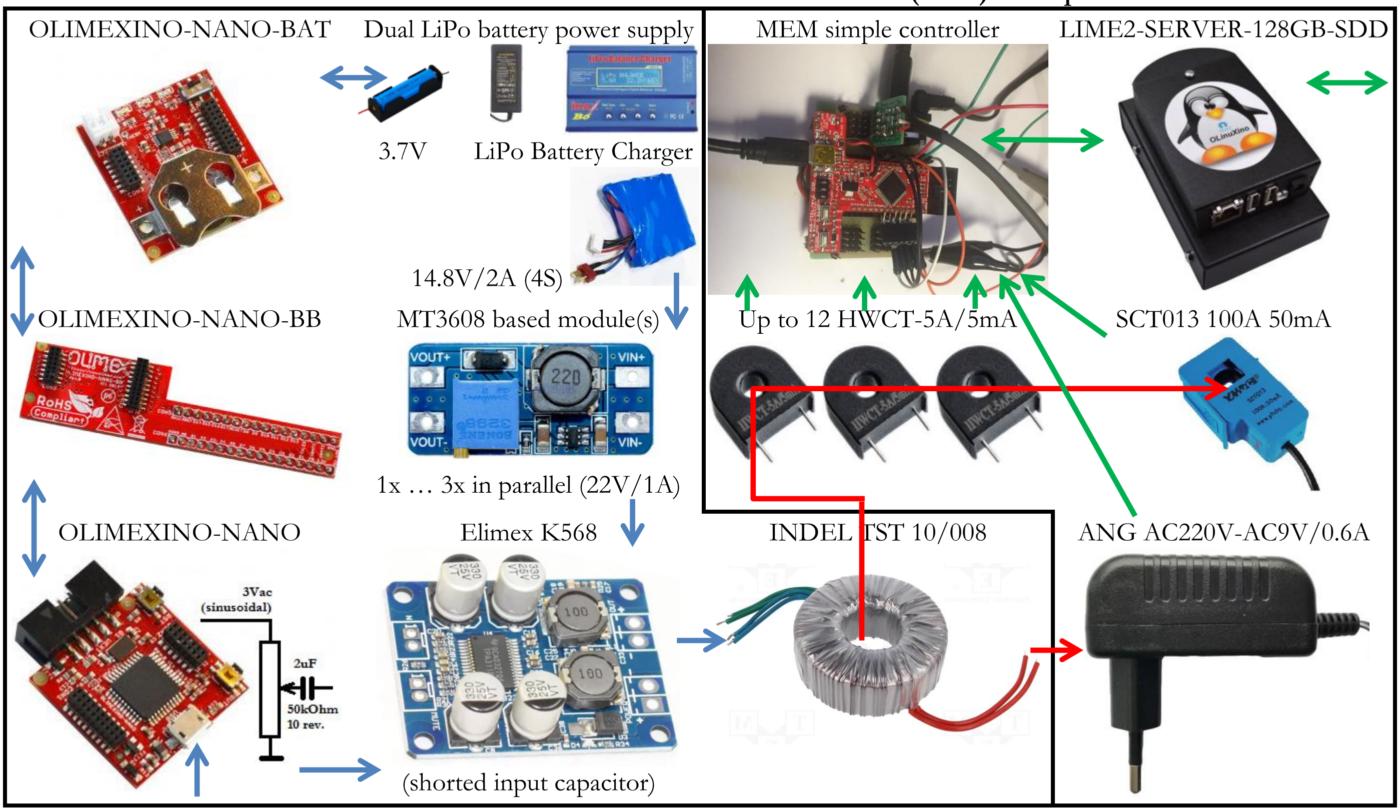
In case of single power supply special attention has to be paid to the common ground to prevent the influence of the high starting current of the audio amplifier on the MCU. The main 12V supply and the common GND should be connected to the DC-DC convertor. Voltage and current measurement device can also be connected between the power supply and the other boards. The output 22V of the DC-DC convertor and its GND should be connected to the audio amplifier. The common GND of the audio amplifier boards should be connected to the MCU board together with its output sinusoidal signal. Only the 5V of the power supply must be connected to the MCU board while the common GND will be taken via the audio amplifier board.

MEM system – test scenario 3rd version final implementation

Test bench (ver. 3) – final implementation



Test bench (ver. 3) – components and interconnections



Notes for final implementation:

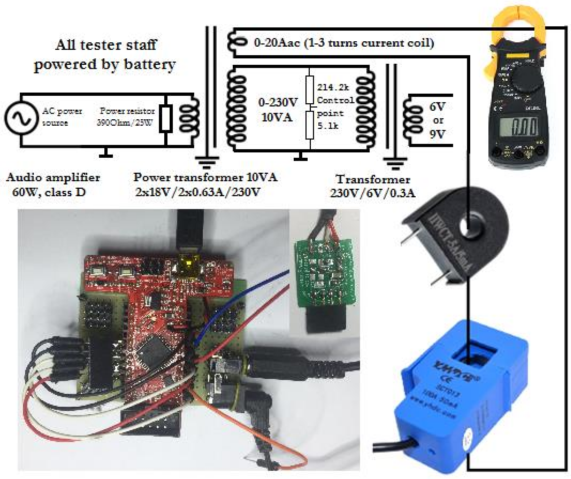
- Dual battery supply is used for separate powering of both Olimexino-Nano and audio amplifier;
- 4x 18650 LiPo batteries connected as 4S pack is provided with intermediate wires for balance charging with Imax B6 charger;
- BB-PWR-3608 is replaced with up to 3x connected in parallel MT3608 based modules with fine tuning of the output voltage;
- Using bigger power supply for the audio amplifier is required for avoiding signal distortion and reaching 250Vac values;
- Multi-turn potentiometer is used instead of linear one and additional load resistor at the amplifier output was removed;
- Input capacitor of the amplifier is shorted and external one with bigger capacity is added to avoid signal distortion.

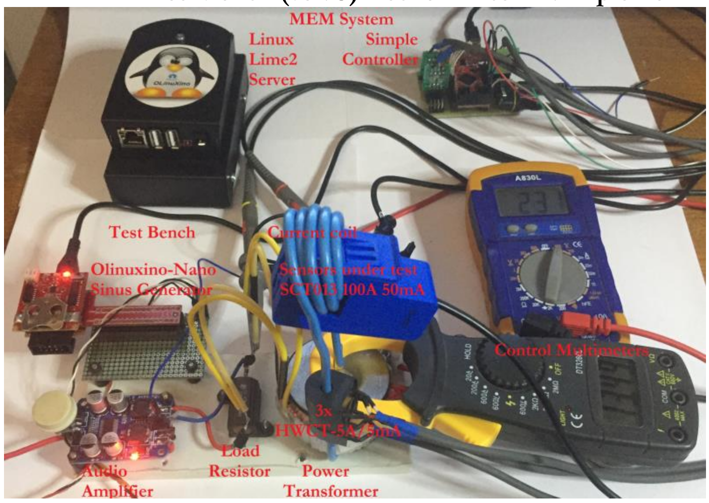
Unfortunately, the shortcut current depends on both wire temperature (require time to stabilize) and number of the strung current sensors (require adjustment by the multi-turn potentiometer or even by the wire length). Testing of both voltage and current sensors can be done separately using different voltage and current values of the transformer secondary coils. Calibration coefficients can be calculated individually by modified software for the controller of the MEM system and stored in nonvolatile memory.

Dual battery supply and DC-DC module(s) are optional and can be replaced by USB power for Olimexino-Nano and 20-24V/1A external power supply for the audio amplifier.

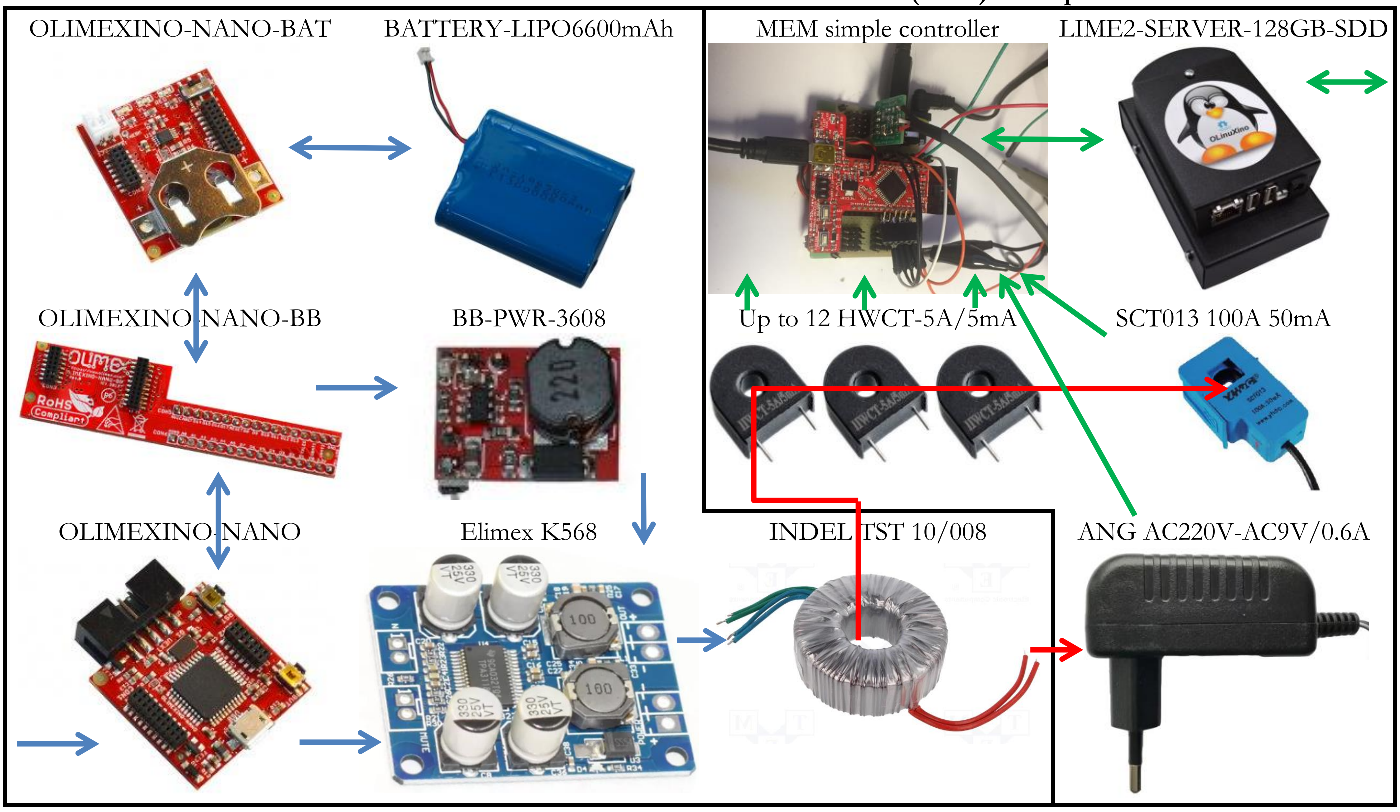
MEM system – test scenario 3rd version implementation

Test bench (ver. 3) – schematics and implementation





Test bench (ver. 3) – components and interconnections

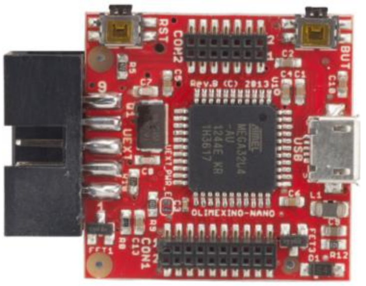


Notes:

- BATTERY-LIPO6600mAh is optional for granting complete isolation of the test bench;
- BB-PWR-3608 can be powered by 5V_USB or optionally by VBAT2 of OLIMEXINO-NANO-BB;
- OLIMEXINO-NANO-BB is stacked with a universal proto-board where low pass filter is mounted;
- Linear potentiometer 10k is mounted at the output of the low pass filter to regulate input voltage of Elimex K568
- Power resistor 390Ohm/25W is mounted in parallel to the primary coil of the transformer;
- Resistive divider with different ratios (43, 230 etc.) is mounted to the terminal block for secondary coil interconnections;
- Resistive divider GND has to be connected to OLIMEXINO-NANO and Elimex K568 GND if oscilloscope is used;
- High voltage of the transformer secondary coil has to be well isolated except the resistive divider GND if connected ;
- Current coil has to be made by a single 4mm^2 wire with isolation and shorted by appropriate terminal block;
- Wire length and turns of the current coil has to be tuned to reach 16A_{AC} at 230V_{AC} on the transformer secondary coil;
- Additional 4-5 turns has to be made from current coil wire outside the transformer for SCT013 100A 50mA sensor;
- Optionally oscilloscope and multimeters like DSO5102P, A830L and DT3266L can be used for monitoring electrical quantities;
- Control equipment with higher precision and individual calibration of the sensors is recommendable if better accuracy is required.

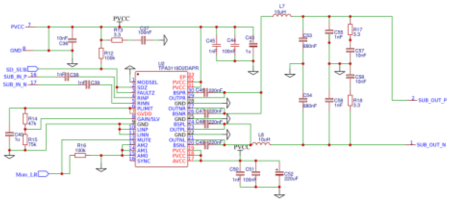
The current coil suffers from some drawbacks. When the current sensors are strung, the current on it decreases. For reaching higher current values, voltage on the amplifier input has to be increased. Unfortunately, the voltage on the secondary transformer coil will also grow up and reaching inadmissible values can damage the voltage sensor and the controller of the MEM system. To prevent any damages voltage sensor can be switched off. The limitation of the voltage and current values is the responsibility of the test bench operator. On the other hand shortcut current will fall down because of heating the wire therefore stabilization has be awaited

Sinusoidal waveform generator 50/60Hz



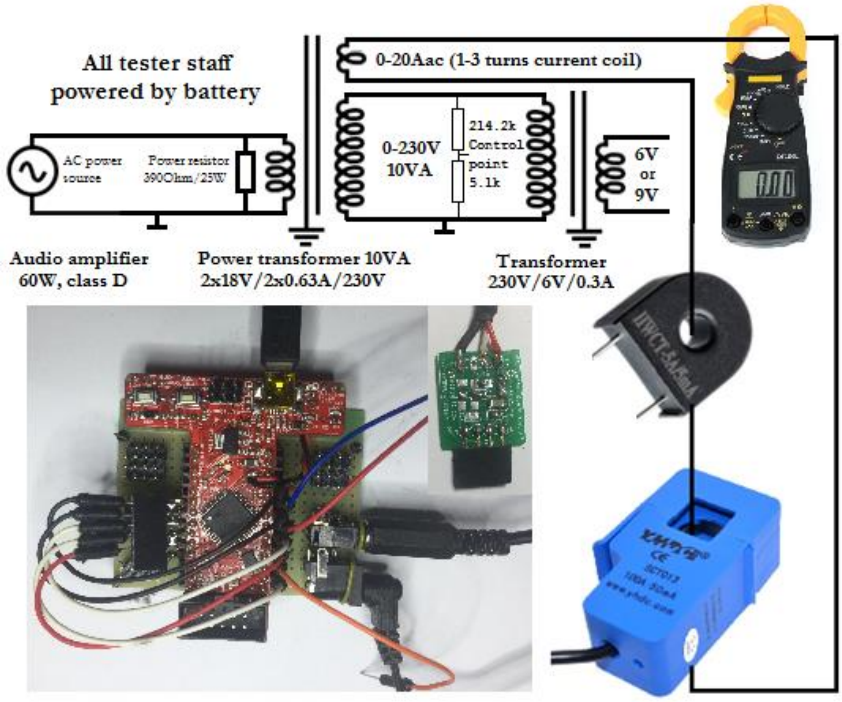
The hardware is based on Olimexino-Nano and includes a triple low-pass filter (F_C 796Hz). The software is based on modified version of FrequencyGenerator ver. 1.00 2-5-21 written by Rick Groome. The waveform is created by 625 points with 9-bit resolution fast PWM on timer4 of ATmega32U4.

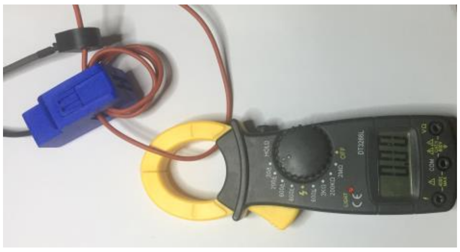
Audio amplifier 24V/60W, class D, mono



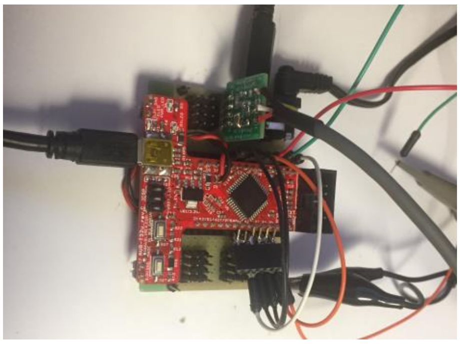
10VA 230V/2x8V/2x0.63A power transformer used as step-up

Voltage sensor under test: W-shaped transformer 1.8VA/230V/6V/0.3A or AC-AC adapter 230V/9V/6VA

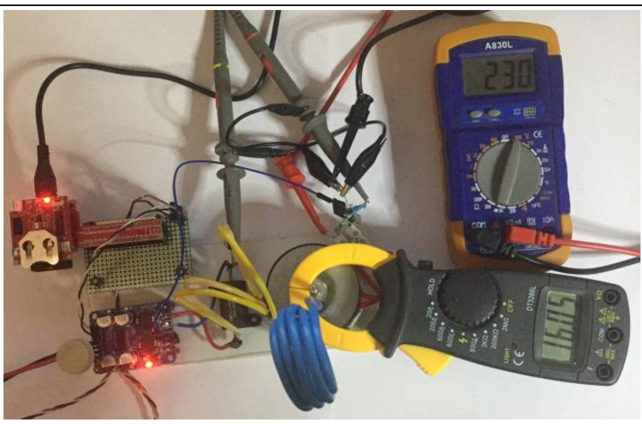




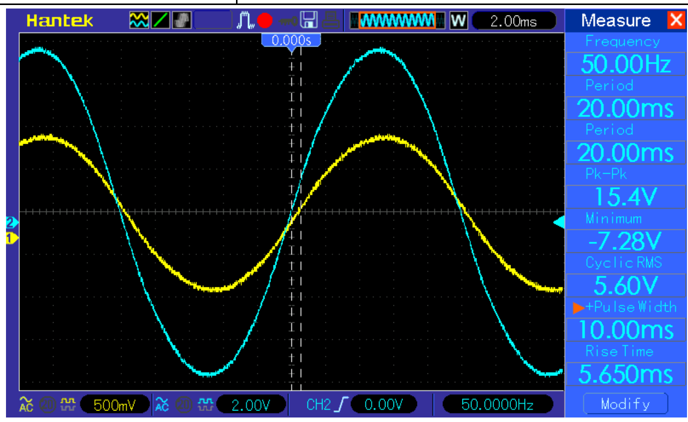
Current sensors under test: SCT013 100A 50mA and HWCT-5A/5mA



MEM system simple alternative single ended variant



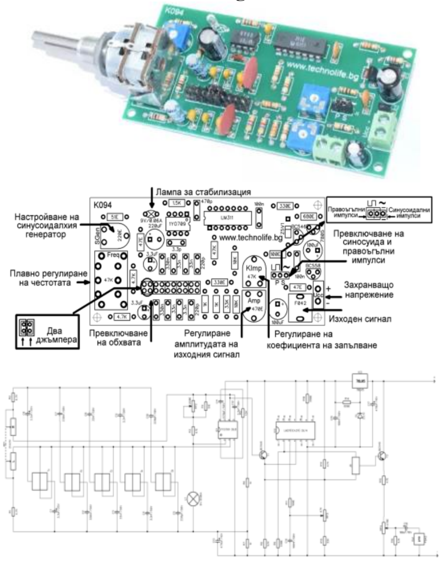
Test scenario ver. 3 – amplifier loaded with power resistor (390Ohm, 25W) and the transformer primary coil



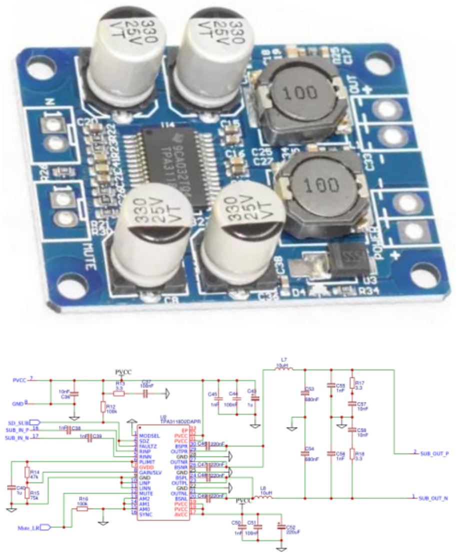
Oscillogram of shortcut current & HWCT & 47Ohm (channel 1, yellow) and output AC voltage divided by 43 (channel 2, blue)

Measured parameters with a triple low-pass filter (Cut-off frequency 796Hz) between the generator and the amplifier: generator frequency 50.00Hz; amplifier input up to $3V_{P-P}$; amplifier output $15.4V_{P-P}$ (on each arm @ $20V_{DC}$ and $1.1V_{P-P}$ input); transformer primary voltage $10.9V_{RMS}$ ($30.8V_{P-P}$); transformer secondary voltage $230V_{RMS}$ ($650V_{P-P}$); shortcut coil current $16.05A_{RMS}$ (3.16mOhm @ 1turn, 74cm 4mm² wire); main consumption 1.1W in idle mode ($0.06A_{DC}$ @ $20V_{DC}$); shortcut coil consumption 0.8 W ($16.05A_{RMS}$ @ 3.16mOhm); load resistor consumption 0.3W ($10.9V_{RMS}$ @ 390Ohm) and total power consumption 2.2W (0.11 A_{DC} @ $20V_{DC}$ or 0.09 A_{DC} @ $24V_{DC}$). Total power consumption is 3.0W (0.15 A_{DC} @ $20V_{DC}$) when MEM system voltage transformer is switched on.

Sinusoidal waveform generator 50/60Hz

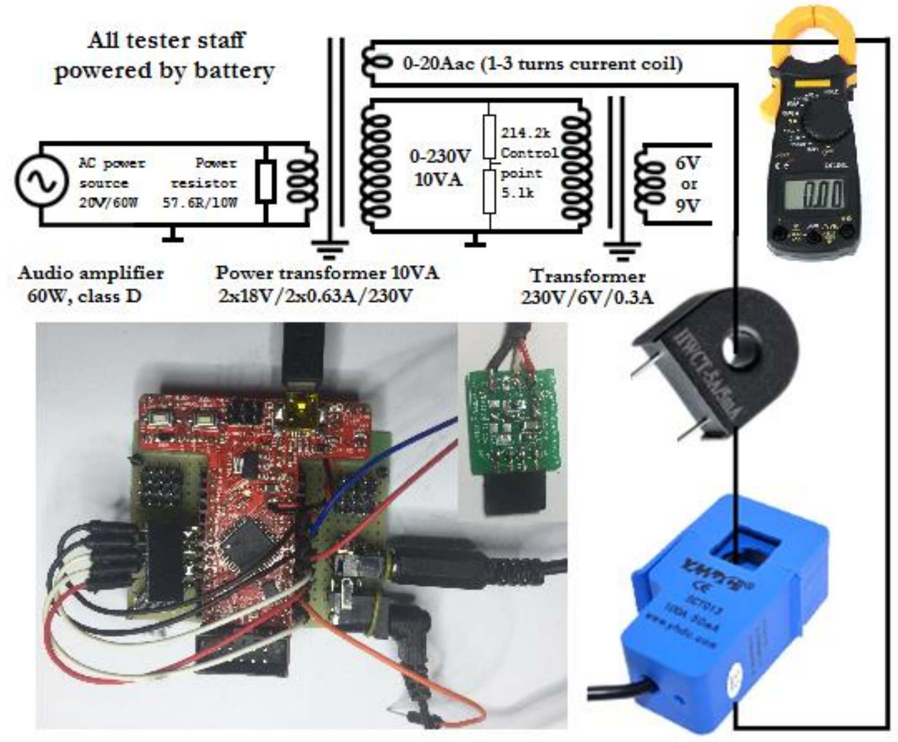


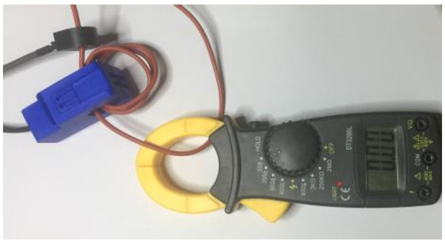
Audio amplifier 60W, class D, mono



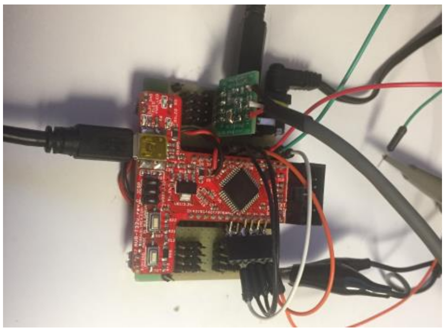
10VA 230V/2x8V/2x0.63A power transformer used as step-up

Voltage sensor under test: W-shaped transformer 1.8VA/230V/6V/0.3A or AC-AC adapter 230V/9V/6VA

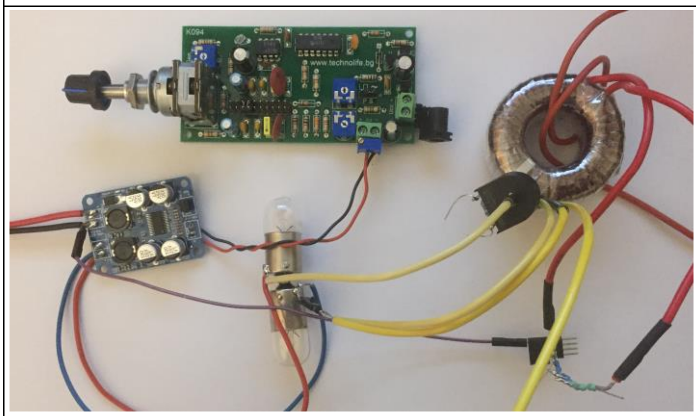




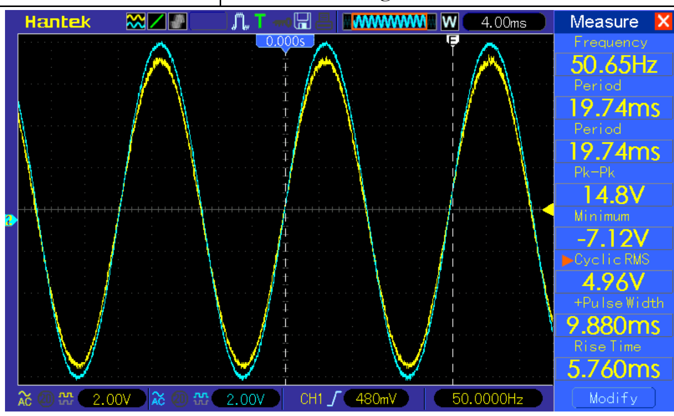
Current sensors under test: SCT013 100A 50mA and HWCT-5A/5mA



MEM system simple alternative single ended variant



Test scenario ver. 2 – amplifier loaded with 2 lamps (5W@12Vdc) in serial and the transformer primary coil



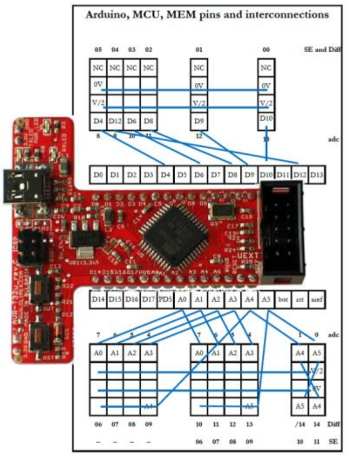
Oscillogram of amplifier output (channel 1, yellow) and secondary coil of the transformer divided by 43 (channel 2, magenta)

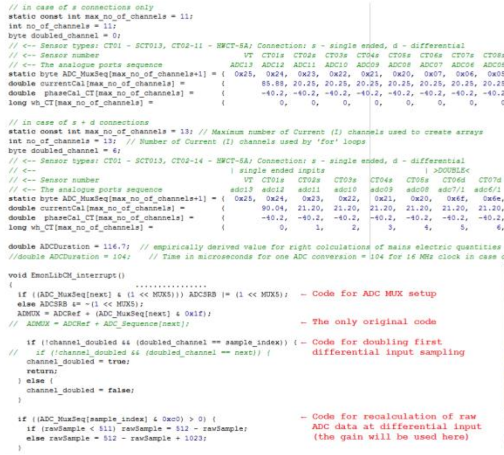
Measured parameters (without any filtering): generator frequency 50.65Hz, amplifier input 1.15V_{P-P}, amplifier output 14.8V_{P-P} (on each arm @ 20V_{DC} power), transformer primary 10.46V_{RMS} (29.6V_{P-P}), transformer secondary 230V_{RMS}, shortcut coil current 10.64A_{RMS} (2turns, 88cm 1.5mm² wire, 10mOhm), shortcut coil consumption 1.13W (10.64A_{RMS} @ 10Ohm), lamp consumption 1.90W (10.46V_{RMS} @ 57.6Ohm) and total power consumption 5W (0.25A_{DC}@20V_{DC}).

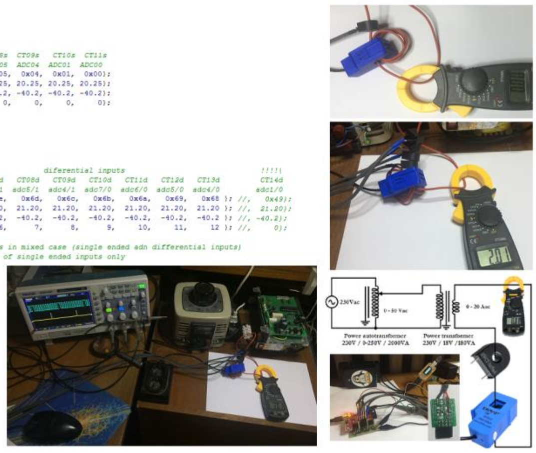
MEM System – summary for both variants of the simple alternative in pictures and graphs

After performing series of tests and modifications of emonLibCM library (Version 2.2.2 15/9/2022) for the both variants (single ended and differential sensor connections) of MEM system (simple alternative) following results could be announced:

Pin assignment, main emonLibCM library modifications and test scenario







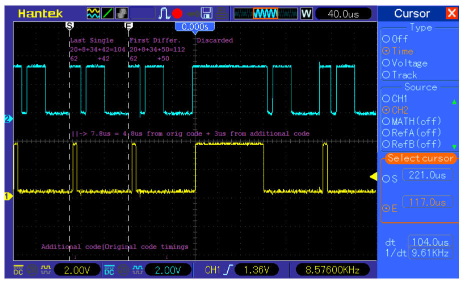
Printouts from both single ended and mixed and interrupt routine timings for mixed variants


```
{ Va: 228.53, Hz: 50.016, Sp: 1,
  Ia: [ 64.269, 16.059, 16.056, 16.068, 16.059, 16.061, 16.056, 16.053, 16.065, 16.063, 16.057 ],
  PF: [ 0.9999, 0.9976, 0.9976, 0.9976, 0.9976, 0.9976, 0.9975, 0.9975, 0.9974, 0.9974, 0.9973 ],
  Wr: [  14687,   3661,   3661,   3663,   3661,   3662,   3660,   3659,   3662,   3661,   3660 ],
  Wa: [  14689,   3670,   3669,   3672,   3670,   3670,   3669,   3669,   3671,   3671,   3669 ],
  Wh: [    100,     25,     25,     25,     25,     25,     25,     25,     25,     25,     25 ],
}
```


Regular printout (over USB serial) in JSON format for all measurement points (1 voltage and 11 currents) – single ended inputs variant

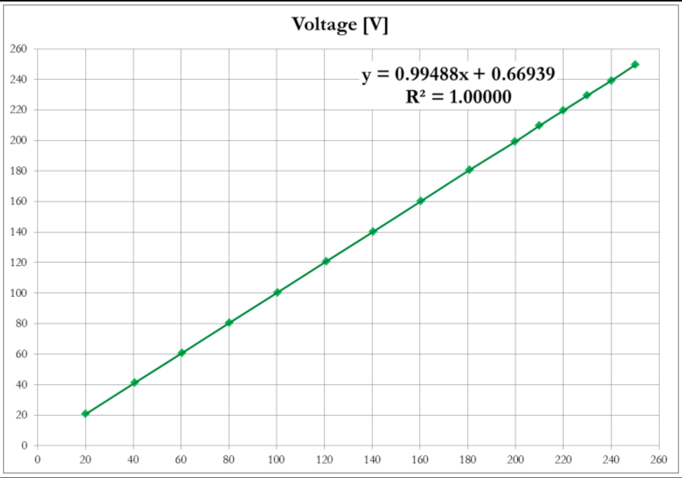

```
{ Va: 229.40, Hz: 50.000, Sp: 1,
  Ia: [ 64.097, 16.008, 16.004, 16.002, 16.001, 16.037, 16.036, 16.035, 16.034, 16.048, 16.040, 16.035, 16.030 ],
  PF: [ 0.9993, 0.9951, 0.9948, 0.9945, 0.9941, 0.9970, 0.9969, 0.9968, 0.9967, 0.9966, 0.9964, 0.9963, 0.9961 ],
  Wr: [  14694,   3654,   3652,   3651,   3649,   3668,   3667,   3667,   3666,   3669,   3666,   3665,   3663 ],
  Wa: [  14704,   3672,   3671,   3671,   3671,   3679,   3679,   3678,   3678,   3682,   3679,   3678,   3677 ],
  Wh: [     24,      6,      6,      6,      6,      6,      6,      6,      6,      6,      6,      6,      6 ],
}
```

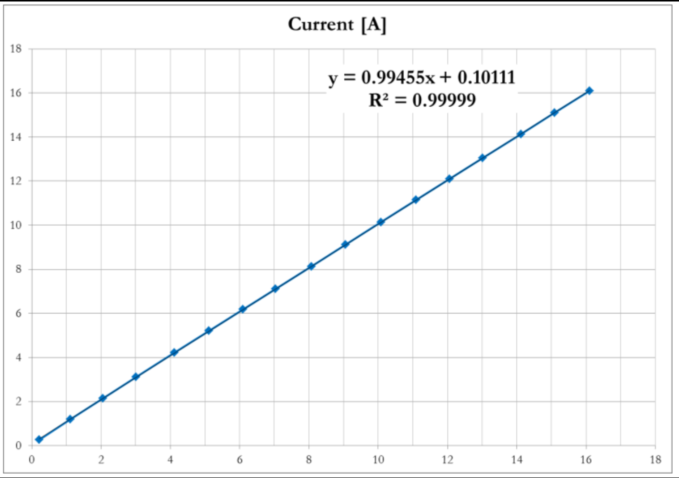

Regular printout (over USB serial) in JSON format for all measurement points (1 voltage and 13 currents) – mixed inputs variant



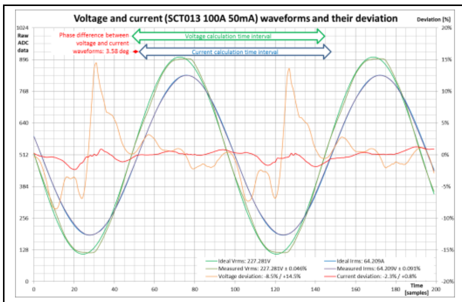
Oscillogram of interrupt timing for the modified emonLibCM (mixed variant)

Calibration graphs for voltage and current sensors of MEM system (simple alternative)

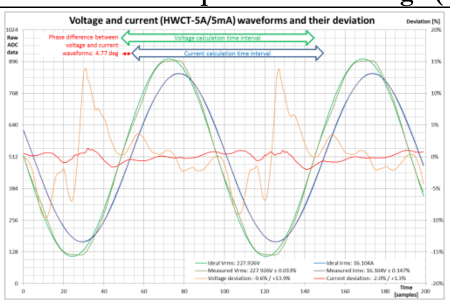




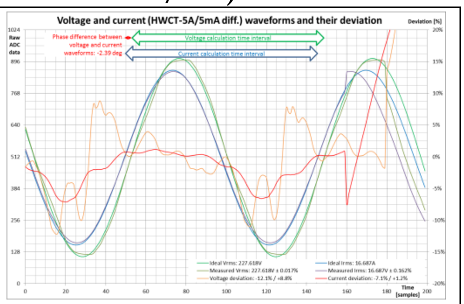
Graphs for used voltage (ANG AC-AC 9V/6VA) and current sensors



SCT013 100A 50mA current sensors over single ended connections



HWCT-5A/5mA current sensors over single ended connections



HWCT-5A/5mA current sensors over differential connections

The next step is the main and sensor boards to be (re-)designed for the final variant of the MEM system (simple alternative). The choice has to be made is if to use Olimex AVR-T32U4 board as-is or to modify it for a single main board solution. The modified board design is preferable because battery power and charging options can be added, which in combination with additional wireless module (like MOD-WIFI-ESP8266) will make its standalone usage possible.

MEM System (simple alternative) – problem with wrong calculations at mixed sequence

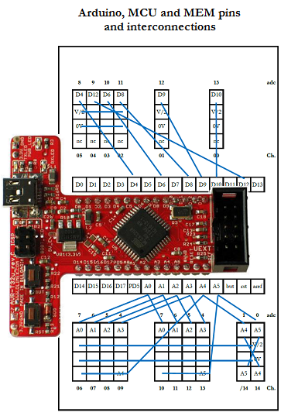
More tests were done with 14 sensors (1 VT and 13 CT) with mixed connection types (6 single ended and 8 differentially). Single ended inputs (1x VT, 1x SCT013 100A 50mA and 4x HWCT-5A/5mA sensors) and differential inputs (8x HWCT-5A/5mA sensors) share 5 real sensors (1x VT, 1x SCT013 100A 50mA and 3x HWCT-5A/5mA).

```
// in case of s + d connections
static const int max_no_of_channels = 13; // Maximum number of Current (I) channels used to create arrays
int no_of_channels = 13;  // Number of Current (I) channels used by 'for' loops
byte doubled_channel = 6;
// <-- Sensor types: CT01 - SCT013, CT02-14 - HWCT-5A; Connection: s - single ended, d - differential
// <--                                        | single ended inpits                      | >DOUBLE<                 diferential inputs                              !!!!|
// <-- Sensor number                              VT  CT01s  CT02s  CT03s  CT04s  CT05s    CT06d  CT07d  CT08d  CT09d  CT10d  CT11d  CT12d  CT13d        CT14d
// <-- The analogue ports sequence             adc13  adc12  adc11  adc10  adc09  adc08  adc7/1 adc6/1 adc5/1 adc4/1 adc7/0 adc6/0 adc5/0 adc4/0       adc1/0
static byte ADC_MuxSeq[max_no_of_channels+1] = { 0x25,  0x24,  0x23,  0x22,  0x21,  0x20,   0x6f,  0x6e,  0x6d,  0x6c,  0x6b,  0x6a,  0x69,  0x68 }; //,  0x49};
double currentCal[max_no_of_channels] =        {       90.04, 21.20, 21.20, 21.20, 21.20,  21.20, 21.20, 21.20, 21.20, 21.20, 21.20, 21.20, 21.20 }; //, 21.20};
double  phaseCal_CT[max_no_of_channels] =      {       -40.2, -40.2, -40.2, -40.2, -40.2,  -40.2, -40.2, -40.2, -40.2, -40.2, -40.2, -40.2, -40.2 }; //, -40.2};
long wh_CT[max_no_of_channels] =               {           0,     1,     2,     3,     4,      5,     6,     7,     8,     9,    10,    11,    12 }; //,     0};
void EmonLibCM_interrupt()
{                          .................
  if ((ADC_MuxSeq[next] & (1 << MUX5))) ADCSRB |= (1 << MUX5);
  else ADCSRB &= ~(1 << MUX5);
  ADMUX = ADCRef + (ADC_MuxSeq[next] & 0x1f); // set up the next-but-one conversion
//  ADMUX = ADCRef + ADC_Sequence[next];      // set up the next-but-one conversion
    if (!channel_doubled && (doubled_channel == sample_index)) {  // above printout
//    if (!channel_doubled && (doubled_channel == next)) {        // below printout
    channel_doubled = true;
    return;
  } else {
    channel_doubled = false;
  }

  if ((ADC_MuxSeq[sample_index] & 0xc0) > 0) { // calculation for differential channels
    if (rawSample < 511) rawSample = 512 - rawSample;
    else rawSample = 512 - rawSample + 1023;
  }
```

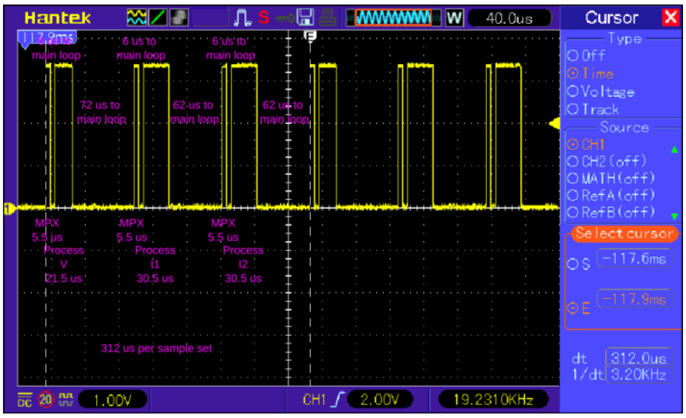
← Code for ADC MUX setup

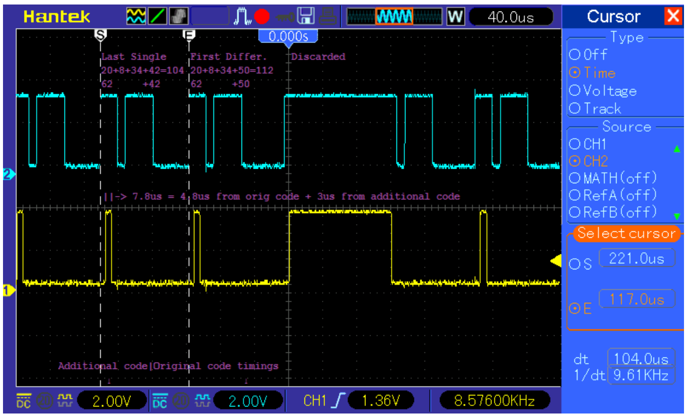
← Code for doubling first differential input sampling

← Code for recalculation of raw ADC data in case of differential input (the gain will be reported here)



Interrupt routine related code added to the original emonLibCM library



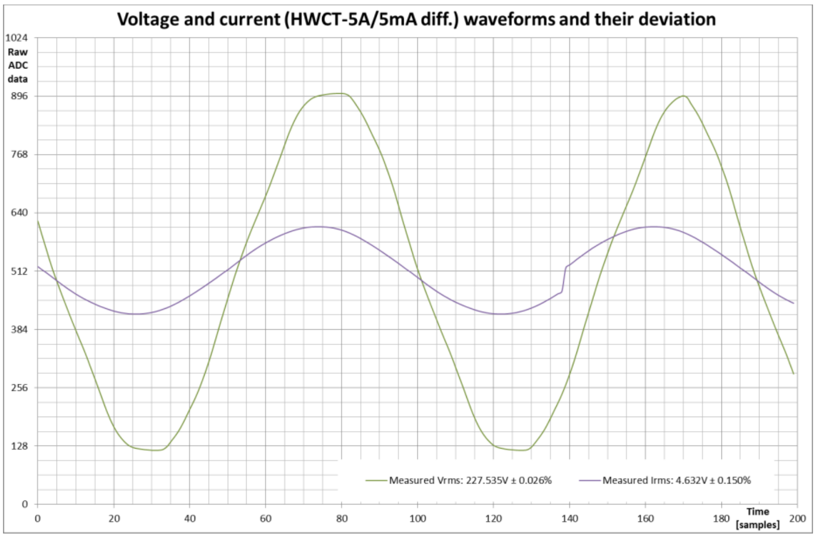


Original emonPi with only 2 current inputs (Robert Wall) **Modified emonLibCM library (Version 2.2.2 15/9/2022)**

As can be seen, the additional code takes 3us. It is also seen the part of the scan sequence with the last single ended input (conversion time 104us) and the first differential one (conversion time 112us). The times at current readings left for the main loop are 42us and 50us instead of 62us but there are no any side effects from that. The time distribution in the interrupt routine is quite similar to that from the original emonLibCM library. It can also be seen doubling and discarding of calculation for the first differential input. There is no observation for overlapping of ADC interrupts at all. These facts suggest that the additional code is not the cause for the wrong calculations as shown on the next left picture. There are also problems with debug scenario if capturing waveforms like in the next right picture where the shapes and current values (must be $16A_{RMS}$) are wrong.

```
int ADCDuration = 104; // Time in microseconds for one ADC conversion = 104 for 16 MHz clock
    if (!channel_doubled && (doubled_channel == sample_index)) { // code for doubling first differential input sca

{ Va: 227.08, Hz: 56.110, Sp: 1,
  Ia: [  8.472,  2.111,  2.111,  2.108,  2.112,  2.083,  2.084,  2.085,  2.083,  2.156,  2.181,  2.171,  2.188 ],
  PF: [ 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 1.0481, 1.0440, 1.0399, 1.0296, 1.0262, 1.0223, 1.0192 ],
  Wr: [   2061,    511,    510,    507,    506,    498,    496,    494,    492,    504,    508,    504,    506 ],
  Wa: [   1924,    479,    479,    479,    480,    473,    473,    474,    473,    490,    495,    493,    497 ],
  Wh: [      0,      1,      2,      3,      4,      5,      6,      7,      8,      9,     10,     11,     12 ],
}

int ADCDuration = 104; // Time in microseconds for one ADC conversion = 104 for 16 MHz clock
    if (!channel_doubled && (doubled_channel == next)) { // code for doubling first differential input scan

{ Va: 228.19, Hz: 56.110, Sp: 1,
  Ia: [  8.531,  2.117,  2.112,  2.115,  0.000,  2.090,  2.094,  2.093,  2.094,  2.350,  2.362,  2.367,  2.374 ],
  PF: [ 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 1.0483, 1.0443, 1.0402, 0.9401, 0.9364, 0.9295, 0.9305 ],
  Wr: [   2085,    516,    512,    512,      0,    502,    501,    499,    497,    504,    505,    502,    504 ],
  Wa: [   1947,    483,    482,    483,      0,    477,    478,    478,    478,    536,    539,    540,    542 ],
  Wh: [      0,      1,      2,      3,      4,      5,      6,      7,      8,      9,     10,     11,     12 ],
}

int ADCDuration = 117; // Time in microseconds for one ADC conversion = 104 for 16 MHz clock
    if (!channel_doubled && (doubled_channel == sample_index)) { // code for doubling first differential input sca

{ Va: 225.34, Hz: 49.796, Sp: 1,
  Ia: [ 64.377, 16.060, 16.060, 16.059, 16.059, 16.088, 16.087, 16.085, 16.086, 16.104, 16.094, 16.087, 16.085 ],
  PF: [ 0.9974, 0.9955, 0.9954, 0.9953, 0.9952, 0.9971, 0.9972, 0.9972, 0.9973, 0.9973, 0.9973, 0.9973, 0.9973 ],
  Wr: [  14469,   3603,   3602,   3602,   3601,   3615,   3615,   3615,   3615,   3619,   3617,   3615,   3615 ],
  Wa: [  14507,   3619,   3619,   3619,   3619,   3625,   3625,   3625,   3625,   3629,   3626,   3625,   3625 ],
  Wh: [    181,     45,     45,     45,     45,     45,     45,     45,     45,     45,     45,     45,     45 ],
}

int ADCDuration = 117; // Time in microseconds for one ADC conversion = 104 for 16 MHz clock
    if (!channel_doubled && (doubled_channel == next)) { // code for doubling first differential input scan

{ Va: 227.23, Hz: 49.877, Sp: 1,
  Ia: [  9.517,  2.358,  2.358,  2.358,  0.000,  2.335,  2.335,  2.334,  2.335,  2.338,  2.336,  2.336,  2.332 ],
  PF: [ 0.9984, 0.9958, 0.9956, 0.9977, 0.0000, 0.9977, 0.9978, 0.9978, 0.9977, 0.9976, 0.9976, 0.9975, 0.9975 ],
  Wr: [   2159,    533,    533,    535,      0,    529,    529,    529,    529,    530,    530,    530,    529 ],
  Wa: [   2163,    536,    536,    536,      0,    531,    531,    530,    531,    531,    531,    531,    530 ],
  Wh: [     99,     24,     24,     24,    168,     24,     24,     24,     24,     24,     24,     24,     24 ],
}
{ Va: 227.36, Hz: 49.796, Sp: 1,
  Ia: [  9.510,  2.357,  2.355,  2.359, 31.314,  2.335,  2.333,  2.333,  2.335,  2.337,  2.334,  2.334,  2.334 ],
  PF: [ 0.9972, 0.9946, 0.9944, 0.9965, 0.8815, 0.9963, 0.9962, 0.9963, 0.9963, 0.9963, 0.9962, 0.9962, 0.9962 ],
  Wr: [   2156,    533,    532,    534,   6276,    529,    529,    528,    529,    529,    529,    529,    529 ],
  Wa: [   2162,    536,    535,    536,   7120,    531,    530,    530,    531,    531,    531,    531,    531 ],
  Wh: [    100,     24,     24,     24,    170,     24,     24,     24,     24,     24,     24,     24,     24 ],
}
```

Printouts vs ADCDuration and condition of the code for doubling the first differential input scan



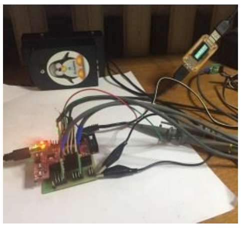
Averaged voltage and current waveforms for differential input (from 20 individual scan sets 96 point each taken sequentially)

The problem with wrongly calculated figures is solved if ADCDuration value is set to 117us instead of 104us or 112us (derived empirically). It is also empirically derived (but not logically explained) that for the right functioning the code for doubling the first differential input scan have to use following condition: (!channel_doubled && (doubled_channel == sample_index)). It can also be seen in the oscillogram (but not logically explained) that the first 112us conversion interval (coming from differentially connected CT) is from regular interrupt routine execution while the second one is from skipped interrupt processing.

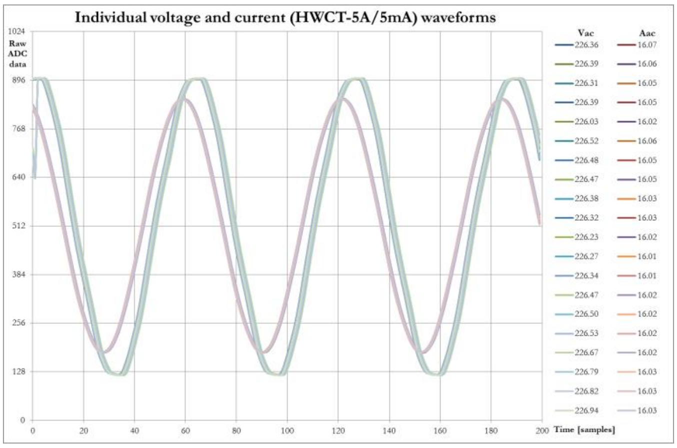
MEM System (simple single ended and differential alternative) – history in pictures and graphs

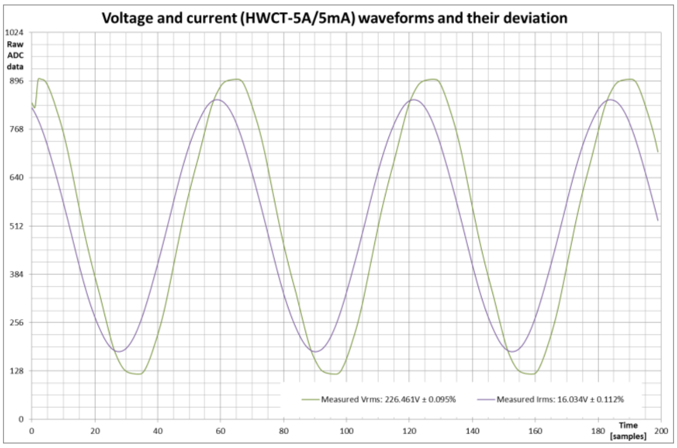
After tests with sequence of only single ended inputs (1 voltage and 11 current sensors) two current sensors (HWCT-5A/5mA) connected to differential inputs is setup. One current sensor (SCT013 100A 50mA) is also connected to a single ended input. Other inputs are connected to the sensors as well. All (1 voltage and 13 current) sensors are scanned in a sequence as shown on a picture below. Preliminary printouts, test scenario and waveform graphs are shown on the pictures below.


```
{ Va: 227.08, Hz: 56.110, Sp: 1,
  Ia: [  8.472,  2.111,  2.111,  2.108,  2.112,  2.083,  2.084,  2.085,  2.083,  2.156,  2.181,  2.171,  2.188 ],
  PF: [ 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 1.0481, 1.0440, 1.0399, 1.0296, 1.0262, 1.0223, 1.0192 ],
  Wr: [   2061,    511,    510,    507,    506,    498,    496,    494,    492,    504,    508,    504,    506 ],
  Wa: [   1924,    479,    479,    479,    480,    473,    473,    474,    473,    490,    495,    493,    497 ],
  Wh: [      0,      1,      2,      3,      4,      5,      6,      7,      8,      9,     10,     11,     12 ],

}
```

Regular printout (over USB serial) in JSON format
for all measurement points (1 voltage and 13 currents)
wrong values in red, debug in green





Results for voltage (ANG AC-AC 9V/6VA) and current (HWCT-5A/5mA connected to differential input) sensors (not complete)

```
// in case of s + d connections
static const int max_no_of_channels = 13; // Maximum number of Current (I) channels used to create arrays
int no_of_channels = 13;  // Number of Current (I) channels used by 'for' loops
byte doubled_channel = 6;
// <-- Sensor types: CT01 - SCT013, CT02-14 - HWCT-5A; Connection: s - single ended, d - differential
// <--                                          | single ended inpits                     |>DOUBLE<                 diferential inputs                              !!!!|
// <-- Sensor number                               VT   CT01s   CT02s   CT03s   CT04s   CT05s   CT06d   CT07d   CT08d   CT09d   CT10d   CT11d   CT12d   CT13d          CT14d
// <-- The analogue ports sequence              adc13  adc12   adc11   adc10   adc09   adc08  adc7/1  adc6/1  adc5/1  adc4/1  adc7/0  adc6/0  adc5/0  adc4/0         adc1/0
static byte ADC_MuxSeq[max_no_of_channels+1] = { 0x25,  0x24,   0x23,   0x22,   0x21,   0x20,   0x6f,   0x6e,   0x6d,   0x6c,   0x6b,   0x6a,   0x69,   0x68 }; //,   0x49};
double currentCal[max_no_of_channels] =        {        90.04,  21.20,  21.20,  21.20,  21.20,  21.20,  21.20,  21.20,  21.20,  21.20,  21.20,  21.20,  21.20 }; //, 21.20};
double  phaseCal_CT[max_no_of_channels] =      {        -40.2,  -40.2,  -40.2,  -40.2,  -40.2,  -40.2,  -40.2,  -40.2,  -40.2,  -40.2,  -40.2,  -40.2,  -40.2 }; //, -40.2};
long wh_CT[max_no_of_channels] =               {            0,      1,      2,      3,      4,      5,      6,      7,      8,      9,     10,     11,     12 }; //,     0};
```


```
{ Va: 227.08, Hz: 56.110, Sp: 1,
                                          Ia: [  8.472,  2.111,  2.111,  2.108,  2.112,  2.083,  2.084,  2.085,  2.083,  2.156,  2.181,  2.171,  2.188 ],
                                          PF: [ 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 1.0481, 1.0440, 1.0399, 1.0296, 1.0262, 1.0223, 1.0192 ],
                                          Wr: [   2061,    511,    510,    507,    506,    498,    496,    494,    492,    504,    508,    504,    506 ],
                                          Wa: [   1924,    479,    479,    479,    480,    473,    473,    474,    473,    490,    495,    493,    497 ],
                                          Wh: [      0,      1,      2,      3,      4,      5,      6,      7,      8,      9,     10,     11,     12 ],
}
```


```
void EmonLibCM_interrupt()
{                                ................
  if ((ADC_MuxSeq[next] & (1 << MUX5))) ADCSRB |= (1 << MUX5);
  else ADCSRB &= ~(1 << MUX5);
  ADMUX = ADCRef + (ADC_MuxSeq[next] & 0x1f); // set up the next-but-one conversion
//  ADMUX = ADCRef + ADC_Sequence[next];      // set up the next-but-one conversion
    if (!channel_doubled && (doubled_channel == sample_index)) {  // above printout
//    if (!channel_doubled && (doubled_channel == next)) {        // below printout
    channel_doubled = true;
    return;
  } else {
    channel_doubled = false;
  }
```

← Code for ADC MUX setup

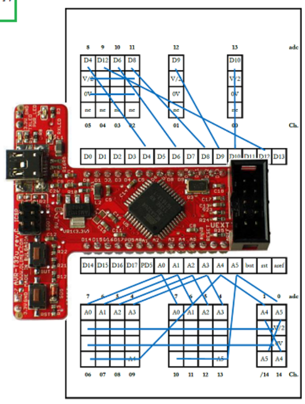
← Code for doubling first differential input sampling

```
  if ((ADC_MuxSeq[sample_index] & 0xc0) > 0) { // calculation for differential channels
    if (rawSample < 511) rawSample = 512 - rawSample;
    else rawSample = 512 - rawSample + 1023;
  }
```

← Code for recalculation of raw ADC data in case of differential input (the gain will be reported here)


```
{ Va: 228.19, Hz: 56.110, Sp: 1,
  Ia: [  8.531,  2.117,  2.112,  2.115,  0.000,  2.090,  2.094,  2.093,  2.094,  2.350,  2.362,  2.367,  2.374 ],
  PF: [ 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0000, 1.0483, 1.0443, 1.0402, 0.9401, 0.9364, 0.9295, 0.9305 ],
  Wr: [   2085,    516,    512,    512,      0,    502,    501,    499,    497,    504,    505,    502,    504 ],
  Wa: [   1947,    483,    482,    483,      0,    477,    478,    478,    478,    536,    539,    540,    542 ],
  Wh: [      0,      1,      2,      3,      4,      5,      6,      7,      8,      9,     10,     11,     12 ],
}
```


Arduino, MCU and MEM pins and interconnections

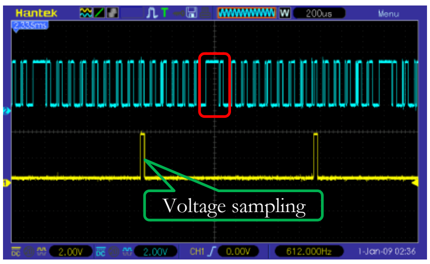


Printout (in green) and changed emonLibCM parts: ADC MUX values setup in red, code to double the first channel in sequence after single ended to differential input change in blue and recalculating of raw ADC data in gold color)

Wrong calculation at switching from single ended to differential inputs is encountered. The reason is explained in ATmega32U4 datasheet (24.5 Changing Channel or Reference Selection).

Special care should be taken when changing differential channels. Once a differential channel has been selected, the stage may take as much as 125µs to stabilize to the new value. Thus conversions should not be started within the first 125µs after selecting a new differential channel. Alternatively, conversion results obtained within this period should be discarded.

The same settling time should be observed for the first differential conversion after changing ADC reference (by changing the REFS1:0 bits in ADMUX).

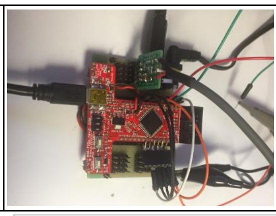


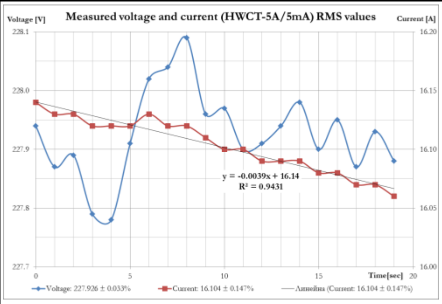
To avoid switching time problem the sampling of the first differential input is doubled and wrong values are discarded as shown on the oscillogram in red. Unfortunately, other values were wrongly calculated (mains frequency and PF – some zero, other greater than one) as shown on the picture above. Voltage and current values are accurate.

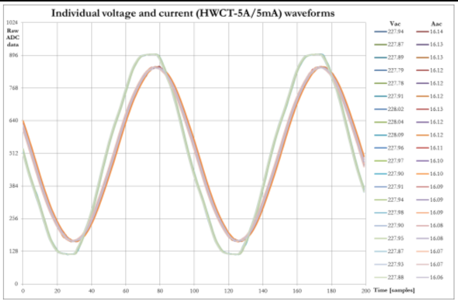
MEM System (simple single ended alternative) – history in pictures and graphs

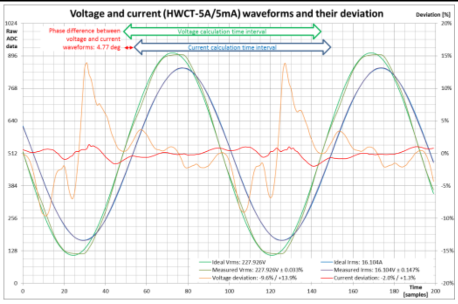

```
{ Va: 228.53, Hz: 50.016, Sp: 1,
  Ia: [ 64.269, 16.059, 16.056, 16.068, 16.059, 16.061, 16.056, 16.053, 16.065, 16.063, 16.057 ],
  PF: [ 0.9999, 0.9976, 0.9976, 0.9976, 0.9976, 0.9976, 0.9975, 0.9975, 0.9974, 0.9974, 0.9973 ],
  Wr: [  14687,   3661,   3661,   3663,   3661,   3662,   3660,   3659,   3662,   3661,   3660 ],
  Wa: [  14689,   3670,   3669,   3672,   3670,   3670,   3669,   3669,   3671,   3671,   3669 ],
  Wh: [    100,     25,     25,     25,     25,     25,     25,     25,     25,     25,     25 ],
}
```


Regular printout (over USB serial) in JSON format
for all measurement points (1 voltage and 11 currents)

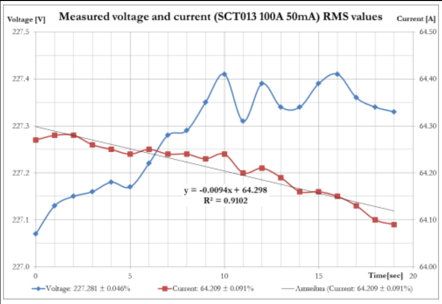


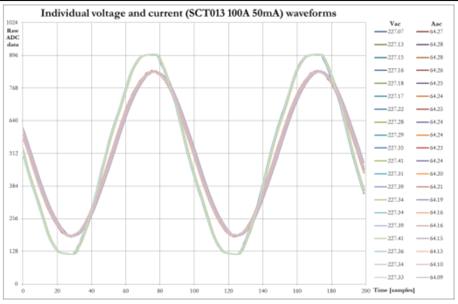


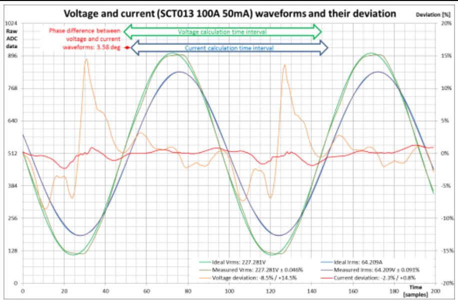




Results for voltage (ANG AC-AC 9V/6VA) and current (HWCT-5A/5mA) sensors



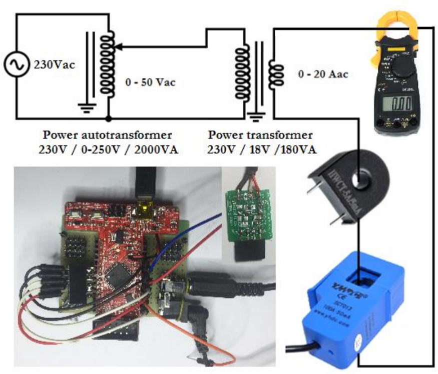




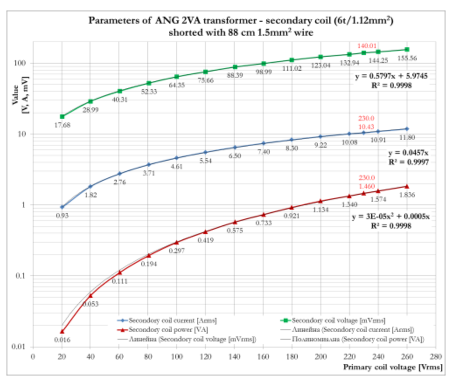
Results for voltage (ANG AC-AC 9V/6VA) and current (SCT013 100A 50mA) sensors


```
{ Va: 227.95, Hz: 49.984, Sp: 1,
  Ia: [ 16.035 ],
  PF: [ 0.9972 ],
  Wr: [   3645 ],
  Wa: [   3655 ],
  Wh: [     67 ],
}
227.95,  527,  500,  475,  450,  428,  407,  386,  367,  348,  329,  307,  283,
262,  240,  218,  196,  178,  164,  151,  140,  131,  125,  122,  120,  118,  117,
117,  116,  116,  116,  117,  123,  133,  148,  163,  179,  198,  215,  234,  254,
275,  300,  323,  353,  379,  406,  434,  461,  488,  514,  540,  564,  587,  609,
629,  648,  668,  689,  711,  732,  754,  776,  798,  818,  837,  852,  865,  876,
886,  892,  895,  897,  898,  899,  900,  901,  901,  901,  900,  894,  884,  869,
855,  839,  820,  802,  785,  766,  745,  719,  693,  668,  640,  613,  585,  558,
531,  505,  479,  455,  432,  410,  389,  369,  350,  331,  310,  289,  267,  244,
223,  201,  182,  165,  153,  141,  132,  126,  122,  120,  118,  117,  117,  116,
116,  116,  117,  122,  130,  147,  159,  178,  193,  213,  231,  248,  271,  293,
320,  348,  373,  401,  429,  456,  482,  509,  535,  560,  583,  605,  627,  647,
665,  684,  705,  727,  748,  771,  793,  815,  833,  849,  862,  874,  884,  891,
894,  896,  898,  899,  900,  901,  901,  900,  900,  898,  885,  871,  860,  842,
823,  804,  790,  769,  746,  723,  700,  675,  646,  618,  590,  563,  536,  510,
484,  460,  436,  416,  395,  374,
 16.03,  635,  616,  595,  574,  552,  531,  509,  487,  465,  443,  421,  399,
378,  358,  339,  320,  303,  287,  271,  257,  243,  231,  219,  208,  197,  187,
180,  174,  173,  169,  170,  168,  172,  175,  180,  187,  192,  203,  213,  225,
239,  254,  269,  286,  304,  323,  342,  361,  381,  401,  422,  442,  463,  485,
506,  528,  551,  573,  595,  616,  638,  658,  677,  696,  713,  729,  745,  759,
773,  786,  798,  809,  819,  827,  833,  840,  843,  846,  848,  848,  845,  842,
837,  834,  824,  816,  805,  793,  780,  766,  750,  733,  715,  697,  678,  659,
639,  619,  599,  579,  557,  537,  513,  492,  469,  447,  425,  403,  382,  362,
343,  324,  306,  290,  274,  260,  246,  233,  221,  210,  199,  192,  182,  177,
174,  170,  169,  171,  173,  174,  178,  184,  190,  200,  211,  223,  236,  251,
266,  283,  301,  319,  338,  357,  378,  397,  417,  438,  459,  479,  503,  525,
547,  569,  591,  613,  634,  655,  674,  693,  710,  727,  742,  757,  771,  783,
795,  807,  815,  826,  835,  838,  845,  846,  848,  847,  849,  843,  839,  832,
826,  818,  807,  795,  782,  768,  753,  736,  719,  700,  682,  662,  642,  623,
602,  581,  561,  540,  519,  496,
```

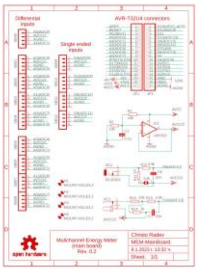

Printout of MEM system firmware
via serial (over USB) in test mode

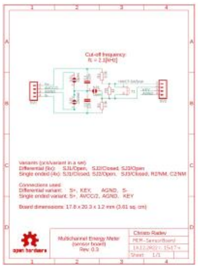


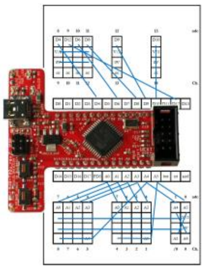
Test scenario for investigation
of MEM system behavior

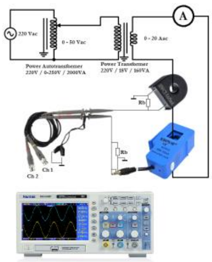


Test for using of VT as both voltage sensor
and current source for CTs calibration

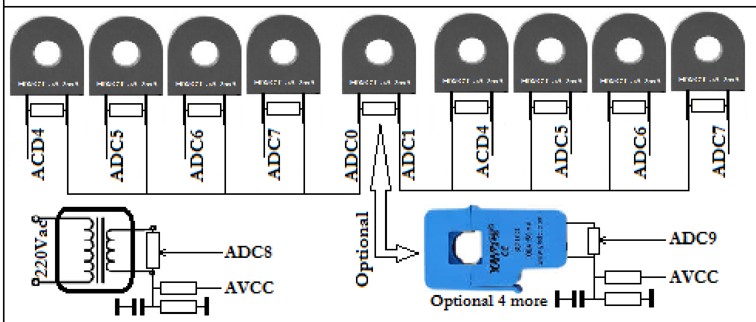


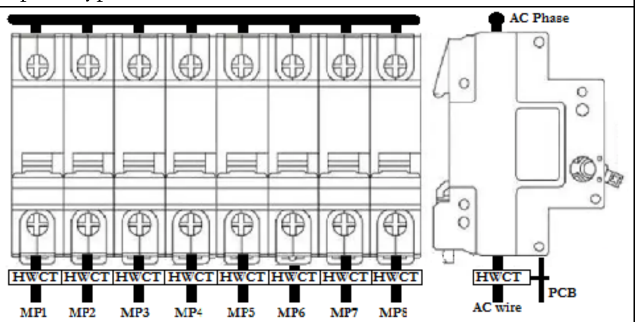






Main and sensor boards schematics, AVR-T32U4 interconnections, MEM prototype and measurement scenario

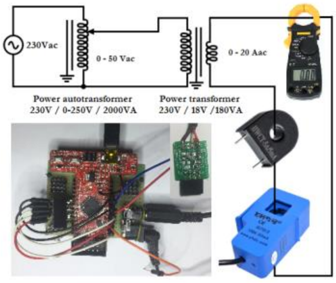


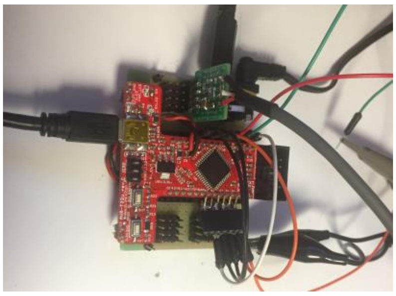


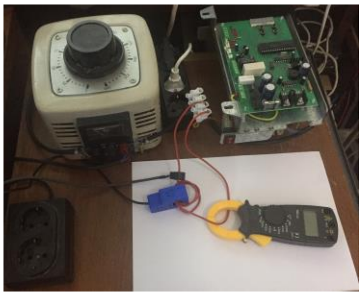
Initial idea: up to 9 current differential measurement points ($16A_{AC}$ each), total I_{RMS} ($64A_{AC}$) and V_{RMS} ($230V_{AC}$)

MEM System (waveform distortion and voltage / current sensing) – continued

The tests to investigate the influence of the waveform distortion over the measurement precision were continued with some changes and expansion. The voltage sensing input resistor divider was changed from 20k/1k to 12k/1k which increase the signal amplitude to 2.5Vp-p. HWCT-5A/5mA sensors was also connected via a sensor board to the system and investigated. Current simulation scenario was changed to use 4 winds for SCT013 100A 50mA sensors for simulating currents up to 80A.

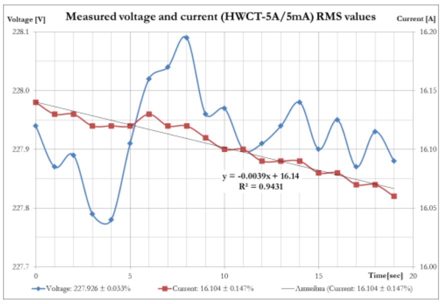


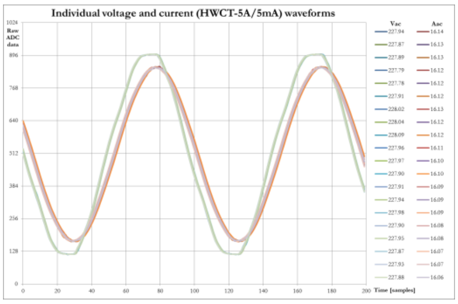


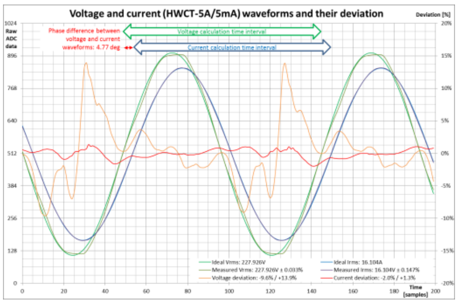


Current simulation schematics and test scenario after changes

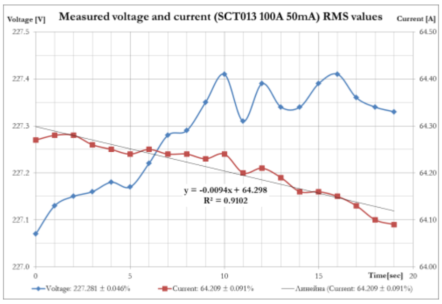
The results from the new tests are shown on figures below.

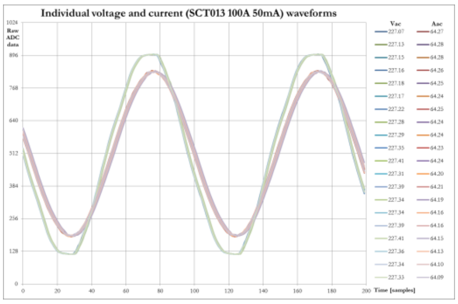


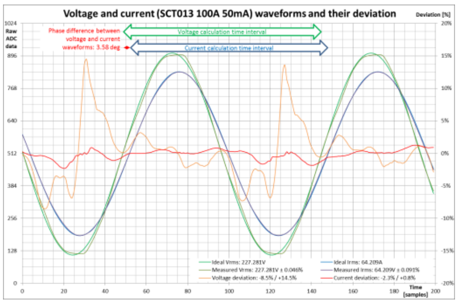




Results for voltage (ANG AC-AC 9V/6VA) and current (HWCT-5A/5mA) sensors



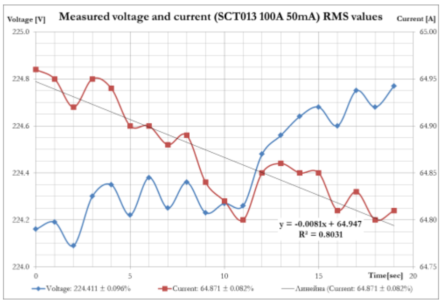


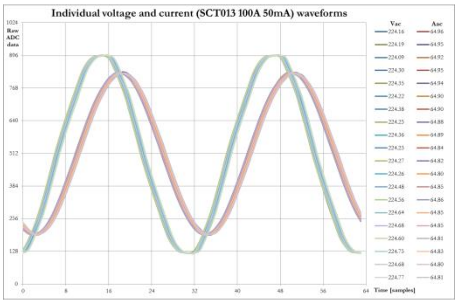


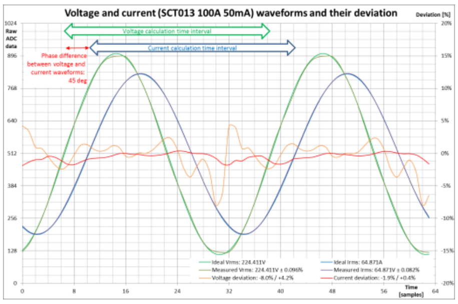
Results for voltage (ANG AC-AC 9V/6VA) and current (SCT013 100A 50mA) sensors

Unfortunately, it is unexplainable increase of deviation figures for both voltage (from -5.0%/+4.7% at the first tests to -8.5%/+14.5% and -9.6%/+13.9% at the next tests) and current (from -0.1%/+0.6% at the first tests to -2.3%/+0.8% and -2.0%/+1.3% at the next tests) waveforms. Fortunately, the correlation between voltage and current waveforms deviations remains approximately the same.

One more test was done with changes of the ADC frequency from CLK/128 to CLK/64 and CLK/32. While the firmware works fine at CLK/64 it stops working in normal way at CLK/32. At the test with CLK/64 (CLK/128 at debug mode) emonLibCM library was extended at the same time to scan all 12 ADCs and use 2 buffers with length of 64 (200 at debug mode) raw data each for capturing samples of voltage and one of the current inputs. These changes are optimal for the system to work normally and not to exceed the limits of the size of the used memory. The sketch was changed to send always via USB serial both captured waveform data and the measurement results of all channels (11 current and a voltage). The idea is to have opportunity to observe waveforms at normal working mode of the firmware (not only in debug one).







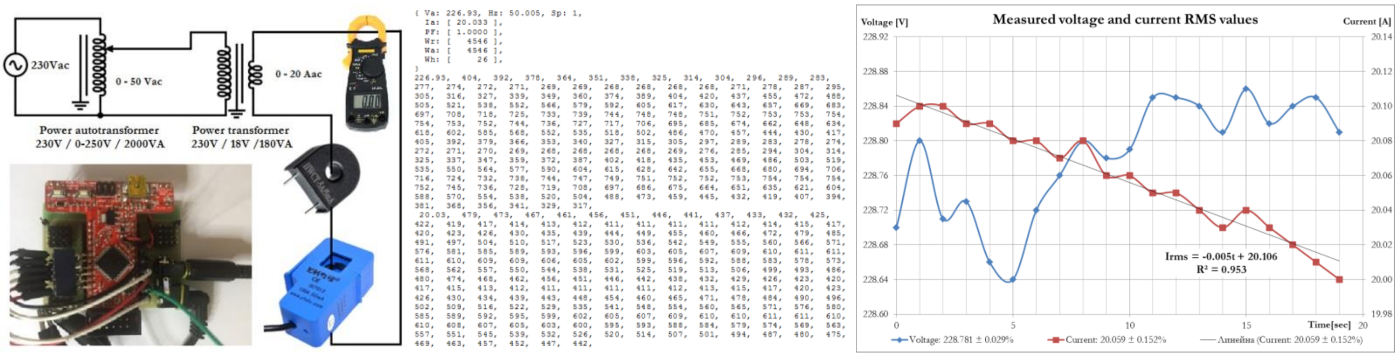
Results for voltage (ANG AC-AC 9V/6VA) and current (SCT013 100A 50mA) sensors at ADC frequency CLK/64

The result is decreasing of waveform data points from 96 to 32. As it can be seen distortion and saturation at voltage waveform is still visible but more tests should be done in case of bigger deviations from sinusoidal shape. On the other hand precise assessment should be done for influence of the bigger ADC frequency over the measurement precision in general. In case of negative influence waveforms capturing will be used at debug mode only.

MEM System (waveform distortion and voltage / current sensing)

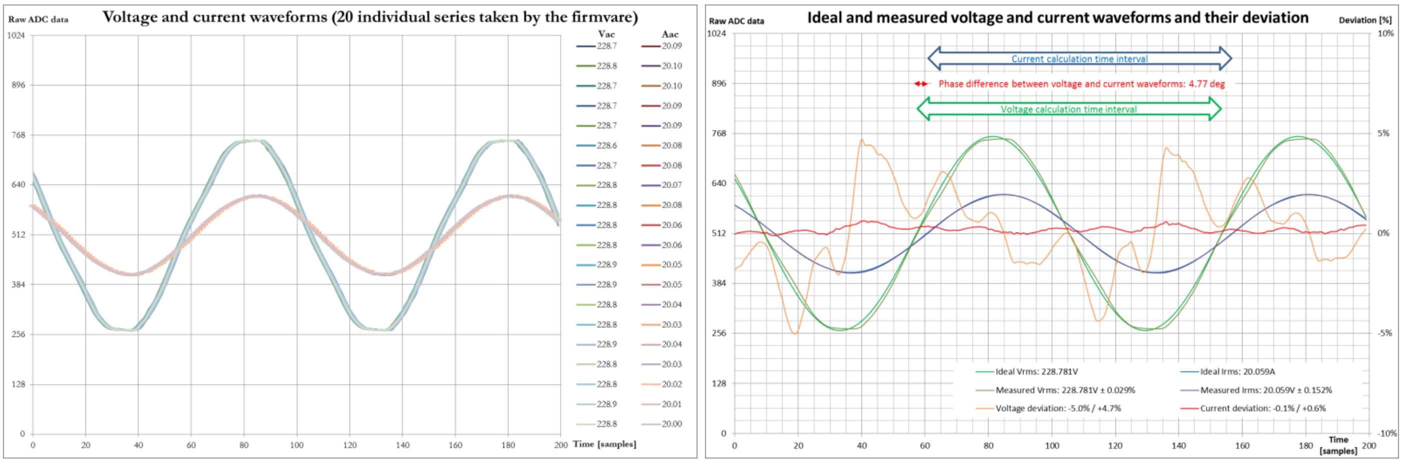
A new test to establish the influence of the waveform distortion was planned and executed. The test scenario scheme is shown in the figure below. ANG standard AC-AC adapter with 6VA transformer (input: 220-230Vac, output: 9Vac/0.66Aac) is used as voltage sensor. It gives 11.1Vac on the secondary coil at 230Vac on its primary coil. Olimex SNS-CURRENT-CT013-100A sensor is connected to CT0 input of the MEM system measuring total current.

Voltage and current values (200 samples each) are captured by a special addition to Robert Wall's emonLibCM library and compared in Excel 2010 with ideal sinusoidal waveform. The printout from the firmware via serial (over USB) output is shown in the figure below. Individual V_{RMS} and I_{RMS} values are calculated by the firmware and printed in the beginning of each row. Measured by the firmware RMS values in time are presented in the graph below and shows tendency I_{RMS} to fall in time probably depending on the temperature of the transformer with shortcut coil which will influence over calibration process.



The power schematics, the firmware output in test scenario and measured voltage and current values in time

Real voltage and current waveforms are averaged from 20 different takes 200 samples each captured one after the other and synchronously. Sinusoidal waveforms are calculated to best fit real once. Real and ideal RMS values and waveform deviations are calculated from both real and ideal waveforms. All they are shown on the figures below.



Individual, ideal and measured voltage and current waveforms and their deviations

As can be seen from the first graph the voltage curves have significant distortion while the current once are much closer to the ideal sinusoidal shape. The same can be seen even better in the second graph, where the averaged real waveforms are compared with the sinusoidal shapes. Deviations between real and ideal waveforms are also calculated and shown for voltage (-5.0% / +4.7%) and current (-0.1% / +0.6%) waveforms. It is clear that because of lower distortion and saturation lack the current waveform has more than one order of magnitude smaller deviation than the voltage one.

Calculated voltage and current RMS values are 228.781V ± 0.029% and 20.059A ± 0.152% respectively. Deviations of measured values mainly depend on mains voltage variation and transformer heating up. Time intervals for RMS calculations are also shown on the second graph. The phase difference between voltage and current waveforms is 4.77 degrees (4 samples by 208us) and mainly depends on the used AC-AC adapter and transformers for current simulation.

The conclusion from previous test and recommendations from ANG experts can be summarized that it is better to use ANG 6VA transformer as both voltage sensor and current source for calibration of CTs. The primary coil has to be for nominal voltage 230Vac. It has to have two secondary coils – one for 9V/10-20mA and other with 5-10 turns wind with 1.12mm wire (thicker is preferable). Long enough 1.5mm² wire with PVC insulation will be used to reach 16A shortcut current thanks to its resistance and for stringing up CTs. Saturation power can be as small as possible for avoiding transformer heating up.

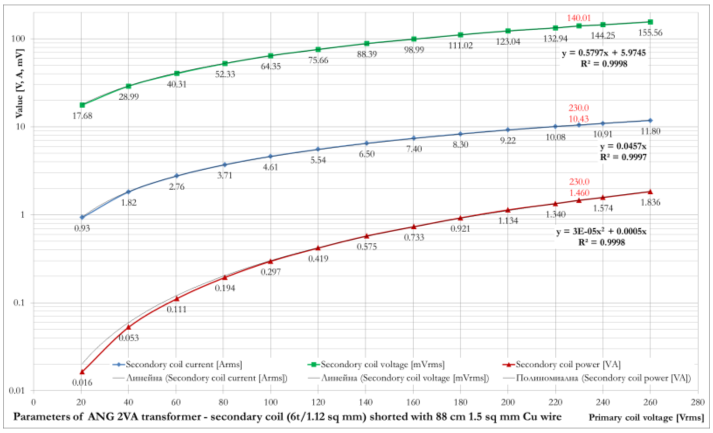
Following conclusions can be made:

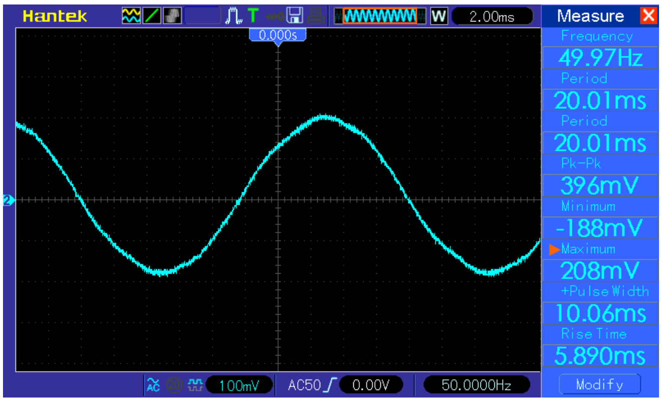
- Olimex SNS-CURRENT-CT013-100A sensor is precise enough for measuring of total currents up to 100A;
- ANG standard AC-AC 230V/9V/0.66A adapter with 6VA transformer is relatively good as voltage sensor;
- Resistive divider for the voltage input should be changed to increase signal amplitude for better precision;
- ANG 6VA transformer with additional secondary coil can be used as current source for CTs calibration;
- Calibration process should be short enough to avoid transformer temperature influence over the current.

Olimex SNS-CURRENT-HWCT-5A-5MA current sensor has to be tested as well. This test has to be repeated with a special ANG 6VA transformer prepared for MEM system usage as voltage sensor and CT calibration current source.

MEM System (voltage sensing and current transformers calibration)

Test with ANG special 2VA transformer (5600 turns x Φ0.07mm / 6 turns x Φ1.12mm) at 230V on a primary coil gives 19.8A on a shorted with 10cm. 1.5mm² wire and 10.43A if shorted with 88cm 1.5mm² wire(10.032mOhm theoretically). Measured voltage on a wire ends was 140mV$_{RMS}$ (396mV$_{P-P}$) which gives 1.46VA power at 230V$_{RMS}$ on a primary coil. Shortcut current waveform and parameters graph are shown on pictures below.



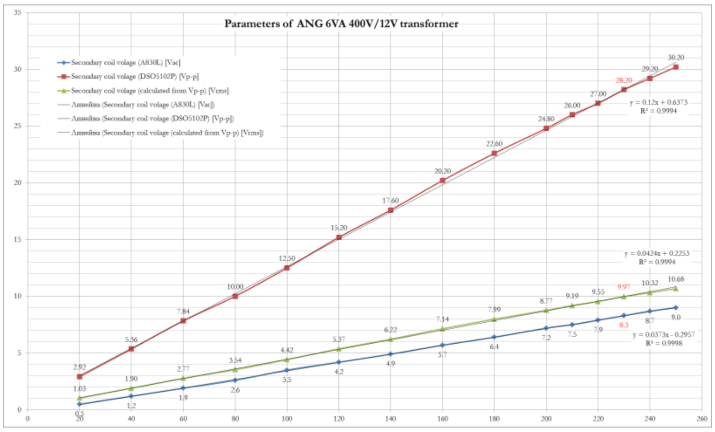


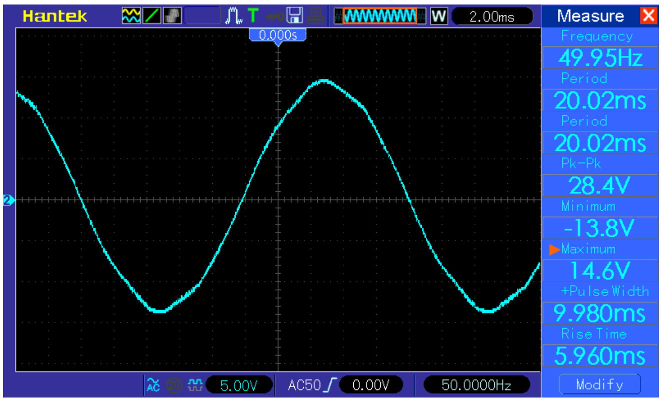
Shortcut current waveform

The waveform is relatively good and probably acceptable for a simple alternative of MEM System. Strange is the phase difference at AC50 synchronization (-37.8 degree) which has to be investigated. Calculated power of 1.46VA at 230V$_{RMS}$ on a primary coil and 10.43A if secondary coil is shorted with 88cm 1.5mm² gives potential for combination of both voltage sensing and current source for CTs calibration on a single transformer. The main idea is to have two secondary coils. The first will be used for voltage sensing giving 9V$_{RMS}$ for example. The second coil will be used as a current source for CTs calibration. It could be wound with 1mm² copper wire and working temperature up to 105°C (optionally with PVC isolation). The wire length of 1m for example will be enough to reach total resistance 10-20mOhms. Some of the wire will be used to wind 5-10 turns as a secondary coil. Other part of the wire will be left free for stringing up the CTs and to short the circuit at calibration. Final length of the wire will be tuned at production process to grant fixed shortcut current (16A$_{RMS}$ for example) at nominal voltage on a primary coil (230V$_{RMS}$). On site calibration will be done with measuring of the voltage from each CT and the voltage of the secondary coil which will be used at calculation of the calibration coefficients. The calibration time has to be minimized to avoid temperature increase which will influence wire resistance.

Maximal current in Amperes vs. insulation material and copper temperature of the wire									
AWG	Wire diameter [mm]	Wire cross section [mm²]	Polyethylene Neoprene Polyurethane Polyvinylchloride (Semi-Rigid)	Polypropylene Polyethylene (High Density)	Polyvinylchloride PVC (Irradiated) Nylon	Kynar (135°C) Polyethylene (Cross-linked) Thermoplastic Elastomers	Kapton PTFE FEP PFA Silicone	Enameled copper wire	Resistance [mOhm/m]
		Temperature	80°C	90°C	105°C	125°C	200°C		20°C
14	1.63	2.082	27.0	30.0	33.0	40.0	45.0	5.9	8.58
15	1.45	1.651	23.0	26.0	28.5	33.0	38.5	4.7	10.81
16	1.29	1.309	19.0	22.0	24.0	26.0	32.0	3.7	13.64
17	1.15	1.039	17.0	19.5	21.0	23.0	28.0	2.9	17.19
18	1.02	0.824	15.0	17.0	18.0	20.0	24.0	2.3	21.68
19	0.91	0.653	12.5	14.5	15.5	17.0	20.5	1.8	27.34
20	0.81	0.519	10.0	12.0	13.0	14.0	17.0	1.5	34.42

For improvement of transformer characteristics as voltage sensor it is important to decrease distortion of the voltage waveform. A good idea is to use transformer with higher power (6VA for example) with primary coil for 400VRMS instead of 230V$_{RMS}$. Open coil voltage waveform and parameters graph of ANG 6VA 400V/12V transformer is shown on pictures below.

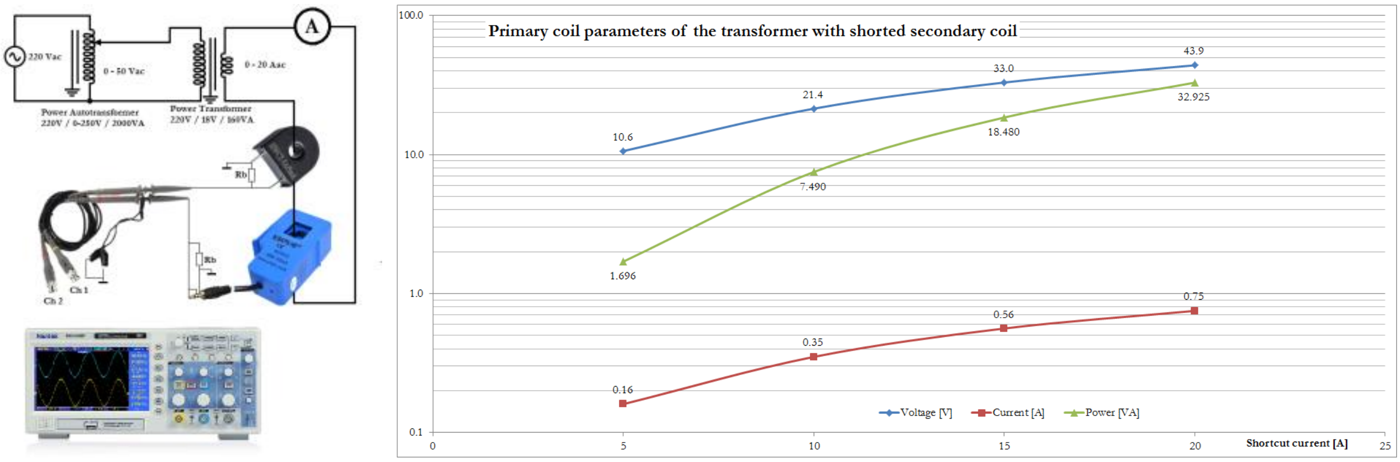




Open coil voltage waveform

The conclusion is that ANG special 2VA transformer has better secondary voltage waveform and lower saturation power. It makes this transformer preferable to 6VA one. The primary coil has to be for nominal voltage (230Vac). The special 2VA transformer has to have two secondary coils – one for 9V/10mA and other 5-10 turns wind with 1 or 1.5mm² wire long enough to reach 16A shortcut current thanks to its resistance at saturation power less than 1.5VA.

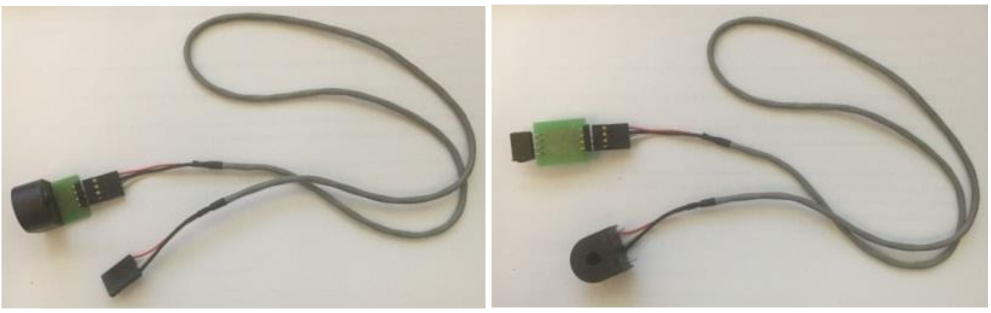
One of the ways to maximize precision of the MEM system is to make on-site calibration. The test scenario, where the CTs measure the shortcut current of secondary coil of a transformer, shows that it is possible to generate relatively high current at low power.



Test scenario and the result of measured primary coil parameters of 180VA transformer with shorted secondary coil

The idea for on-site MEM system calibration is to use voltage transformer (VT) with additional coil to generate big enough shortcut current. The shortcut wire can be used to string up the CTs, measure the current and recalculate calibration coefficients. One potential problem is the possibility the shortcut current to influence measurement coil voltage and has to be investigated. Fortunately, this influence can be measured and taken into account at calculation of the calibration coefficients.

Other influence over the system precision is the noise induced in CTs and connection cables. While nothing to do with CT itself the cable can be shielded and the location of the burden resistor and the filter has to be investigated.

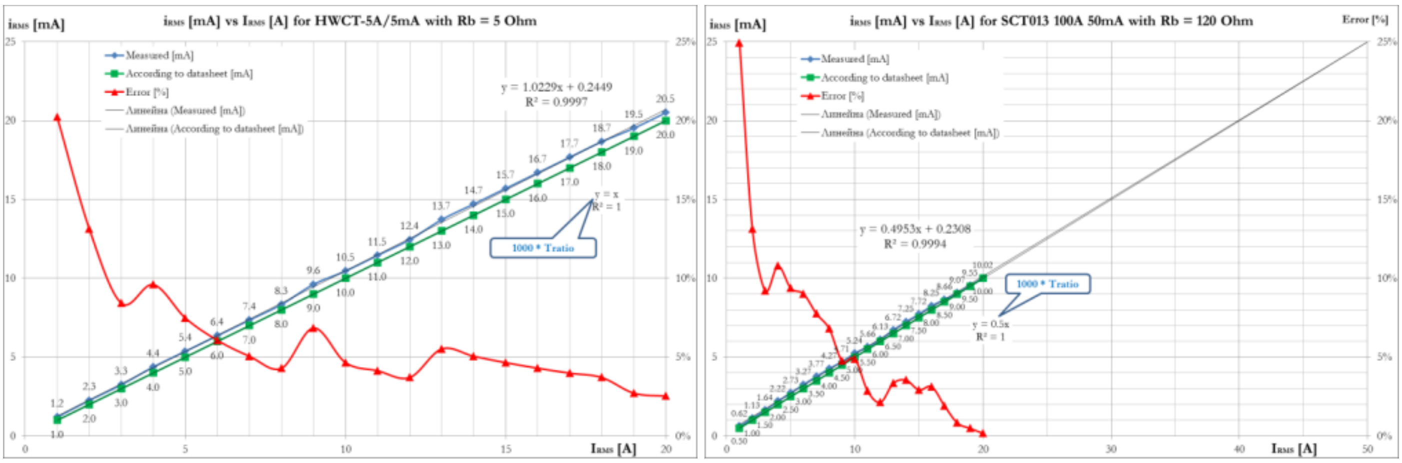


Sensor set CT:	**HWCT-5A/5mA**
Calibration coefficient:	**21.28**
Attached to MEM channel: ***5***	
Current circuit name:	
lighting / kitchen / living room / parlour / bedroom 1 / bedroom 2 / bathroom 1 / bathroom 2 / boiler 1 / boiler 2 / oven 1 / oven 2 / refrigerator 1 / refrigerator 2 / other:	

Sensor set variants **Exemplary label**

Without matter where they will be located all components (CT, the cable, the burden resistor and the filter components) can be mounted together and calibrated at production process. This is the main idea to develop separate sensor board carrying all relevant components. In addition recalibration can be made by the user and eventually periodically.

Individual calibration coefficient has to be printed on a label, fixed to the sensor set and used at MEM system on-site setup. The label can also be used to write down MEM channel and current circuit name attached to. All this information collected together will help the user in system setup process.

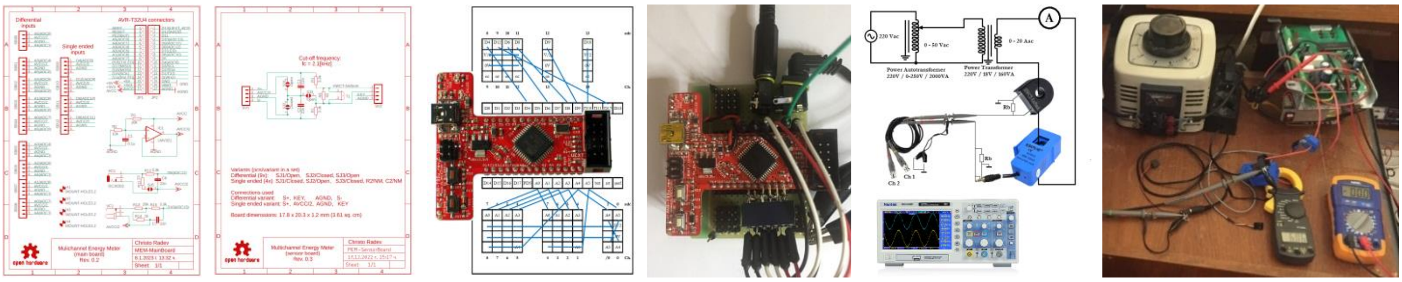


Calculation ratio and error for used CTs

Other big issue is the great error at measuring of small currents. This problem can be solved with using built-in operational amplifier to increase the signal from CTs. It is possible only if differential ADC inputs are in use. One drawback is the noise amplification but the influence over MEM system precision has to be investigated.

MEM System (simple alternative prototype and first tests with single ended ADC inputs)

The simple alternative of MEM system prototype as hardware is implemented with universal PCB (as a main board) stacked with Olimex' AVR-T32U4 board (Leonardo compatible). AVR-T32U4 board is preferred to Olimexino-Nano because all ADC inputs are free for use. Unfortunately, AVCC and AGND are not wired to the connector and it has no battery supply but these problems can be solved with adding its modified variant to the main board itself because it is OSHW licensed.



Main and sensor boards schematics, AVR-T32U4 interconnections, MEM prototype and measurement scenario

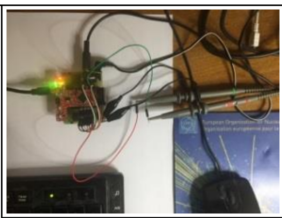
For testing is used scenario with 0-250V/2kVA autotransformer and 220V/18V/180VA transformer with secondary coil shorted. ANG AC-AC 9V/0.66A adapter is used as VT (connected to ADC13 and the oscilloscope channel 1) and a single SCT013-000 100A 50mA is used as CT (connected to ADC12 and the oscilloscope channel 2). Other 10 ADC inputs are connected to ADC12. Hanteck's DSO5102P oscilloscope is used to observe waveforms. DT3266L multimeter with current clamp is used to measure short cut current.

Robert Wall's emonLibCM library and EmonTxV34CM_min.ino sketch are used for the first test. The main changes made in the sketch are to set pins 6-11 (ADC8-13) as inputs in setup function and to form appropriate JSON output to serial (over USB) channel. In emonLibCM.cpp except extending arrays from 4/5 to 11/12 members following essential changes (marked in red) were made:

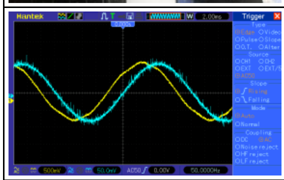
```
// <-- Sequence in which the analogue ports are scanned, first is Voltage, remainder are currents
static byte ADC_MuxSeq[max_no_of_channels+1] =    {0x25,0x24,0x23,0x22,0x21,0x20, 0x07,0x06,0x05,0x04,0x01,0x00}; // added
static byte ADC_Sequence[max_no_of_channels+1] = {  11,  10,   9,   8,   7,   6,    5,   4,   3,   2,   1,   0}; // changed

// in function void EmonLibCM_interrupt() is added:
  if ((ADC_MuxSeq[next] & (1 << MUX5)))
    ADCSRB |= (1 << MUX5);
  else
    ADCSRB &= (0 << MUX5);
  ADMUX = ADCRef + (ADC_MuxSeq[next] & 0x1f);      // set up the next-but-one conversion

// instead of:
//  ADMUX = ADCRef + ADC_Sequence[next];      // set up the next-but-one conversion
```

The result sent via USB serial is:

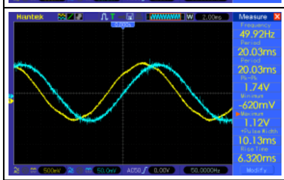
```
EmonTx v3.4 EmonLibCM Continuous Monitoring Minimal Demo
Datalog period: 1.0 seconds
ADC Input channels:
ch00: getLogicalChannel: 00, mux value: 0x25
ch01: getLogicalChannel: 00, mux value: 0x24
ch02: getLogicalChannel: 00, mux value: 0x23
ch03: getLogicalChannel: 00, mux value: 0x22
ch04: getLogicalChannel: 00, mux value: 0x21
ch05: getLogicalChannel: 00, mux value: 0x20
ch06: getLogicalChannel: 00, mux value: 0x07
ch07: getLogicalChannel: 00, mux value: 0x06
ch08: getLogicalChannel: 00, mux value: 0x05
ch09: getLogicalChannel: 00, mux value: 0x04
ch10: getLogicalChannel: 00, mux value: 0x01
ch11: getLogicalChannel: 00, mux value: 0x00

Case 1: Immediately after starting up at 5A
{ Va: 227.76, Hz: 50.016, Sp: 1,
  Ia: [  5.084,  5.063,  5.058,  5.057,  5.057,  5.060,  5.053,  5.056,  5.052,  5.056,  5.056 ],
  PF: [ 0.9981, 0.9984, 0.9986, 0.9987, 0.9988, 0.9988, 0.9989, 0.9989, 0.9989, 0.9988, 0.9988 ],
  Wr: [   1156,   1151,   1150,   1150,   1150,   1151,   1150,   1150,   1149,   1150,   1150 ],
  Wa: [   1158,   1153,   1152,   1152,   1152,   1152,   1151,   1152,   1151,   1151,   1152 ],
  Wh: [      0,      0,      0,      0,      0,      0,      0,      0,      0,      0,      0 ],
}

Case 2: Later on at 16A
{ Va: 227.90, Hz: 50.016, Sp: 1,
  Ia: [ 16.098, 16.080, 16.074, 16.075, 16.077, 16.076, 16.075, 16.077, 16.077, 16.075, 16.074 ],
  PF: [ 0.9997, 0.9998, 0.9999, 0.9999, 0.9999, 0.9999, 0.9999, 0.9998, 0.9998, 0.9997, 0.9997 ],
  Wr: [   3668,   3664,   3663,   3663,   3664,   3663,   3663,   3663,   3663,   3662,   3662 ],
  Wa: [   3669,   3665,   3663,   3664,   3664,   3664,   3664,   3664,   3664,   3663,   3663 ],
  Wh: [     47,     46,     46,     46,     46,     46,     46,     46,     46,     46,     46 ],
}

Case 3: Later on at 0A (second transformer switched off)
{ Va: 225.40, Hz: 49.953, Sp: 1,
  Ia: [  0.146,  0.122,  0.118,  0.118,  0.119,  0.124,  0.132,  0.126,  0.129,  0.133,  0.109 ],
  PF: [ 0.5149, 0.1331, -0.1077, -0.1499, -0.1815, -0.2350, -0.1731, -0.1663, -0.1771, -0.2000, -0.1255 ],
  Wr: [     17,      4,     -2,     -3,     -4,     -6,     -4,     -4,     -4,     -5,     -2 ],
  Wa: [     33,     28,     27,     27,     27,     28,     30,     28,     29,     30,     25 ],
  Wh: [    483,    478,    476,    476,    476,    476,    476,    476,    476,    476,    476 ],
}

Case 4: Later on at 0.19A  (autotransformer moved to lower position)
{ Va: 224.81, Hz: 49.953, Sp: 1,
  Ia: [  0.324,  0.298,  0.295,  0.292,  0.288,  0.290,  0.288,  0.288,  0.290,  0.293,  0.285 ],
  PF: [ 0.9520, 0.9421, 0.9417, 0.9361, 0.9320, 0.9301, 0.9299, 0.9309, 0.9324, 0.9344, 0.9303 ],
  Wr: [     69,     63,     62,     61,     60,     61,     60,     60,     61,     62,     60 ],
  Wa: [     73,     67,     66,     66,     65,     65,     65,     65,     65,     66,     64 ],
  Wh: [    484,    479,    477,    477,    476,    476,    476,    476,    476,    476,    476 ],
}
```



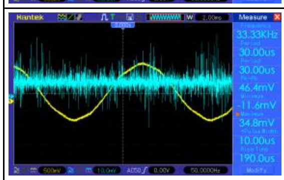
Prototype in action



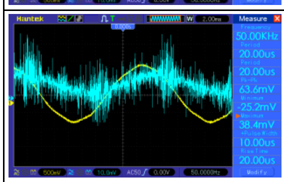
Case 1-2



Case 1-2



Case 3



Case 4

Problems found are marked in red. Wrong getLogicalChannel return result probably reflects to impossibility to setup some of the channels to scan (currently out of the scope of the development). Other problems are the big noise and wrong results in case 3. Used transformers in measurement scenario add big phase shift (~40°) compensated by calibration value (phaseCal_CT).

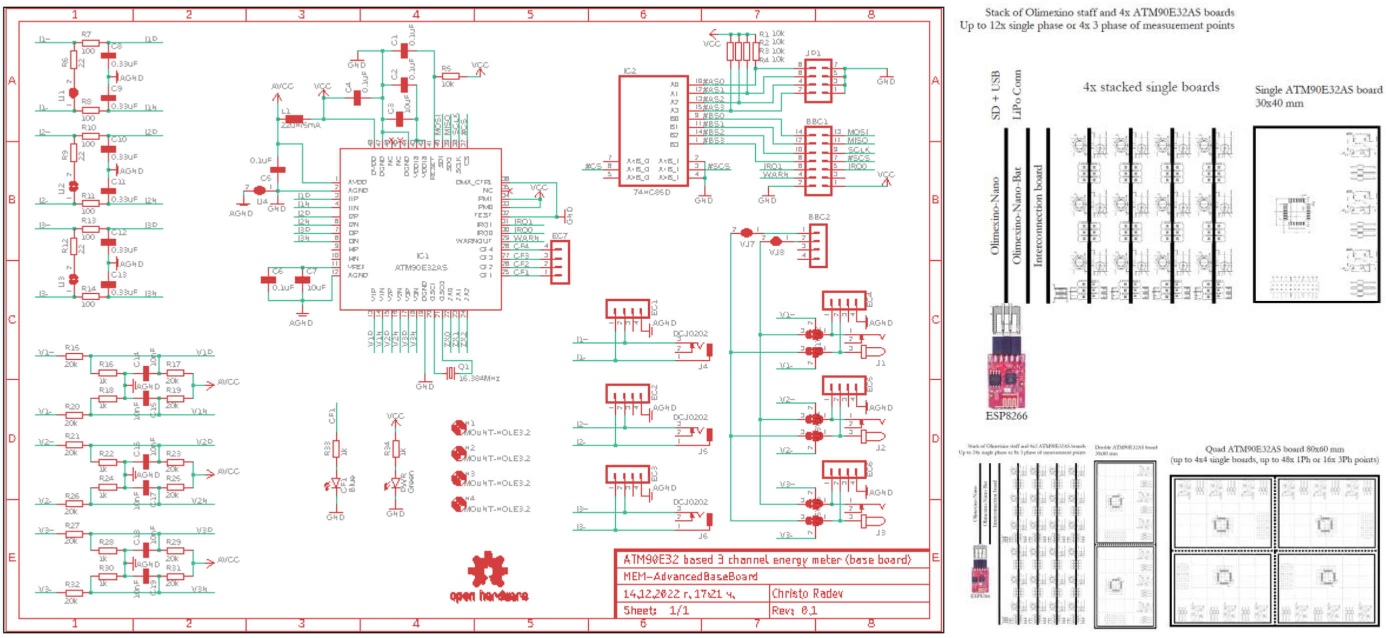
Multichannel Home Electricity Monitoring System (advanced alternative)

This alternative of the project is inspired by CircuitSetup's Expandable 6 Channel ESP32 Energy Meter based on Microchip's ATM90E32AS IC for precise metering of three-phase four-wire (3P4W, Y0) or three-phase three-wire (3P3W, Y or Δ) electricity consumption and ESP32 for communication. The solution consists of almost the same boards (base and add) with up to 2 voltage and 3 current inputs. Apart from the high price and strange 3 phase solution (to use 2 chips while single one supports that) it is very ineffective to have 2 almost the same boards with SPI connectivity. On the other hand it is inefficient to connect over audio jacks many CTs like SNS-CURRENT-HWCT-5A-5MA (offered by Olimex for 1€ instead of SNS-CURRENT-CT013-100A for 10€). For example for monitoring of my apartment with 9 local circuits (up to 16Aac each) and total input (up to 64Aac) the price is between $274.58 and $366.58 without VAT and delivery taxes. If add 115€ (without VAT and delivery taxes) for Olimex' OSHW Lime2-Server (minimal configuration with 120GB SSD) I have to pay approximately 800BGN without VAT and delivery taxes or something like 1000BGN (500€) total. The half of that price is for 2x 6 channel measurement boards and 9x YHDC SCT006. Provided I manage to save 10% (which is overrated) on my electricity bill this cost will be recouped in more than 6 years. This calculation does not include the cost of electrical appliances that must be replaced to actually reduce the bill. In conclusion, the purchase and installation of such a household electricity consumption monitoring system is more a matter of feeling in control of running costs mainly in view of the current crises.

For the above reasons, reducing the price and combining the monitoring system with other activities is imperative. A simple and lower in price alternative is discussed later on and it is based on Lime2-Server hardwired via USB with Olimexino-Nano, HWCT-5A/5mA CTs and OpenEnergyMonitor project (especially emonLibCM by Robert Wall and emonCMS). A simple interconnection board has to be developed and for the BOM of 150€ (including Lime2-Server, Olimexino-Nano, CTs, VT) the system can be used for additional home applications. The disadvantage is that such a system will not be precise enough (it is hard to reach 1% precision) to control the bill which is essential for a countries like Bulgaria.

As a result of the reasoning, a more precise solution based on the ATM90E32AS IC (4.6€ at small quantity) is proposed. To avoid the shortcomings of the CircuitSetup's system, a different design of the measurement board is planned. The main ATM90E32AS based board will consists of a single IC with 3x current and 3x voltage channels and SPI bus with enough GPIOs for selecting enough ICs individually. Using all 3x current and 3x voltage inputs many 3 phase consumers can be monitored easily. In addition to optional audio jacks a cheap pin header can be used to connect directly CTs. The IC voltage inputs can be selected to use external transformers (up to 3x on each board with optional power jacks) or single one connected to any of the voltage inputs. The powering of the boards will be over USB from Olimexino-Nano so the voltage sensors can be smaller like 1-2VA transformers and 1.3mm power jacks for reaching lower price and the board dimensions like 30x40mm. The optional jacks will also decrease dramatically the BOM and end price in case of using CTs like HWCT-5A/5mA (10 times cheaper than SCT-006/SCT-013). Double and quadruple board variants will be achieved by simple multiplication of a single board. All measurement board variants can be stacked with cheap 2.54mm pin header connectors. A simple interconnection board will also be developed for stacking with Olimexino-Nano. It will also carry LiPo battery when possible. On the other hand Olimexino-Nano can be stacked with Olimexino-Nano-Bat and ESP8266 WiFi module for wireless communication with Lime2-Server in case of usage of the monitoring unit as a remote node in multi-node installations.

Maximal number of single boards could be addressed via SPI is 16 so up to 48x 1 phase or up to 16x 3 phase measurement point are possible. The final BOM for comparable number of CTs will exceed the BOM (Olimex sale price of 150€ including Lime2-Server, Olimexino-Nano, CTs, VT) of the simple alternative with less than 50€ even if optional jacks (half of that price) are mounted. It can be supposed that for a typical installation with 12 measurement points with single voltage sensor and usage of HWCT-5A/5mA current sensors final price like 250€ (or 500BGN without VAT and delivery taxes) is feasible.



Single, double and quadruple variants of the measurement part of the system (ESP8266 and LiPo battery are optional)

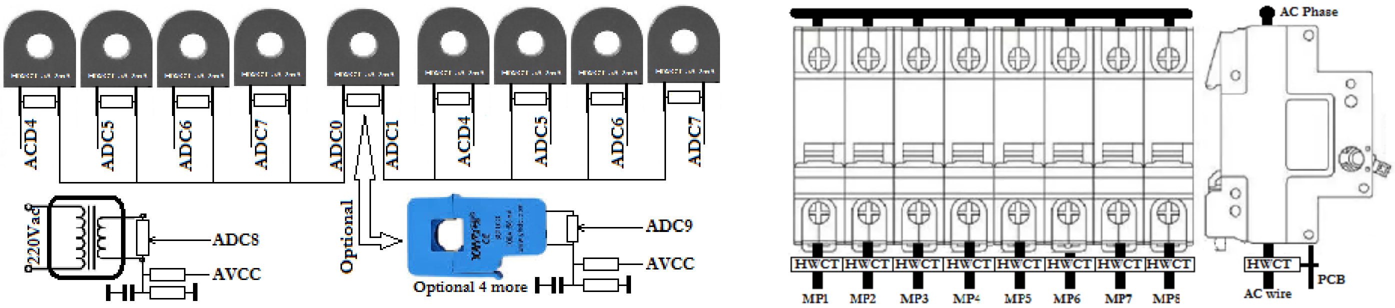
In addition to above a simple weather station and room climate monitoring units based on ESP8266 and appropriate temperature, humidity, light etc. sensors can be used. Currently only electric company's electrometer is hard to connect because in blocks of flats they are in locked cabinets in the basements. In houses they are located on the streets and optical counter sensor wirelessly connected to Lime2-Server by ESP8266 can be used but the problem is the vandal protection and distance.

And finally, the commercial usage of such a system is also relevant because of possibility to monitor all electric consumers (including 3 phase once) for optimizing their electric bills. In such installations ESP8266 WiFi module could be changed to RS485/RS422 one (like MOD-RS485-ISO or MOD-RS485) with or without galvanic isolation usable for long distances of full or half duplex communication in noisy environments.

Notes: The prices above are approximate. The calculations do not include any production expenses. All they can be used for reference only.

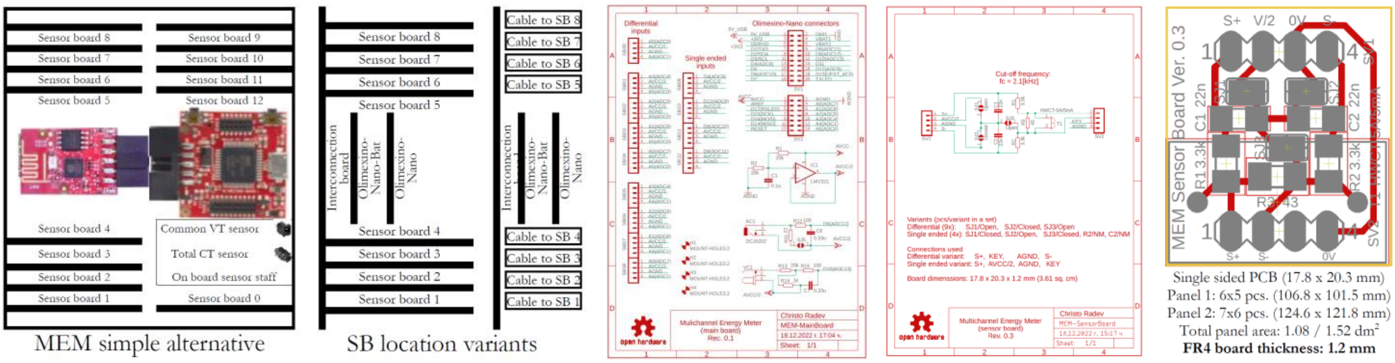
Multichannel Home Electricity Monitoring System (simple alternative)

The simple alternative as hardware will be based on low cost (a hundred euros) and low consumption (a few watts) Linux server like Olimex' OSHW LIME2-SERVER (with battery backup and SSD) and web application written on JavaScript and using Web Sockets (WS). Real time data will be processed by Arduino application working in Atmega32u4. Data will be archived on the SSD. The system could be connected via Gigabit Ethernet, Wi-Fi or 3G/4G Mobile and accessed locally or globally from Internet. The compact and contactless current sensors like HWCT-5A/5mA can be added to an existing electricity switchboard without modifications and additional safety requirements. In case of wireless communication in local network the system will be completely isolated and safe. Of course, general safety rules have to be applied when installing the sensors in the electricity switchboard. In case of wired communication the standard rules for computer equipment powering will be applied.



Real scenario: up to 9 current differential measurement points (16A each), total I_{RMS} ($64A_{AC}$) and V_{RMS} ($220V_{AC}$)

Production candidates: current / voltage sensors, Olimexino-Nano and Olinuxino-Lime2-Server (150€ BOM)



Different interconnection scenarios grant big flexibility of the simple alternative of MEM system

The idea to separate CT resistor and filter on an additional sensor board will simplify the main MEM board and will add flexibility. A single sensor board can be used for both differential and single ended connections to ADC. It can be used in both simple and advanced MEM alternatives. On the other hand the sensor board can be located at CT, main board sides even in the middle. The same idea can be applied for voltage sensors which will make possible to use different kinds of VTs.

Optionally, internal and external temperature (DS18B20 based) and other environmental sensors could be connected as well. The low consumption Lime2-Server with built-in UPS itself can be used to host also other home services like WEB, TOR, NextClowd, HomeAssistant etc.

Built-in analytical and long term observation can be used for optimizing and decreasing the home electricity consumption, from the one hand. On the other hand, the metering accuracy can be certified by an authorized organization and served to control the electricity supply company.

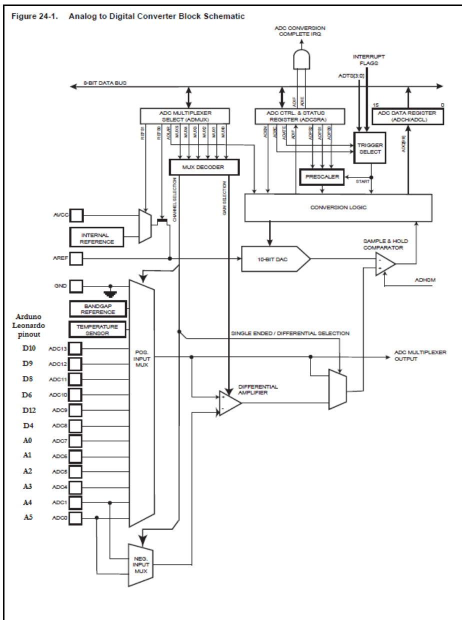
The limitation in monitoring of two-way interconnected homes can be avoided in future by using advanced measurement algorithms and probably more resourceful real time processing unit (based on ARM Cortex-M4 MCUs like STM32F3xx/4xx). The other direction in Multichannel Home Electricity Monitoring System development could be the measurement and the observation of the self-produced electricity from photovoltaic, wind generator, geothermal etc. equipment targeting to reach sustainable green homes.

Consumption control based on time zones and priorities could be added as functionality in addition to metering. In case of unidirectional or two-way connectivity some home appliances can be limited to user defined time zones. In case of self-production of electricity all home appliances can be divided in groups with different priorities and corresponding powering rules. For implementing of such functionality current circuits should be switched on and off using relays controlled by real time processing unit. In case of self-production of electricity without two-way connectivity switching devices should also be used. In such advanced use cases a special electricity switchboard should be used as well.

HWCT-5A/5mA and SCT013-000 100A 50mA measurement scenario based on Arduino ATmega 32u4 (Olimex' OLIMEXINO-NANO board), David Pilling's Differential ADC library and Arduino DiffADCInterrupts sketch

The idea is inspired by OpenEnergyMonitor project, David Pilling's Differential ADC library and appropriate current transformer (CT) sensors offered by Olimex. According to Figure 24-1 and Table 24-4 (Input Channel and Gain Selections) in the Atmel's AVR 8 Atmega32u4 datasheet it can be seen that MCU has 9 differential inputs combined with 3 gain selections for the built-in amplifier. A possible data capture scenario could be Free Running mode with auto trigger enabled and ADC interrupt at sampling end. In such a set up conversion takes 14 ADC clocks. In case of using 9.6 KHz sample rate (divide by 128 pre-scaler) it can be captured 178 samples for 20ms (1 AC cycle) which is enough for precise RMS value calculation of the selected channel. It probably will be possible to calculate sum of squared values in interrupt routine which will stop after each 178-th sample. In main loop it has to be set up the cannel selection before starting capture and will be calculated RMS for given value after that. Two more capture cycles have to be done for calculating of V_{AC} and total I_{AC} taken form electricity mains via transformer and SCT013 connected to the single ended ADC inputs (ADC8 – ADC13). As a result ten RMS values (V_{RMS} and $I1_{RMS}$ – $I9_{RMS}$) can be obtained for 200ms and up to 5 measurements per second will be possible. Of course, additional processing will down this rate but even a single measurement of the AC power for 8+1 home electricity consumers per second is quite attractive and completely reachable.

Figure 24-1. Analog to Digital Converter Block Schematic



Including pinout conformity with Olimexino-Nano (Arduino Leonardo compatible)

Table 24-4. Input Channel and Gain Selections

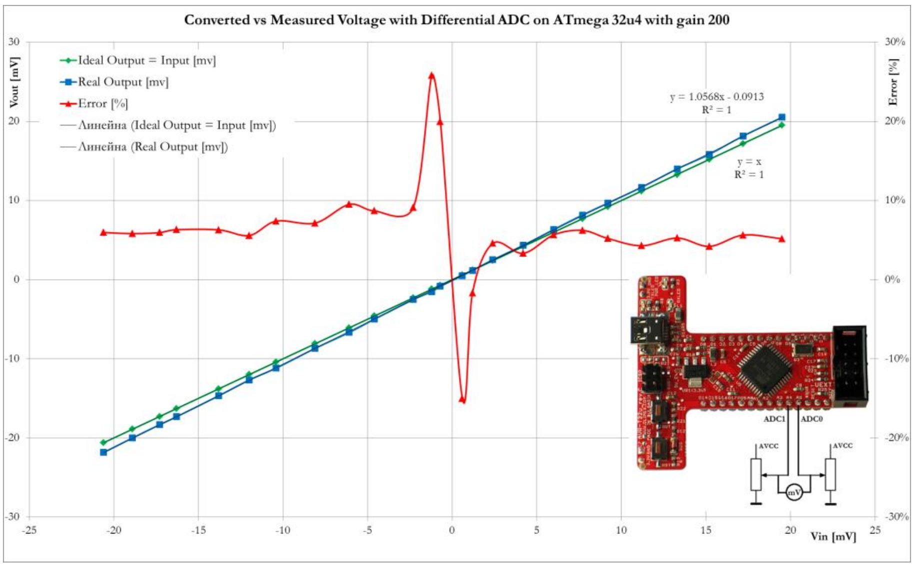
MUX5..0[1]	Single Ended Input	Positive Differential Input	Negative Differential Input	Gain
000000	ADC0	N/A		
000001	ADC1			
000010	N/A			
000011				
000100	ADC4			
000101	ADC5			
000110	ADC6			
000111	ADC7			
001000	N/A	N/A	N/A	N/A
001001		ADC1	ADC0	10x
001010		N/A	N/A	N/A
001011		ADC1	ADC0	200x
001100		N/A		
001101				
001110				
001111				
010000		ADC0	ADC1	1x
010001	N/A	N/A		
010010				
010011				
010100		ADC4	ADC1	1x
010101		ADC5	ADC1	1x
010110		ADC6	ADC1	1x
010111		ADC7	ADC1	1x
011000		N/A		
011001				
011010				
011011				
011100				
011101				
011110	1.1V ($V_{Band Gap}$)			
011111	0V (GND)			

Table 24-4. Input Channel and Gain Selections

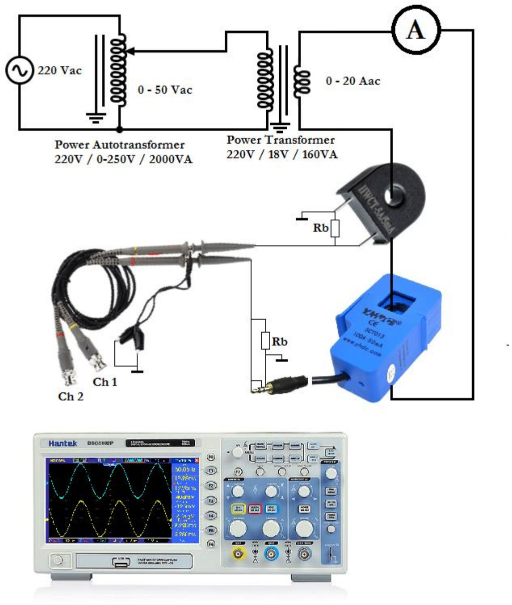
MUX5..0[1]	Single Ended Input	Positive Differential Input	Negative Differential Input	Gain
100000	ADC8			
100001	ADC9			
100010	ADC10			
100011	ADC11			
100100	ADC12			
100101	ADC13			
100110	N/A	ADC1	ADC0	40x
100111	Temperature Sensor			
101000	N/A	ADC4	ADC0	10x
101001		ADC5	ADC0	10x
101010		ADC6	ADC0	10x
101011		ADC7	ADC0	10x
101100		ADC4	ADC1	10x
101101		ADC5	ADC1	10x
101110		ADC6	ADC1	10x
101111		ADC7	ADC1	10x
110000		ADC4	ADC0	40x
110001		ADC5	ADC0	40x
110010		ADC6	ADC0	40x
110011		ADC7	ADC0	40x
110100	N/A	ADC4	ADC1	40x
110101		ADC5	ADC1	40x
110110		ADC6	ADC1	40x
110111		ADC7	ADC1	40x
111000		ADC4	ADC0	200x
111001		ADC5	ADC0	200x
111010		ADC6	ADC0	200x
111011		ADC7	ADC0	200x
111100		ADC4	ADC1	200x
111101		ADC5	ADC1	200x
111110		ADC6	ADC1	200x
111111		ADC7	ADC1	200x

Note: 1. MUX5 bit make part of ADCSRB register.

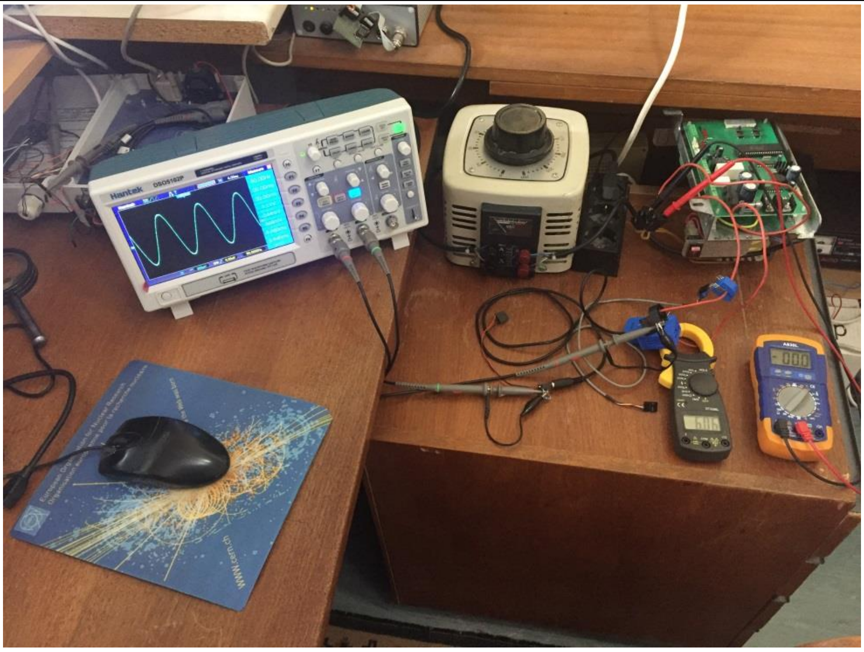
Testing differential inputs on ATmega32u4 with 200 gain of the built-in amplifier

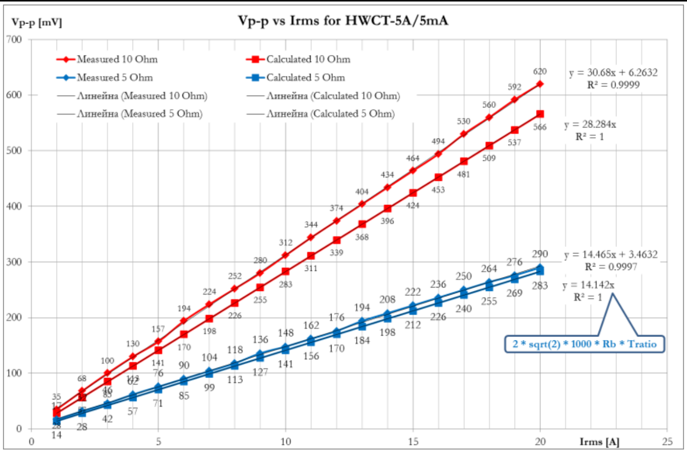


HWCT-5A/5mA and SCT013-000-100A-50mA sensors calibration charts

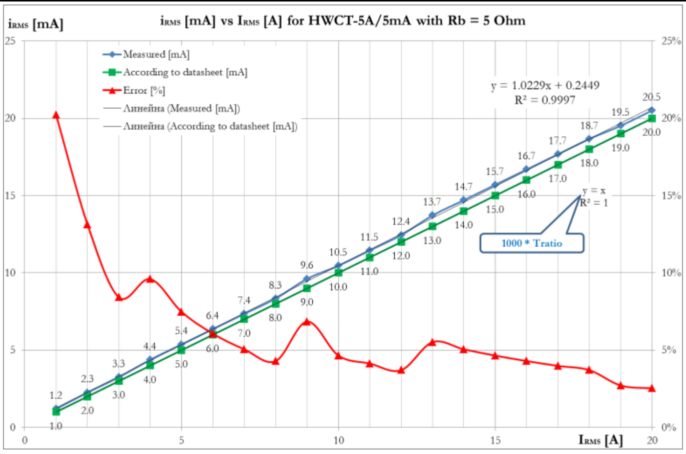


Modified test bed

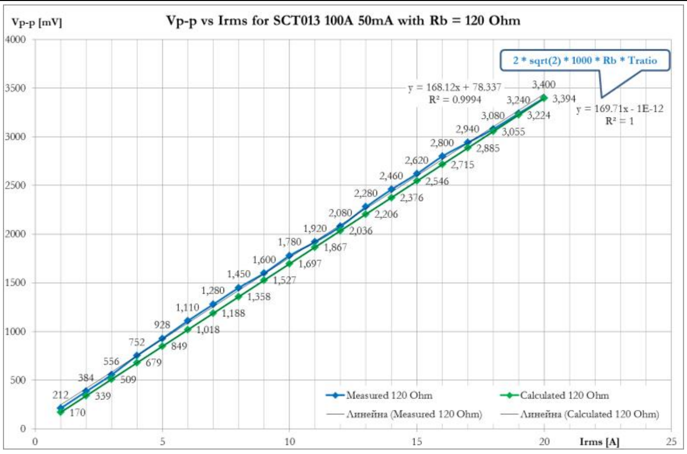




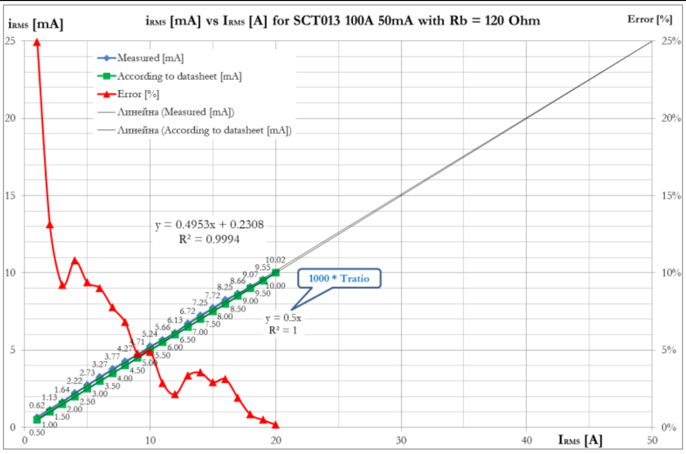
Back calculated T_{ratio} is 1:922 and 1:978 at 10 and 5 Ohm R_b instead of 1:1000 (7.8% and 2.2% error respectively)



To measure I_{RMS} up to 16A and V_{p-p} up to 3.3V R_b should be 7.06 Ohm ±0.1% and gain 10



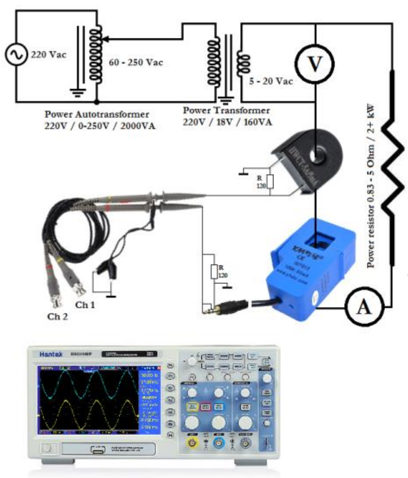
Back calculated T_{ratio} is 1:2019 at 120 Ohm R_b instead of 1:2000 (9.4% error)



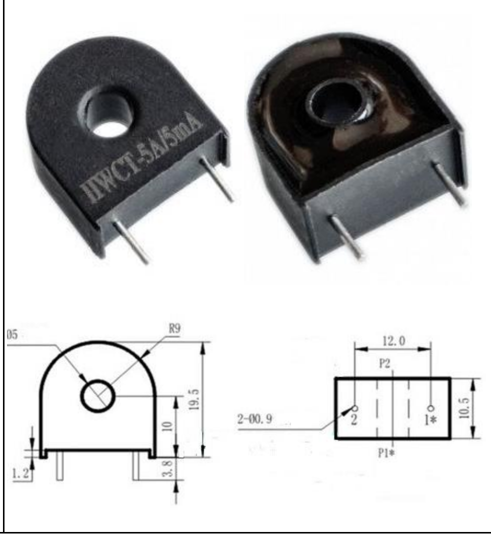
To measure I_{RMS} up to 64A and V_{p-p} up to 3.3V R_b should be 36.1 Ohm ±0.1% and gain 1

Notes: The measurement in the tests till now is not precise enough,
Power circuit current is not more than 20A for safety reasons,
More precise calibration should be done before final usage.

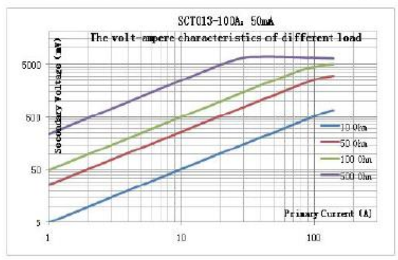
Feature	HWCT-5A/5mA		SCT013-000 100A 50mA	
	Datasheet	Measured	Datasheet	Measured
Nominal current	5 A	1 A	100 A	1 A
Maximum current	20 A		120 A	
Turns ratio	1:1000	1:833	1:2000	1:1667
Current ratio	5A:5 mA	1A:1.2mA	100A:50mA	1A:0.6mA
DC resistance	155 Ohms	45 Ohms		103 Ohms
Load resistor	2 Ohms	120 Ohms	10 Ohms	120 Ohms
Accuracy	±2%		±1%	
Linearity			≤0.2%	



Test bed

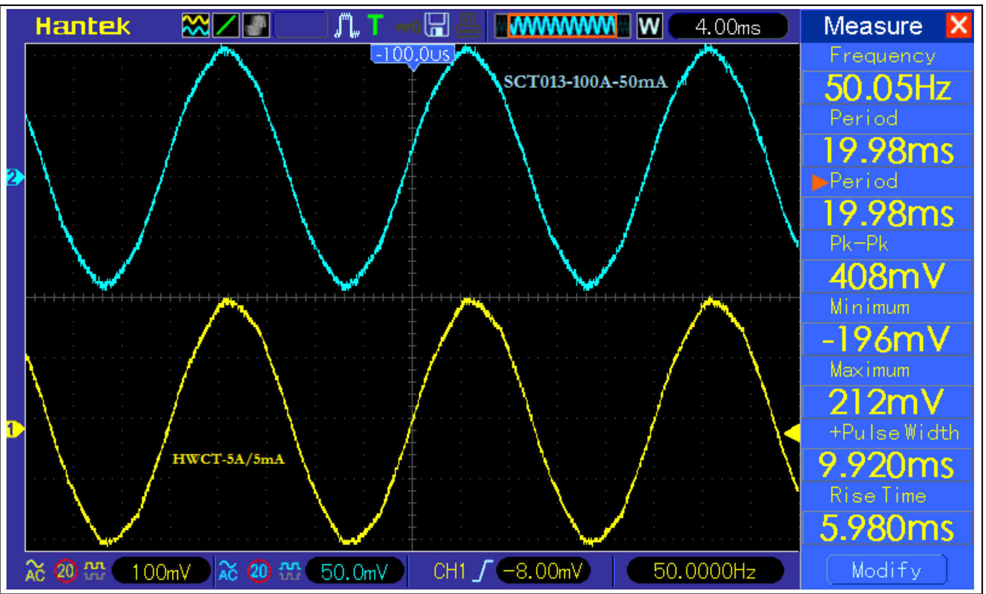


Characteristic curve in different load volt-ampere:



First test results (measured AC voltage at given AC current in the power chain)

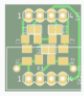
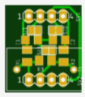
	HWCT-5A/5mA	SCT013-100A 50mA
Test conditions		
R_{pow}	5 Ohms	5 Ohms
V	5 V_{RMS}	5 V_{RMS}
A	1 A_{RMS}	1 A_{RMS}
R	120 Ohms	120 Ohms
Calculations (datasheet based)		
$Vp\text{-}p = 2 * \sqrt{2} * I * R * \text{Turns ratio}$		
Vp-p	**339.4 mV**	**169.7 mV**
Test results		
Ch.	1	2
Scale	100 mV/div	50 mV/div
Vp-p	**408 mV**	**204 mV**
Diff.	**20%**	**20%**



The big difference for the both sensors can eventually be explained mainly with not very precise measurement. On the other hand there is a quite big difference in declared in the data sheet DC resistance (155 Ohms) and measured (45 Ohms) for the HWCT-5A/5mA sensor.

JLCPCB – Chineese PCB manufacturer (sensor board ver. 0.3 order)

SensorBoard-Ver-03-CAMOutputs_Y2(replacefile)
Order Number: Y2-5305664A
Gerber file: SensorBoard-Ver-03-CAMOutputs_Y2(replacefile)
Build Time: 2-3 days
Base Material: FR-4
Layers: 1
Dimension: 20.3 mm* 17.8 mm ~~17.8mm* 20.3mm~~
PCB Qty: 10
Product Type: Industrial/Consumer electronics
Different Design: 1
Delivery Format: Single PCB
PCB Thickness: 1.2
Impedance Control: no
PCB Color: Green
Silkscreen: White
Surface Finish: HASL(with lead)
Deburring/Edge rounding: No
Outer Copper Weight: 1
Gold Fingers: No
Flying Probe Test: Fully Test
Castellated Holes: no
Remove Order Number: No
Paper between PCBs:No
Appearance Quality:IPC Class 2 Standard
Confirm Production file:No
Silkscreen Technology:Ink-jet/Screen Printing Silkscreen
Package Box:With JLCPCB logo
4-Wire Kelvin Test:No

Product Detail	Product File	Price	Order Status	Operate
2022-12-19 | W202212191721250				+ Add new item
 PCB Prototype Order #: Y1-5305664A Build Time: 2-3 days 10 pcs €4.70 Product Details	SensorBoard-Ver-03-CAMOu... Audit Failed 1.Hi Sir/ Madam, there is no board outline in your...	Merchandise Total: €0.00 Shipping Charge: €0.00 Order Total: €0.00	Order Cancelled	Order Details
 PCB Prototype Order #: Y2-5305664A Build Time: 2-3 days 10 pcs €4.70 Product Details	SensorBoard-Ver-03-CAMOu... Data Preparation	Merchandise Total: €4.79 Shipping Charge: €18.17 Customs duties & taxes: €4.52 Order Total: €27.47	In Production The order cannot be cancelled once it has been put into production.	Order Details Invoice

This picture refers to the original order

Submitted	Reviewed	Paid	In Production	Shipped
2022-12-19 21:56	2022-12-20 02:02	2022-12-20 02:02	2022-12-20 21:48	2022-12-25 12:22

This shipment is handled by: **DHL Express**

Delivered

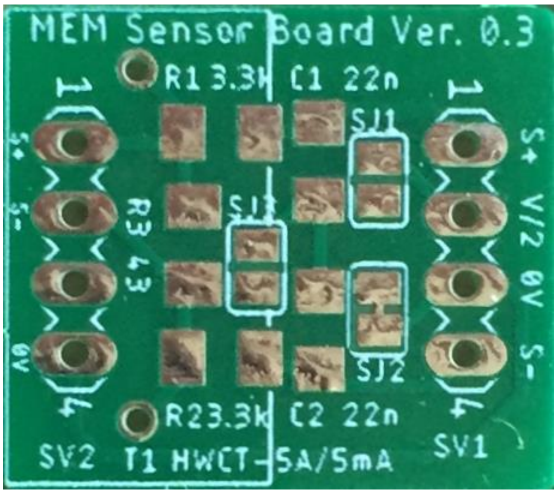
29. December 2022 12:51 Local time, Service Area: SOFIA - BULGARIA

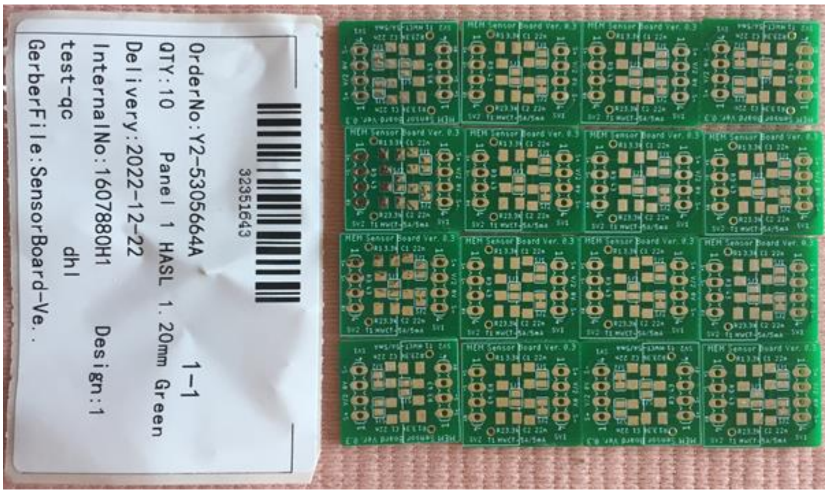
Service Area: ZHUJIANG DELTA AREA - CHINA MAINLAND

Service Area: SOFIA - BULGARIA

2022/12/29 10:51:00 Delivered, PLOVDIV - BULGARIA
2022/12/29 07:12:00 Shipment is out with courier for delivery, PLOVDIV - BULGARIA
2022/12/29 04:23:00 Arrived at DHL Delivery Facility PLOVDIV - BULGARIA, PLOVDIV - BULGARIA
2022/12/28 09:49:00 Shipment has departed from a DHL facility SOFIA - BULGARIA,SOFIA - BULGARIA
2022/12/28 07:42:00 Processed at SOFIA - BULGARIA,SOFIA - BULGARIA
2022/12/28 07:31:00 Clearance processing complete at SOFIA - BULGARIA,SOFIA - BULGARIA
2022/12/28 07:06:00 Shipment is on hold,SOFIA - BULGARIA
2022/12/28 07:05:00 Arrived at DHL Sort Facility SOFIA - BULGARIA,SOFIA - BULGARIA
2022/12/28 05:15:00 Customs clearance status updated. Note - The Customs clearance process may start while the shipment is in transit to the destination.,SOFIA - BULGARIA
2022/12/28 05:01:00 Customs clearance status updated. Note - The Customs clearance process may start while the shipment is in transit to the destination.,SOFIA - BULGARIA
2022/12/28 04:39:00 Shipment has departed from a DHL facility LEIPZIG - GERMANY,LEIPZIG - GERMANY
2022/12/27 23:35:00 Processed at LEIPZIG - GERMANY,LEIPZIG - GERMANY
2022/12/27 20:24:00 Arrived at DHL Sort Facility LEIPZIG - GERMANY,LEIPZIG - GERMANY
2022/12/27 11:58:00 Shipment has departed from a DHL facility BAHRAIN - BAHRAIN,BAHRAIN - BAHRAIN
2022/12/27 09:39:00 Shipment is in transit to destination,BAHRAIN - BAHRAIN
2022/12/26 21:58:00 Shipment has departed from a DHL facility HONG KONG - HONG KONG SAR, CHINA,HONG KONG - HONG KONG SAR, CHINA
2022/12/26 15:53:00 Clearance processing complete at HONG KONG - HONG KONG SAR, CHINA,HONG KONG - HONG KONG SAR, CHINA
2022/12/26 15:52:00 Processed at HONG KONG - HONG KONG SAR, CHINA,HONG KONG - HONG KONG SAR, CHINA
2022/12/26 15:02:00 Arrived at DHL Sort Facility HONG KONG - HONG KONG SAR, CHINA,HONG KONG - HONG KONG SAR, CHINA
2022/12/26 12:48:00 Customs clearance status updated. Note - The Customs clearance process may start while the shipment is in transit to the destination.,HONG KONG - HONG KONG SAR, CHINA
2022/12/26 12:11:00 Clearance processing complete at ZHUJIANG DELTA AREA - CHINA MAINLAND,ZHUJIANG DELTA AREA - CHINA MAINLAND
2022/12/26 10:18:00 Clearance event,ZHUJIANG DELTA AREA - CHINA MAINLAND
2022/12/26 09:41:00 Arrived at DHL Sort Facility ZHUJIANG DELTA AREA - CHINA MAINLAND,ZHUJIANG DELTA AREA - CHINA MAINLAND
2022/12/26 08:25:00 Shipment has departed from a DHL facility ZHUJIANG DELTA AREA - CHINA MAINLAND,ZHUJIANG DELTA AREA - CHINA MAINLAND
2022/12/26 07:15:00 Processed at ZHUJIANG DELTA AREA - CHINA MAINLAND,ZHUJIANG DELTA AREA - CHINA MAINLAND
2022/12/26 06:48:00 Shipment picked up,ZHUJIANG DELTA AREA - CHINA MAINLAND

2022/12/25 12:22:37 Packaged,waiting for pick up by the carrier,Tracking #: 9400645741
2022-12-25 06:22:16 Awaiting carrier pickup Except Sunday, orders packaged before 12am normally will be picked up on the same day, otherwise postponed to the next pick-up date.
2022-12-24 09:13:48 All orders have arrived at shipping center, ready to be packed.
2022-12-22 17:23:08 Y2-5305664A arrived at shipping center.
2022-12-20 15:45:57 In Production Y2-5305664A is producing in Factory JLCPCB Factory 3. Estimated finish time: 2022-12-22 21:32:34, view progress
2022-12-20 02:27:39 All orders finished data preparation, ready for PCB fabrication.
2022-12-20 02:27:39 Y2-5305664A manufacturing data finished.
2022-12-19 20:02:50 Data Preparation Order paid, waiting for engineers to produce the manufacturing data.
2022-12-19 16:06:04 All orders have been reviewed, waiting for payment now.
2022-12-19 15:56:26 Reviewing Y1-5305664A has been replaced by Y2-5305664A, waiting for file review.
2022-12-19 14:17:42 Y1-5305664A audit failed, you can replace files when problem solved.
2022-12-19 11:22:01 Order submitted.Waiting for file review, review will be completed in 10-60 mins when business hours.





Component orders (Comet.bg, Farnell.com, Olimex.com, ANG-Bg.com etc.)

Поръчка No				11480674/16.12.2022							
№	Код на стока	Каталог	Продукт	Описание	Поръчано количество	Единична цена	Стойност BGN	ДДС BGN	Общо BGN	* Време за доставка
1	6380	Comet	RW25MF 47R 1%	рез.металослоен 1/4W(2.5x6.8) 1% 50ppm 47R	50	0.09736	4.87	0.97	5.84	На склад
2	35297	Comet	R1206 39R 1% YAG	RES SMD 1206 1% 100ppm 39R 1/4W	100	0.02067	2.07	0.41	2.48	1 раб.ден
3	35445	Comet	R1206 43R 1% YAG	RES SMD 1206 1% 100ppm 43R 1/4W	100	0.02067	2.07	0.41	2.48	1 раб.ден
4	35310	Comet	R1206 51R 1% YAG	RES SMD 1206 1% 100ppm 51R 1/4W	100	0.02067	2.07	0.41	2.48	1 раб.ден
5	5793	Comet	C1206 22nF 100V X7R SAMSUNG	22nF 100V X7R +-10%	100	0.08397	8.4	1.68	10.08	1 раб.ден
6	24962	Comet	R1206 3.3K 1% YAG	RES SMD 1206 1% 100ppm 3.3K 1/4W	100	0.02067	2.07	0.41	2.48	1 раб.ден
7	25331	Comet	PNB1X4	съединител гнездов, височина на тялото 14mm, 1x4, прав за кабел, P2.54мм - основа	100	0.08235	8.24	1.65	9.88	1 раб.ден
Всичко							29.79	5.96	35.75	

Поръчка No				11480675/16.12.2022						
№	Код на стока	Каталог	Продукт	Описание	Поръчано количество	Единична цена	Стойност BGN	ДДС BGN	Общо BGN	* Време за доставка
1	3881	Comet	AP351B	захранваща букса ?2.5mm, L 9mm, гнездова	5	0.81	4.05	0.81	4.86	На склад
2	24563	Comet	YDJ-1136	захранваща букса ?2.5mm	5	0.51	2.55	0.51	3.06	На склад
3	3970	Comet	YPJ-8174X	букса O 3.5mm	5	1.3	6.5	1.3	7.8	1 раб.ден
Всичко							13.1	2.62	15.72	

Поръчка No				11480676/16.12.2022						
№	Код на стока	Каталог	Продукт	Описание	Поръчано количество	Единична цена	Стойност BGN	ДДС BGN	Общо BGN	* Време за доставка
1	2857740	Farnell	ATM90E32AS-AU-R	POLY PHASE ENERGY METERING IC, TQFP-48	5	8.99	44.95	8.99	53.94	3-4 раб.дни до склад на Комет Електроникс
2	2445266	Farnell	74HC85PW,118	COMPARATOR, MAGNITUDE, 4CH, TSSOP-16	5	1.3	6.5	1.3	7.8	3-4 раб.дни до склад на Комет Електроникс
Всичко							51.45	10.29	61.74	

Поръчка No				11480678/16.12.2022						
№	Код на стока	Каталог	Продукт	Описание	Поръчано количество	Единична цена	Стойност BGN	ДДС BGN	Общо BGN	* Време за доставка
1	2819289	Farnell	9C-16.384MBBK-T	CRYSTAL, 16.384MHZ, 20PF, 11.4MMX4.35MM	5	0.29	1.45	0.29	1.74	3-4 раб.дни до склад на Комет Електроникс
2	1825373	Farnell	LMV321WG-7	IC, OP AMP, 2.7V/5.5V, SOT25	5	1.18	5.9	1.18	7.08	3-4 раб.дни до склад на Комет Електроникс
Всичко							7.35	1.47	8.82	

Поръчка No				11480685/16.12.2022						
№	Код на стока	Каталог	Продукт	Описание	Поръчано количество	Единична цена	Стойност BGN	ДДС BGN	Общо BGN	* Време за доставка
1	46364	Comet	SN74LVC1G10DBVR	NAND Gate 1-Element 3-IN CMOS	5	0.34	1.7	0.34	2.04	1 раб.ден
2	24965	Comet	R1206 10K 1% YAG	RES SMD 1206 1% 100ppm 10K 1/4W	100	0.02067	2.07	0.41	2.48	1 раб.ден
3	4453	Comet	R1206 20K 1%	RES SMD 1206 1% 100ppm 20K 1/4W	100	0.0366	3.66	0.73	4.39	1 раб.ден
4	4450	Comet	R1206 22R 1%	RES SMD 1206 1% 200ppm 22R 1/4W	100	0.0366	3.66	0.73	4.39	1 раб.ден
5	29770	Comet	R1206 1.0K 1%	RES SMD 1206 1% 100ppm 1.0K 1/4W	100	0.0366	3.66	0.73	4.39	На склад
6	48000	Comet	LQH32CN220K23L	дросел 22uH 710mOhm 250mA 10%	20	0.17	3.4	0.68	4.08	1 раб.ден
7	23499	Comet	C1206 100nF 50V X7R SAMSUNG	100nF 50V X7R +-10%	50	0.04077	2.04	0.41	2.45	1 раб.ден
8	8307	Comet	C1206 10uF 16V X7R SAMSUNG	10uF 16V X7R +-10%	20	0.11	2.2	0.44	2.64	1 раб.ден
Всичко							22.39	4.48	26.87	

Olimex Ltd., 2 Pravda Str,Plovdiv 4000, Bulgaria
phone: +359-32-626259, fax: +359-32-621270

	Изделие	Митнически код	Количество		Цена		Общо	
1	LIME2-SERVER-128GB-SSD	8543900090	1	бр.	211.2264	BGN	211.23	BGN
2	AVR-T32U4	8543900090	1	бр.	25.3276	BGN	25.33	BGN
3	Допълнително - ППП		1.5	%	236.5600	BGN	3.55	BGN
4	ДДС		20	%	240.1100	BGN	48.02	BGN
							288.13	BGN

	Изделие	Митнически код	Количество		Цена		Общо	
1	CAR-BATTERY-METER	8543900090	1	бр.	9.7790	BGN	9.78	BGN
2	USB-POWER-METER	8543900090	1	бр.	6.8453	BGN	6.85	BGN
3	SNS-CURRENT-CT013-100A	90303399	1	бр.	19.4602	BGN	19.46	BGN
4	SNS-CURRENT-HWCT-5A-5MA	90303399	10	бр.	1.7602	BGN	17.60	BGN
5	Speedy стандарт - INSURED		1	бр.	7.1519	BGN	7.15	BGN
6	Допълнително - ППП		1.5	%	60.8400	BGN	0.91	BGN
7	ДДС		20	%	61.7500	BGN	12.35	BGN
							74.10	BGN

Vikiwat – Plovdiv (https://vikiwat.com/):

Microphone cable, 2x0.125mm2, XLR, Cu, grey, COTR15011GY100, NEDIS	**– 1,20 BGN**	**10m**
Heat shrinkable hose 4mm, 2:1, black	– 0,45 BGN	5m

Conrad – Plovdiv (http://steinberger.bg/)

AC-AC Adapter 9 V/600 mA (http://ang-bg.com/)	**– 11,82 BGN**	**1 pc.**
Heat shrinkable hose 2 mm, 2:1, black	– 0,41 BGN	5 m

Google for: cd rom drive audio cable (https://www.circuitspecialists.com/10-190.html)