

Meters for domestic kWh metering

Measurements on site, discussions, literature search and lab tests

February – March 2010

Summary

There is a suspicion that utility's customer's electricity meters have errors. Measurements on site do not reveal any irregularities. Five meters have been tested in lab, three of the offending brand and type and two other brands. The results show that all meters behave reasonably well under constant and cycled load. When subject to cycled and thyristor (dimmer) controlled load, the suspect meters show errors that are literally hundreds of percent (tables on page 12 and 13) while 'brand B and C' behave flawlessly with errors in the one – two percent range. Test set-up is available at GKE lab (can also be moved) for verification or extended tests.

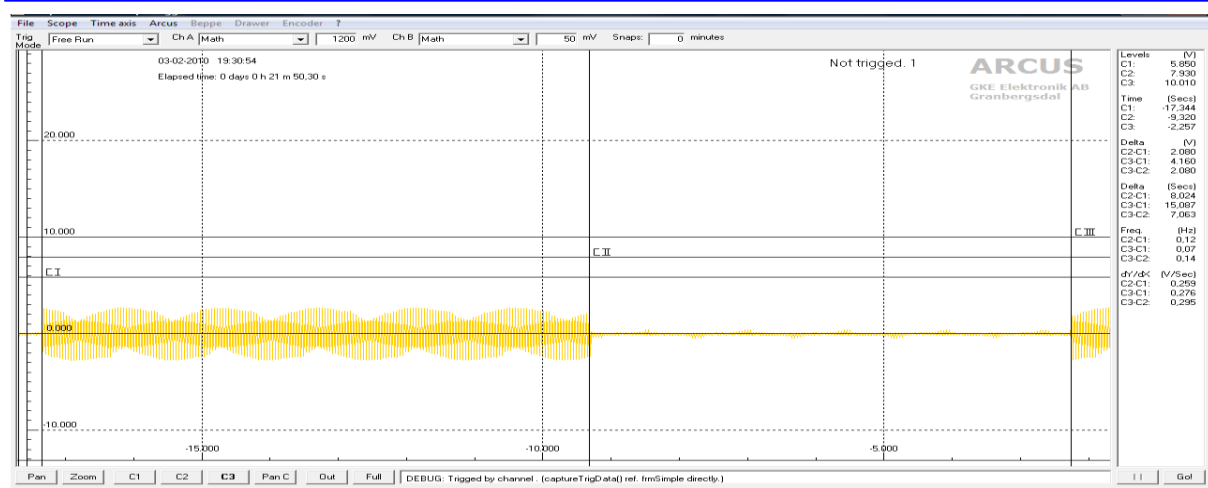
Background

One of the utility's customers has observed that his energy bill seems to be on the high side. A modest estimation from his side is that he is paying for around 15 percent more energy than he actually uses. The utility has done extensive tests with double and triple meters, that have verified the customer's observations. They also hired an external consultant, S-E Berglund Elkonsult AB, to find out if there are any anomalies in grid or installation. Nothing spectacular was found. Meter supplier has also made measurements on site, but no results from that investigation are available to the utility. When asked, the supplier only mentions that he "Found something".

There was a suspicion that high-frequency phenomena or extraordinary aberrations were present and GKE was contacted to find out if that was the case. Measurements on site were made Thursday February 11, 2010. This report is about findings from that occasion as well as observations made during discussions and lab measurements made by GKE.

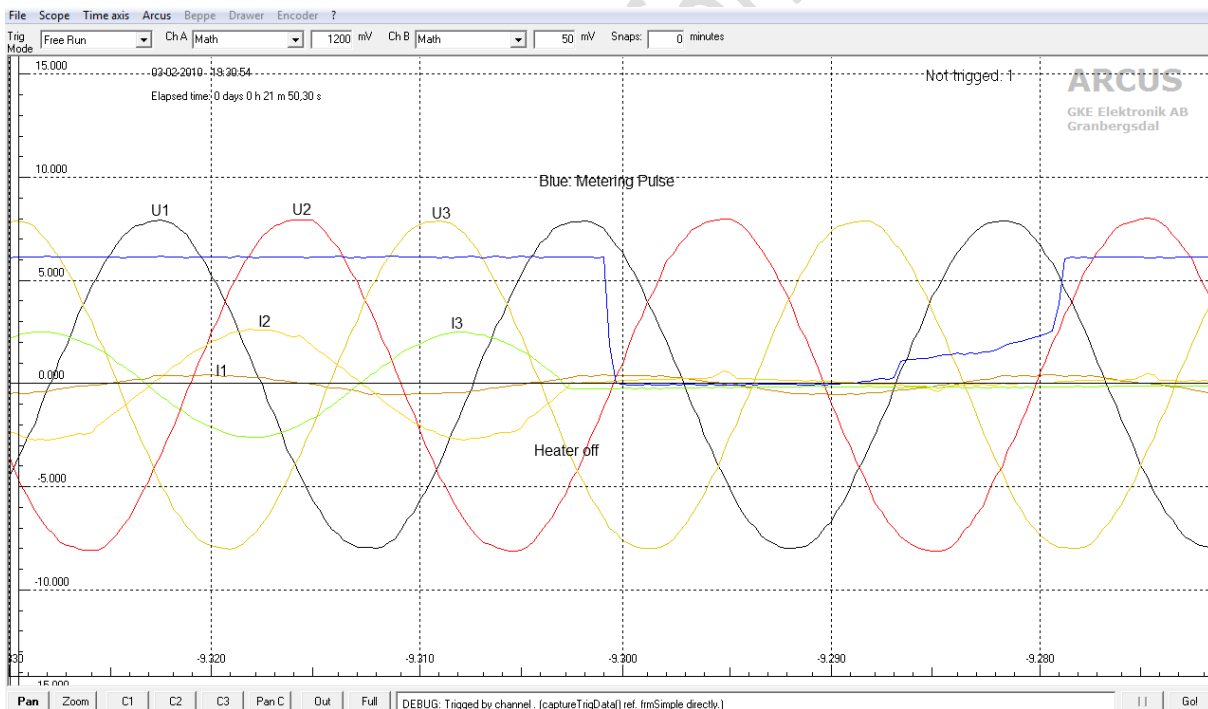
Findings on site

Several measurements were made with different loads activated. No high-frequency phenomena were found and no exceptional distortion. One characteristic load is a 2 kW heater connected to 400 V, it is cycled on/off quite rapidly. A recording is shown in picture 1 (visual aliasing present).



Picture 1. Heater cycled on for 8 seconds and off for 7 seconds (C1, CII and CIII)

A zoomed (around 250x horizontally) part of picture 1 shown in picture 2. Picture 1 shows only one current for less clutter, picture 2 shows all channels.



Picture 2. Voltages and currents zoomed. Metering pulse also shown.

Currents I2 and I3 are obviously one and the same, flowing between U2 and U3 (400 V connection). U2 has an additional switch mode supply connected, the little hump in I2 coincides with U2 peak, which is a sure sign. U1 does not have much connected, and the little there is seems to be a linear load that draws a sinewave with inductive phase-angle.

Discussion after visit on site

When looking through the recordings, one unexpected feature was noted – the fact that the metering pulses seemed to be delayed with regard to actual power. There must always be a delay, producing a pulse ‘in advance’ is impossible, but the delays observed were longer than expected. Furthermore, there seemed to be a bias with regard to power cycling so that delay was less at the beginning of a high power cycle than at the end. On several occasions, there was also an extra pulse following close to the ‘ordinary’ pulse after power was cycled back to low. Such a bias could be an explanation to the observed differences between recorded energy and expected energy.

It was decided that GKE should have a closer look at the power/pulse frequency relation and see if there was a systematic error in the meter type.

Tests at GKE lab

It was soon realized that a wider variation in cycle duration and duty cycle was needed in order to see any significant and consistent differences between real energy and energy recorded by the meter. The utility sent a meter to GKE and a set of tests were carried out. The test plan included:

1. Calibration of transducers and recording equipment with constant power
2. Building a pulsed load that could be adjusted with regard to power levels and on/off cycling
3. Design and test of an Excel spreadsheet that would allow close examination of recorded energy vs actual energy
4. Verification that transducers and recording equipment errors were within acceptable limits also when load was phase controlled (thyristor control) and cycled
5. Running the actual tests with load in a range from 35 W up to near 3 kW and cycle times from half a second to tens of seconds.
6. Analysis and, if necessary, rechecking results
7. Report

Transducers and recording equipment calibration

Even if the task is not an audit round, it is important to have all tools in good order. So, a rough test and calibration was done. It is described in appendix 1.

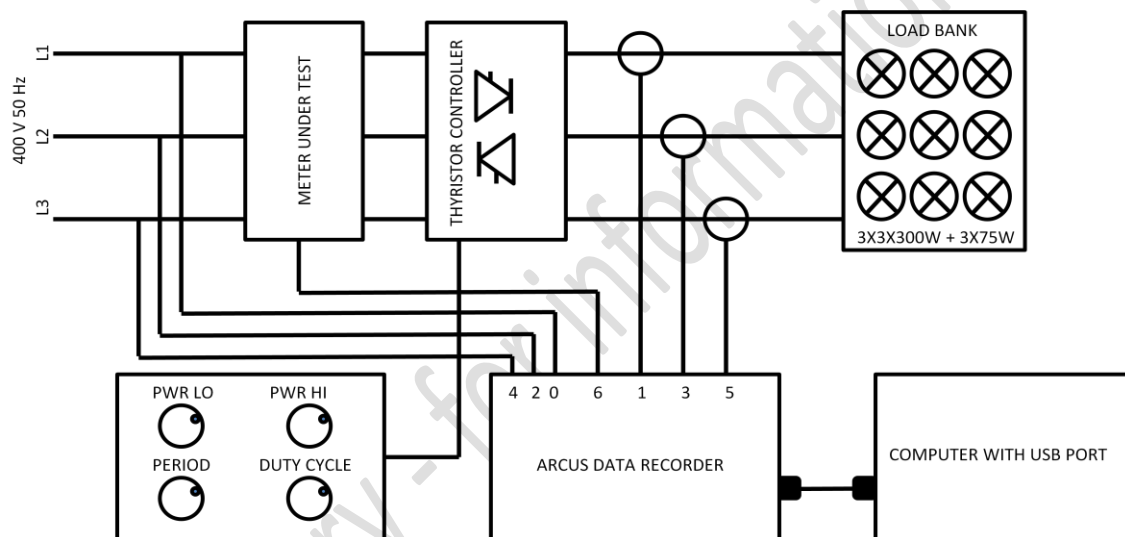
The tests and calibrations resulted in a couple of changes in the original plans: Introduction of two power levels instead of switching one power level on/off and substituting shunt resistors for current clamps.

The two power levels were necessary in order to avoid cold start inrush current in the incandescent lamps in the load bank. Starting current up to four times rated current was recorded. Such high peaks consume at least two bits of resolution in the A/D converter and by using a preheat power level, the

inrush current could be reduced to insignificant levels. Also, it is necessary to have a certain power flowing through the meter in order to maintain pulse output. The Ws pulse goes constantly true if power is zero and that disturbs the measurements.

AC current clamp transformers work well for continuously varying currents. But with thyristor controlled currents, there is a disturbing DC level when primary current is zero. Rather than discussing if that is tolerable or not, we decided to use shunt resistors with low inductivity instead. The nominal scale factor is 1 V/A. Small adjustments for actual resistance are made in the spreadsheet for power calculation, but not in the ARCUS recordings.

Test set up



Picture 3. Test set up, simplified diagram. Auxiliary power, N and PE connections not shown.

The test rig is an ad hoc collection of bits and pieces available in the lab. The control unit (lower left) is a function generator with settable cycle time and duty cycle. It controls a relay that connects a potentiometer (PWR HI) to the control input of the 400 V, 35 A thyristor controller. The low power level is set with another potentiometer (PWR LO).

The load bank is a set of incandescent lamps that are used for various tests and are very well suited also for this test. One more load bank is available (with 12x300 W) for a total load of around 5.5 kW. Lamps can easily be unscrewed for different loads (in addition to setting levels with the control unit) and also for unsymmetrical loads.

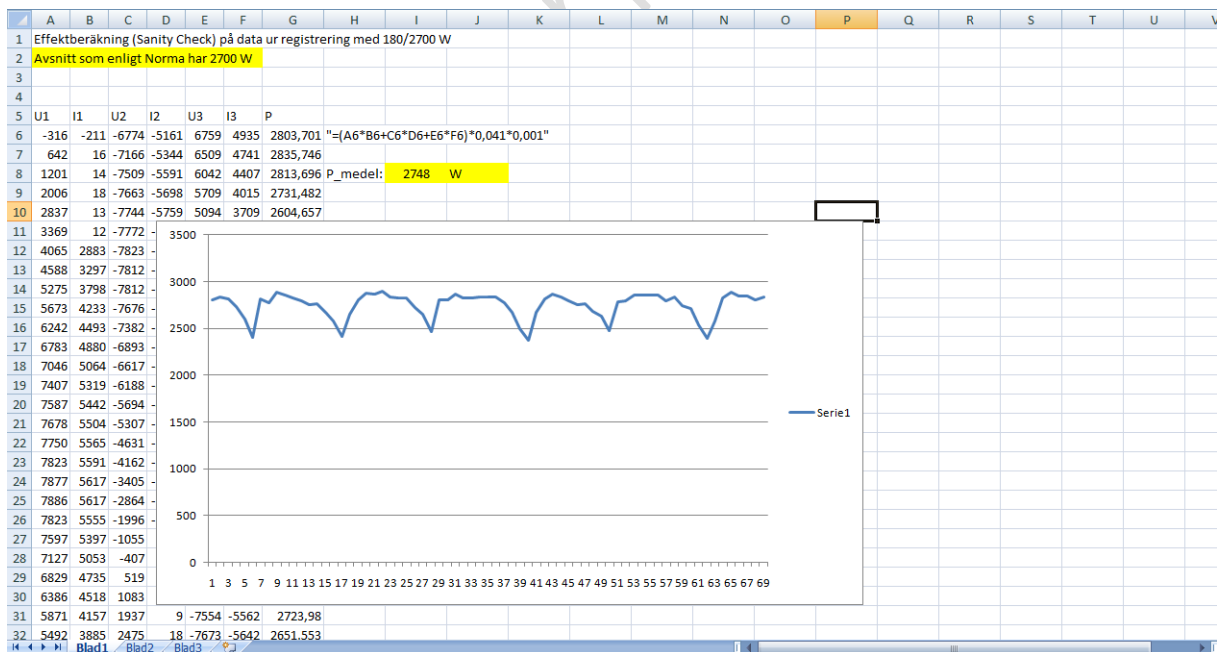
Heavy duty alligator clips connect the load bank to the thyristor controller output. It is possible to connect them to the thyristor controller input for 'cleanest' possible waveforms. Load levels then have to be controlled by screwing lamps in and out.

The ARCUS has ten channels available. Channel 6 is used for metering pulses, which are picked up from the LED on front of the meter under test. A dual pulse counting and comparison feature is available, but is not used in this application. ARCUS 'talks' to the PC over a USB link and data are streamed directly to disk. Data can then be used in Matlab or Excel. The ARCUS software has generous cursor measurement possibilities, there is also a possibility to define 'palettes' with measurements crafted to different applications. A presentation and a data sheet are available in appendix 2.

The Excel sheet

The rather high sampling rate of the ARCUS results in a massive amount of data. A 60 seconds recording produces close to 200 000 lines with ten columns in the Excel sheet. The tight sampling and good accuracy makes accurate calculation of power and energy, also with very distorted waveforms, possible. The main error sources are the voltage and current transducers, which can be calibrated against known good instruments see appendix 1. There is also a possible source of inaccuracy in the exact determination of the sample rate that will affect energy calculations. That is also discussed in appendix 1.

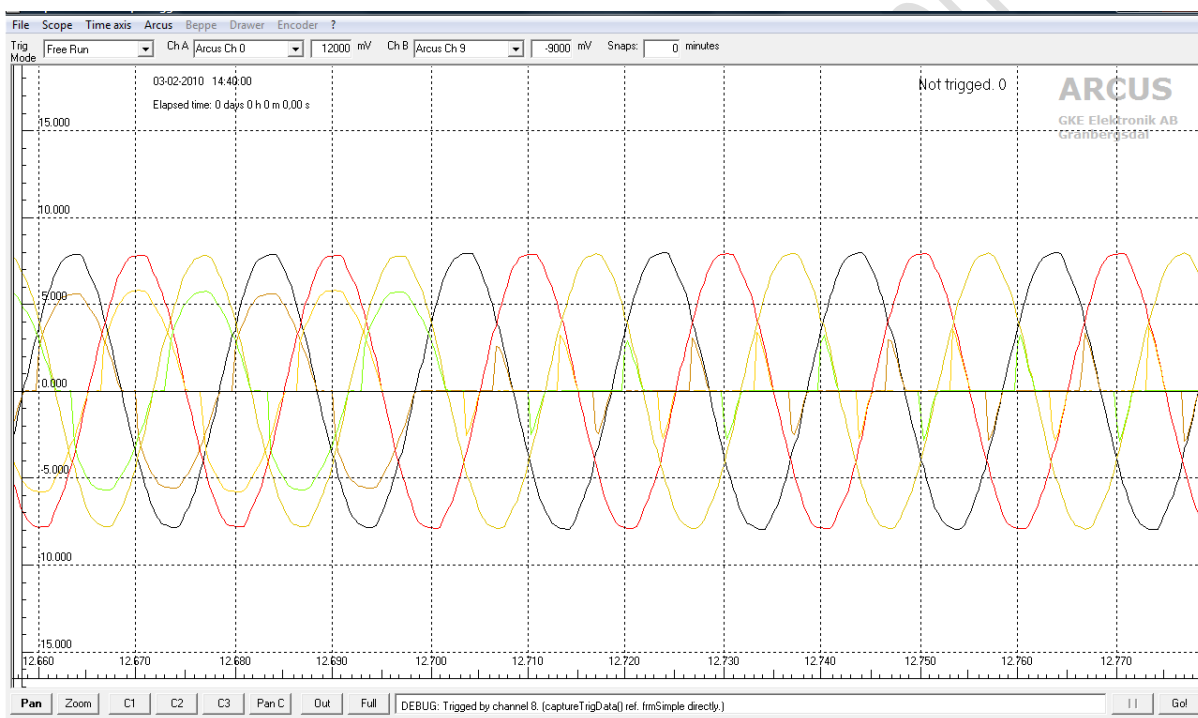
A sample Excel sheet is shown in picture 4.



Picture 4. Excel sheet.

The example Excel sheet shows a 'sanity check' made with around 2700 W power level. Columns A – F contain voltages and currents. The values shown are in millivolts and the scale factors used are 0.041 V/mV and 0.001 A/mV.

Column G calculates instantaneous power using the formula shown in box H6. The resulting graph is shown as Serie 1. This graph should be a straight line (power is constant in a three-phase sine wave system), but it is not. The reason is that we a) have some distortion in the waveforms and b) that the first part of each current cycle is cut out by the thyristors. Picture 5 shows an example of the waveforms resulting in the data in picture 4. The yellow box "P_medel" is the mean power in column G. It corresponds quite well, error is less than 2 percent, to the power measured with the Norma class 0.2 electrodynamic power meter. Proof that the sanity check worked out well.



Picture 5. Showing power being switched from high to low level.

Picture 5 shows maximum power during the first 400 milliseconds, and thereafter minimum power level. The different traces can be identified using the international resistor colour code (0=black, 1=brown, 2 is red etcetera).

It is interesting to note that the current peaks are low just after the switch from high to low power. The reason is an 'inverse inrush effect' where the filaments are quite hot at first and then cool down so that resistance decreases and current peaks increase.

That fact that the first part of the sine wave (current) is missing also at maximum power level results in the variations of total power shown in the graph in picture 4.

Lab tests

First run, one meter tested

The test set-up shown in picture 3 was used for preliminary tests of one of the offending meters. S0 pulses were picked up optically from the LED on front of the meter and the blink rate was compared to recordings made with the ARCUS and a modified program.

The meter behaved well as long as the load was constant and linear. Cycled load and phase controlled load resulted in large deviations between meter perception of power and what was measured with ARCUS/Excel and also indicated by the analogue meter.

Discussions with officers at the utility led to a decision to test not just one, but several, of the offending meters. Two other meter brands should also be tested and comparison should be made within the group of meters as well as to actual power and energy measured by the ARCUS/Excel system and the analogue class 0.2 electrodynamic meter. So, we were now testing five meters in all. The meters will be identified as #1, 2, 3, 4 and 5 in the following tables and discussions. #1 is the original meter, #2 and 3 are same brand and type while #4 and 5 are other brands.

The original plan, to use the S0 outputs for meter pulses, did not work. Meters #1 – 3 have coded output signals and not the simple Ws/pulse relation found in the panel LEDs. Meters #4 and 5 have the simple Ws/pulse relation on their S0 outputs. To resolve the situation, a set of improved optical pick-ups was fabricated and used for all meters. Picture 5 shows part of the test set-up. The optical pick-ups (black/yellow wires) are seen attached to the front of the meters.



Picture 5. Test set-up.

All meters were connected in series and then, via a thyristor module, to the load bank seen to the left. There is also a power relay parallel to the thyristor module for direct switching without any phase delay. Thyristor module and relay are controlled by the function generator situated between meters and analogue instrument. A set of shunt resistors and their cooling fan can be seen just to the right of the function generator. The ARCUS data acquisition unit is to the extreme right in picture 5.

Test variables

The only variable that isn't changed during the tests is the mains voltage and its frequency. It remains at its incoming value and is not controlled in any way. All other variables can be changed within wide limits. Table 1 shows the possible variations. All domestic load variations can be run, except motor loads, computers, TV sets, low energy lamps and other similar equipment. They can, however, be added to the load bank if needed.

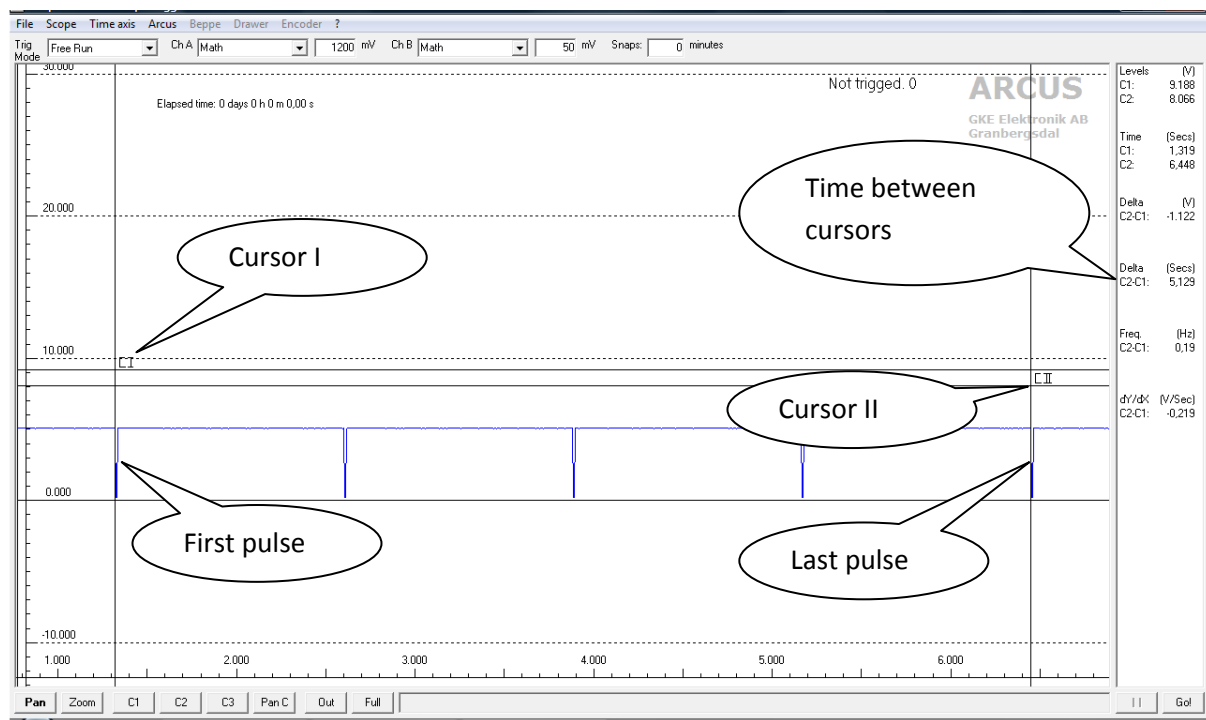
Variable type	Controlled by	Limits	Remark
Total Load	# of lamps connected	0 – 2925 W	Nominal power at 400 V
	Thyristor phase angle	10 – 180 degrees	0 – 2850 W
Load period	Relay	0.5 – 10 seconds	
	Thyristors	0.1 – 10 seconds	
Duty Cycle	Relay	10 – 90 %	Only when period > 1 s
	Thyristors	10 – 90 %	Over full range
Load imbalance	# of lamps connected	0 – 100 %	100 % when all lamps in one phase are disconnected
Phase angle	Thyristors	0 – 170°	Delay in current on
“True” phase angle	Re-arranging load between phases	None, but restricted to certain angles	Phase angle changed in steps by connecting “wrong way”
Distortion	Thyristors	0 – ‘very high’	Highest distortion at 170°

Table 1. Load characteristics and limits.

The number of possible combinations is close to infinite, so a set of variable combinations was decided on. The tests are presented in the order they were carried out.

Test method

All meters are connected in series and to one and same mains voltage. Different loads were run and all data were logged with an ARCUS recorder. Six channels record voltages and currents and four channels record Ws-pulses output via the LED on the meter's front panel. Time between number of pulses and number of pulses were counted from the recordings and corresponding power level calculated. U and I recordings are used to calculate power in Excel. Picture 6 shows the principle.



Picture 6. Showing principle for pulse evaluation in ARCUS.

The number of pulses shown is five. The number of intervals between pulses is four. Each pulse interval represents 3600 watt-seconds (or joule) and by dividing total energy (in this case 4×3600 Ws) by total time, an accurate measure of the power – as perceived by the meter – over the interval can be calculated. In this example, the power is $4 \times 3600 / 5.129 = 2808$ W.

ARCUS can accept up to four Ws pulse channels and it is thus possible to compare four meters under identical conditions. Comparison can be made against a 'known-good' meter or against power calculated from ARCUS collected voltage and current data.

The power metering function in ARCUS is based on the samples collected during the test and a typical 30 seconds run results in around 100 000 data points for each channel. Or, in other words, 70 samples per mains cycle (at 50 Hz). It is, therefore, possible to measure true power also when waveforms are badly distorted or severely cut by thyristor phase control.

The power calculation can be done in Excel, but a 'pulse_search_and_Power_calculator' module is available in ARCUS for computers that do not have Office installed or when the simplicity of working within one program environment is preferred over the 'bells and whistles' that Excel excels in.

Test with continuous load, no switching, no thyristors

Four meters were tested in a test run with direct on line connection and power level selected by screwing lamps out or in the load bank.

Three power levels were used with all lamps available (3x975 W), medium level (2x300 W) and low level (3x75 W). All power levels are nominal, the exact power is dependent on mains voltage and the actual power consumed by the lamps.

Continuous power, no switching, no thyristors

Maximum power, 60 seconds recording.

Meter	Reading 1	Reading 2	Power	Remarks
1	46 pulses	58.989 s	2807 W	
2	46 pulses	58.989 s	2807 W	
3				
4	46 pulses	59.188 s	2798 W	
5	20 pulses	2.578	3161 W	10 000 pulses/kWh HIGH
W-meter				
ARCUS			2826 W	

Medium power, 60 seconds recording.

Meter	Reading 1	Reading 2	Power	Remarks
1	20 pulses	42.274 s	1703 W	
2	22 pulses	44.325 s	1787 W	
3				
4	20 pulses	42.319 s	1701	
5				
W-meter				
ARCUS			1791 W	

Low power, 60 seconds recording.

Meter	Reading 1	Reading 2	Power	Remarks
1	3 pulses	46.244 s	234 W	
2	3 pulses	46.429 s	233 W	
3				
4				
5				
W-meter				
ARCUS			239 W	

Looks just about right. Meter 5 high in one case. Meters 1 and 2 lower than meter 5 and ARCUS in one case. More on meter 5 later.

Test with on/off switching using power relay – no thyristors

Maximum power, 60 seconds recording, 1 Hz, 50 % Duty Cycle

Meter	Reading 1	Reading 2	Power	Remarks
1	17 pulses	38.925 s	1572 W	Double checked
2	15 pulses	36.704 s	1667 W	Double checked
3				
4				
5				
W-meter				
ARCUS			1531 W	Inrush current clipped on negative side

Medium power, 60 seconds recording, 1 Hz, 50 % Duty Cycle

Meter	Reading 1	Reading 2	Power	Remarks
1	11 pulses	41.707 s	949 W	
2	11 pulses	41.665 s	950 W	
3				
4				
5				
W-meter				
ARCUS			966 W	

Low power, 60 seconds recording, 1 Hz, 50 % Duty Cycle

Meter	Reading 1	Reading 2	Power	Remarks
1	1 pulse	29.572 s	122 W	
2	1 pulse	29.980 s	120 W	
3				
4				
5				
W-meter				
ARCUS			126 W	

Power cycling between 0 and nominal power cannot be done with too low a frequency. Most meters switch off below a certain current level. Cycling at 1 Hz is safe and does not switch meters off.

Power cycling was believed to one of the reasons for meter errors. But it does not seem to influence meters significantly. At least not when switching at 1 Hz. Next test is with thyristor controlled switching. The customer's load seemed to be thyristor controlled.

Pulsed load, thyristor controlled switching

Nominal maximum power 2700 W, 1 Hz, 50 % Duty Cycle

Meter	Reading 1	Reading 2	Power	Remarks
1	13 pulses	28.289 s	1654 W	HIGH
2	13 pulses	28.442 s	1645 W	HIGH
3				
4	11 pulses	27.664 s	1431 W	OK
5	20 pulses	4.892	1472 W	10 000 pulses/kWh OK
W-meter				
ARCUS			1470 W	

Nominal maximum power 2700 W, 1 Hz, 12 % Duty Cycle

Meter	Reading 1	Reading 2	Power	Remarks
1	10 pulses	26.795 s	1344 W	VERY HIGH
2	10 pulses	26.377 s	1365 W	VERY HIGH
3				
4	3 pulses	21.205 s	509	OK
5	20 pulses	13.804 s	522 W	OK
W-meter				
ARCUS			534 W	

Nominal maximum power 900 W, 1 Hz, 12 % Duty Cycle

Meter	Reading 1	Reading 2	Power	Remarks
1	3 pulses	27.011 s	400 W	VERY HIGH
2	3 pulses	27.424 s	392 W	VERY HIGH
3				
4	0 pulses			Not enough power to produce one pulse in 30 s
5	10 pulses	20.404 s	176	360 Ws/pulse OK
W-meter				
ARCUS			188 W	

Cycling load with thyristors produces large errors. So large, in effect, that a very painstaking search for all possible sources of error was conducted. Alternative measurement equipment and transducers were used and detailed scrutiny of waveforms, math, everything was undertaken. No errors were found. Also, the fact that meters #4 and 5 and ARCUS agreed closely was taken as an indication that meters #1 and 2 were behaving very erratic. A test with continuous (not cycled) thyristor controlled load was done. Results on next page.

Continuous, level controlled with thyristor firing delay

Maximum power, 30 seconds recording.

Meter	Reading 1	Reading 2	Power	Remarks
1	16 pulses	27.351 s	2106 W	LOW
2	16 pulses	27.436 s	2099 W	LOW
3				
4	20 pulses	28.612 s	2516 W	OK
5	20 pulses	2.869 s	2509 W	10 000 pulses/kWh OK
W-meter			2496 W	3x832 W
ARCUS			2556 W	

Medium power, 30 seconds recording.

Meter	Reading 1	Reading 2	Power	Remarks
1	11 pulses	27.460 s	1442 W	VERY HIGH
2	11 pulses	27.288 s	1451 W	VERY HIGH
3				
4	5 pulses	24.480 s	735 W	OK
5	20 pulses	9.763 s	737 W	10 000 pulses/kWh OK
W-meter			645 W	215 W on L1, uneven currents – L3 higher
ARCUS			756 W	

Low power, 30 seconds recording.

Meter	Reading 1	Reading 2	Power	Remarks
1	11 pulses	27.758 s	1427 W	Triple checked EXTREMELY HIGH
2	11 pulses	27.634 s	1433 W	Triple checked EXTREMELY HIGH
3				
4	1 pulse	16.253 s	221 W	OK
5	16 pulses	26.454	218 W	10 000 pulses/kWh OK
W-meter			222 W	3x74 W
ARCUS			233 W	

The algorithms in meters #1, 2 and 3 (which are all of the same brand and type) seem to have big problems with non-sinusoidal currents. It looks like it is not the load cycling per se that is causing the meter errors, but the current's waveform.

Finally, a test with load connected between L1 and L3 was carried out. This is to separate the error mechanisms that produce the large error in meters # 1 – 3. If the error is an inability to take care of phase angles other than zero (a rather unlikely assumption, but easily checked) then the extra 30 degrees should produce a corresponding error. Results in the following table.

Test with load connected L1 – L3 instead of L1, L2, L3 – N.

Meter	Reading 1	Reading 2	Power	Remarks
1	17 pulses	54.691 s	1119 W	OK
2	17 pulses	54.723 s	1119 W	OK
3	17 pulses	54.823	1112 W	OK
4	18 pulse	54.823 s	1116 W	OK
5				
W-meter			1110 W	
ARCUS				

All meters behave as expected. Also when extra 30 degrees of phase shift introduced.

The conclusion is that meters #1 – 3 seem to have a “smart” algorithm that somehow checks for current position with regard to voltage and uses that information to calculate power. That strategy may work quite well for currents where the distance between zero crossings is one half cycle. But, the resulting power when current is cycled with less than 180 degree conduction angle is not only questionable – it is totally and completely wrong.

Meters #4 and 5 do not try to be smart. They sample often enough to measure current and voltage correctly and multiply instantaneous values to arrive at correct power and energy.

It is time to talk to the meter manufacturer about this. The test set-up will be kept for a while if more measurements need to be made.

Granbergsdal, March 8, 2010

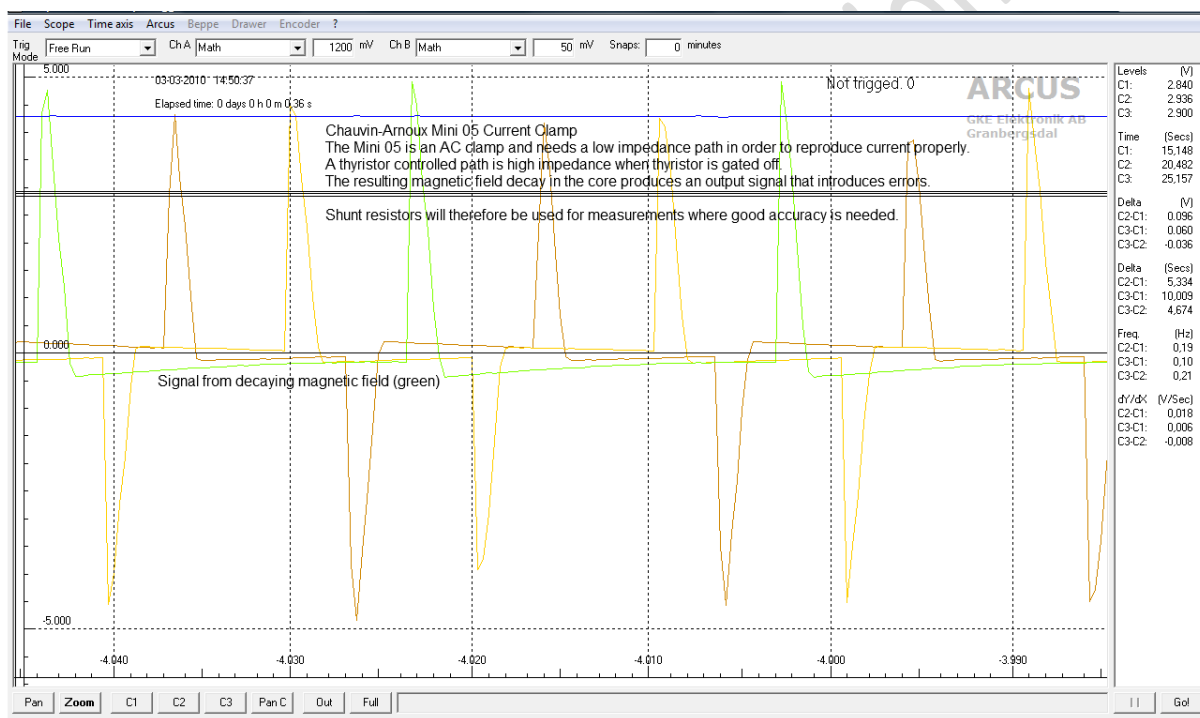
Gunnar Englund

APPENDIX 1

CALIBRATION OF ARCUS AND TRANSDUCERS

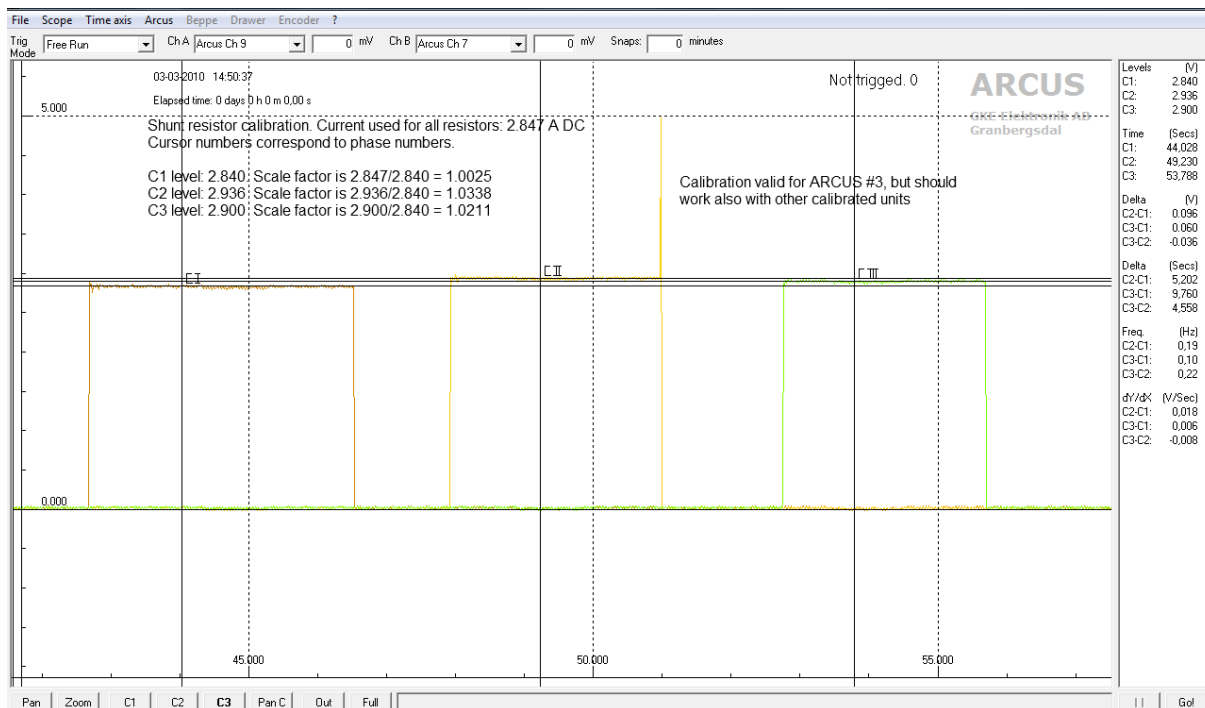
Current transducers

The Chauvin-Arnoux Mini 05 current clamps that were used on site are AC clamps and there is a problem when thyristors are switched off. The magnetic field in the clamp core collapses when the continuous current path is interrupted by the thyristor (similar to inductive kickback, but milder) and induces a voltage in the secondary coil. The voltage will influence the calculated power and introduce a considerable error in the measurements. It was therefore decided not to use the Mini 05 and work with calibrated shunt resistors instead. Picture A1.1 illustrates the problem with decaying field.



Picture A1.1 False signals when thyristors gated off.

The shunt resistors were constructed from standard 1 ohm, 4 W wire-wound power resistors in a series-parallel configuration so that four resistors resulted in a 16 W resistor with almost zero percent resulting error. Unfortunately, there were not enough resistors with the required plus and minus tolerances to produce more than one zero error combination. The two other combinations therefore have 'normal' deviations from nominal value. By calibrating the three shunt resistors against a known current and in their intended channel allocation, we had the double benefit of having traceability 'from current to screen'. Picture A1.2 shows calibration and resulting scale factors.



Picture A1.2 Shunt resistor calibration and resulting scale factors.

The scale factors are close enough to unity and the resistors were used without any correction in the ‘sanity check’ measurement described in the section about Excel sheet. It should also be noted that the power reading was also a little rough. The purpose of the check was simply to check that all parts were doing their work properly.

The resistors are used in the same phases as they have been numbered above. See table A1.1.

Phase	Scale Factor [A/V]
L1	1.0025
L2	1.0338
L3	1.0211

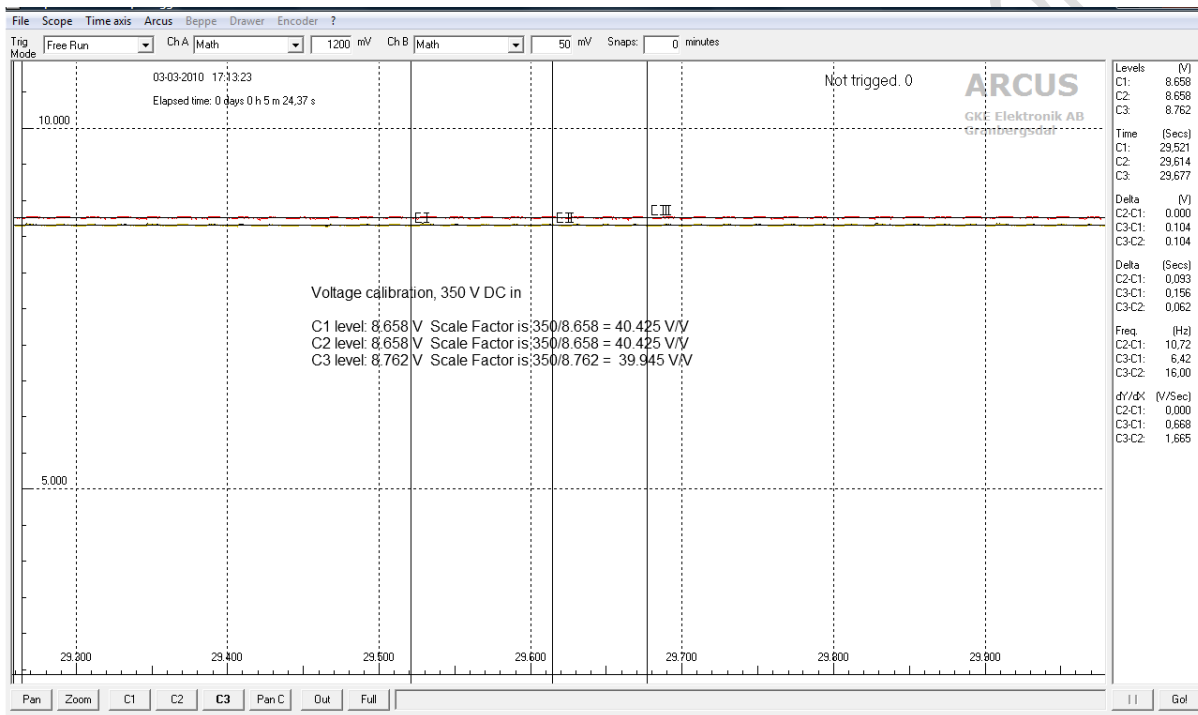
Table A1.1 Shunt resistor scale factors

Voltage divider

Arcus has a basic input range from -10 V to +30 V. That range has been selected for several reasons, the recorder is designed for simplicity and reliability and also for use in industrial applications where analogue signals in the +/-10 V range and control signals usually are between 0 – 12 or 24 V. The

chosen input range is adapted to such signals. The fact that process signals (4-20 mA) usually develop a voltage drop between 5 and 10 V, full range across receivers and that all input pairs can be configured to measure differential signals in that range with good common-mode rejection makes the ARCUS an ideal recorder for industrial use. For other signals, adapters have to be used.

One range that is easily adapted by means of passive voltage dividers is the mains voltage. The voltage divider used in these measurements was originally used as an 'artificial zero' for measurements on VFDs. Adding three 1 kohm resistors makes it useful as a simple three-phase voltage divider. Calibration can be seen in picture A1.3:



Picture A1.3 Voltage divider calibration and scale factors

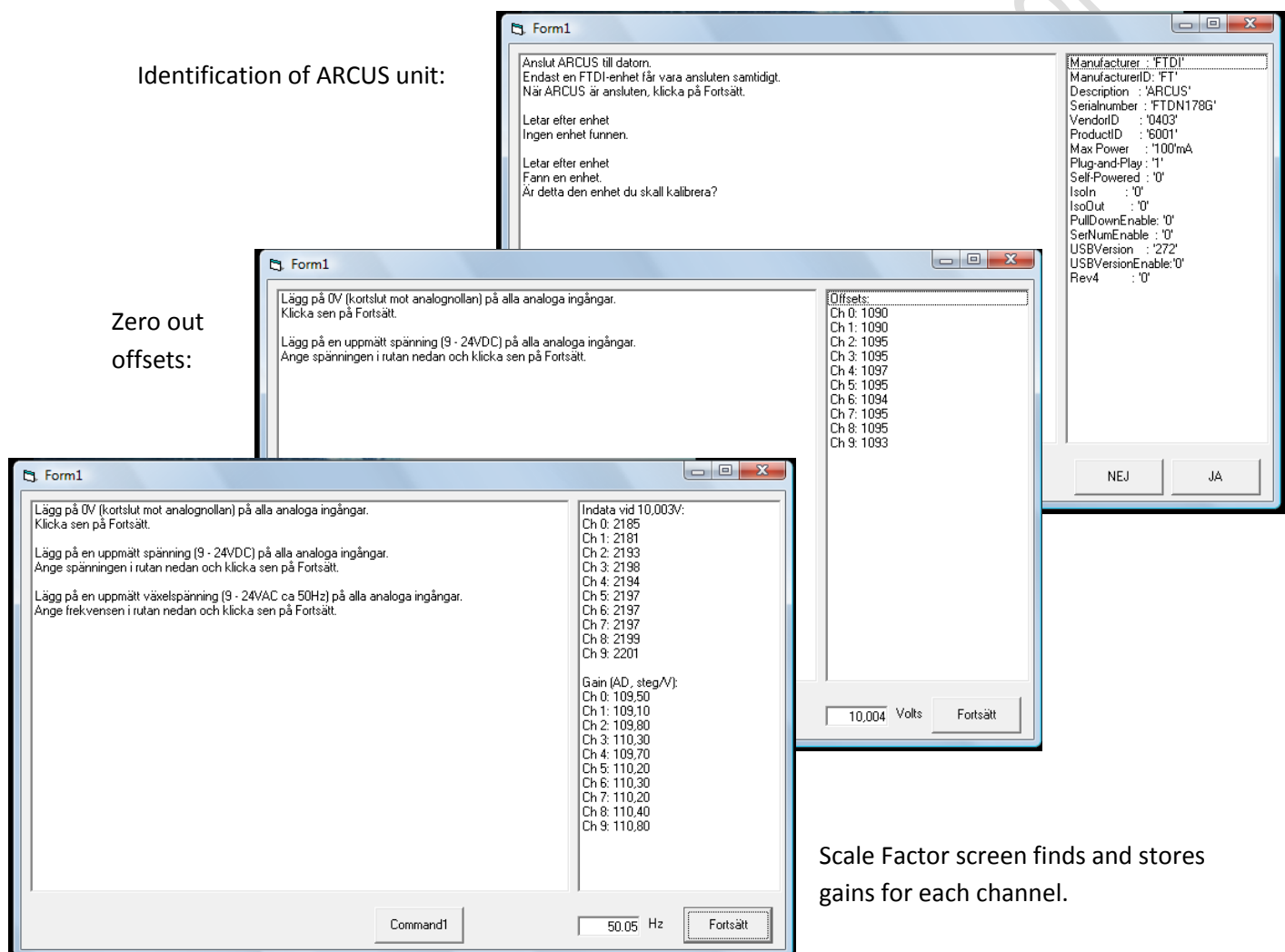
Phase	Scale Factor [V/V]
L1	40.425
L2	40.425
L3	39.945

Table A1.2 Voltage divider scale factors

ARCUS calibration

The ARCUS analogue front end does not contain any amplifiers. That makes the device very stable, the scale factor is determined by metal film resistors and the A/D converter's reference voltage. Both are stable with time and temperature so that, once a calibration has been carried out, the scale factors remain for long time and over a wide temperature range.

Calibration is a simple procedure that utilizes the "arcus_setup_and_calibration.exe" program. Running it produces the following screens:



Identification of ARCUS unit:

Zero out offsets:

Scale Factor screen finds and stores gains for each channel.

The calibration procedure takes less than five minutes and results in an overall accuracy better than +/-0.2 percent of range. Offsets and gains are stored in non-volatile memory on-board the ARCUS device and is not dependent on any data stored in the PC.