Energy Measurement with Precision Power Analyzer LMG600

The *ENERGY* Menu of LMG600 displays energy values, such as the active energy in Wh (watt-hours), the reactive energy in varh, the apparent energy in VAh and the charge in Ah. The user can select if the energy measurement will be directly or externally controlled. In the first case, the user selects when the energy measurement will start and when will stop. In the second case the duration of the energy measurement is controlled by an external signal/pulse. The duration of the energy measurement is displayed on the screen. A useful feature for different kind of applications.

1. Energy Measurement Uncertainty

The uncertainty of the energy measurement is calculated based on the following equation:

$$\Delta E = t * \Delta P + P * \Delta t$$
(1.1)

with
t: duration of the energy measurement
ΔP: power uncertainty
P: reading of the active power
Δt: time uncertainty

While the duration of the energy measurement and the reading of active power are displayed on LMG's screen, the uncertainty of time and power needs to be calculated and found on LMG's brochure, respectively.

Power Uncertainty

ZES ZIMMER provides detailed information about the voltage, current and power uncertainty at different frequencies.

Let us assume that the measured signal has the following characteristics:
Voltage: 230 V
Current: 5 A
Frequency: 50 Hz
Power Factor = 1
Energy Measurement Duration = 5 s
Energy = 5 750 Ws

The power uncertainty at 50 Hz for a LMG600 A-channel will be equal to:

Power Error = ± (0.015 % of measured value + 0.01 % of maximum peak value) (1.2)

*Measured value = voltage reading * current reading = 230 V · 5 A = 1 150 W*
Current range: 250 V nominal value, 400 V peak value
Voltage range: 5 A nominal value, 15 A peak value
*Maximum peak value = voltage peak range * current peak range = 400 V · 15 A = 6 000 W*

⇨ Power Error = ± (0.015 % * 1150 W + 0.01 % * 6000 W) ⇨ Power Error = ±0.7725 W
Time Uncertainty during Energy Measurement

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During an energy measurement the following uncertainties exist:

$$Time\ Uncertainty_{MAX} = Timebase\ Uncertainty + Energy\ Measurement\ Uncertainty_{MAX} + Cycle\ Time\ Uncertainty_{MAX} \qquad (1.3)$$

→ $Timebase\ Uncertainty$:

The time base uncertainty of energy measurement is defined on LMG's manual.

$$Timebase\ Uncertainty = \pm 50\,ppm * (Energy\ Measurement\ Duration) \qquad (1.4)$$

→ $Energy\ Measurement\ Uncertainty_{MAX}$:

The duration of the energy measurement on LMG has the following characteristics:

- the measuring cycle (hereinafter only referred to as 'cycle') during which the measurement starts is included in the real measurement
- then the integration time adjusts accordingly
- the cycle during which the measurement stops is not included in the real measurement
- there is a time difference between the desired and the LMG duration.

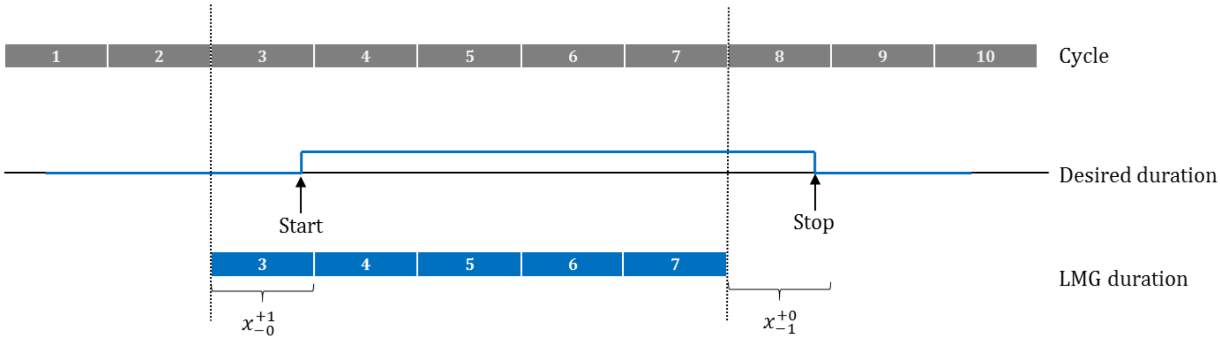

Figure 1: Energy Measurement Uncertainty

If the energy measurement starts at the beginning of a cycle, then there is no time uncertainty. But if the energy measurement starts at the end of a cycle, the whole cycle will be included in the measurement. Similarly, if the energy measurement stops when a new cycle starts, then there is no difference between the desired and the LMG duration and the uncertainty is equal to 0. If the energy measurement stops at the end of a cycle, this cycle is not included in the measurement.

This error is therefore maximum equal from 0 to +1cycle during the start and -1 cycle to 0 during the stop of the energy measurement.

$$Energy\ Measurement\ Uncertainty_{MAX} = \pm 1\ Cycle \qquad (1.5)$$

For the 5s energy measurement in the example and with selected cycle time of 30 ms, the delay will be equal to ± 1 cycle, ± 30 ms. The relative error is 30 ms/5 s, 0.6 %.

Let us now assume that the energy measurement runs for 100s. The energy measurement uncertainty is fixed, depends only on the cycle time and it will be again maximum equal to 30ms. The relative error is now equal to: 30 ms/100 s= 0.03 %

- You can minimize the energy measurement uncertainty by selecting a longer duration for the energy measurement!
- Please note that this is the maximum uncertainty and the actual is usually lower.
- *Δten* measures the LMG duration and is displayed on LMG.

→ $Cycle\ Time\ Uncertainty$:

The power analyzer ensures to integrate respectively calculate the measurands over a number of complete signal periods. Hence every time a current cycle ends and a new cycle starts, the LMG extends the cycle time until the last positive zero crossing of every signal is measured. The same applies for the start of the cycle. Please refer to figure 2. Example:

50 Hz signal -> 20 ms signal period

Set cycle time = 30 ms

The measurement starts. The first cycle will have an actual measuring period of 40 ms to measure not only 1.5 but 2 complete signal periods. The second cycle will have a measuring period of 20 ms, so that in average the cycle time is 30 ms and again a complete signal period has been measured.

For further information please refer to the Application Note *"Synchronized Measurements with LMG Precision Power Analyzer"*.

Depending on the frequency of the signal, this leads to a time difference. The duration of an energy measurement is greater than one cycle. But, there is a delay only in the cycle the energy measurement starts and in the cycle the energy measurement stops.

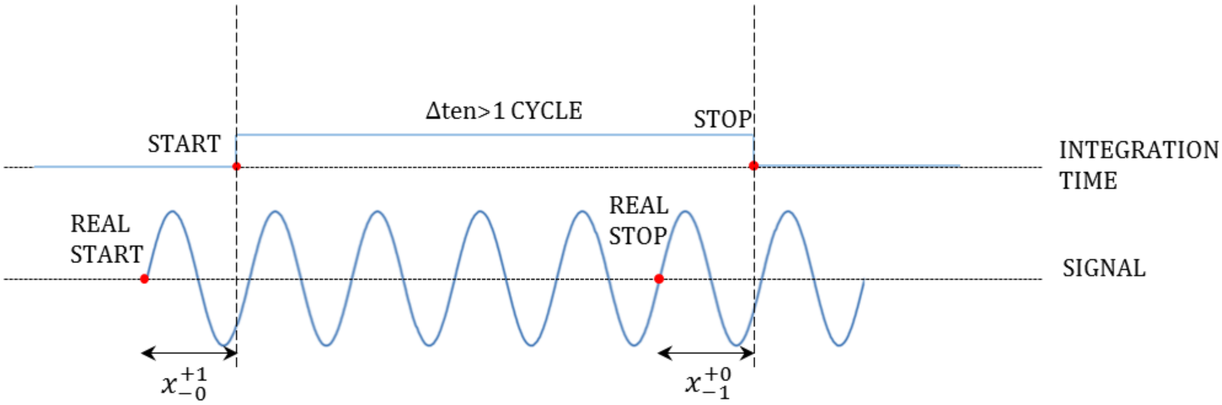

Figure 2: Cycle Uncertainty during Energy Measurement

This time uncertainty is maximum equal to $\pm\ (\frac{1}{f_{signal}})$.

$$Cycle\ Uncertainty_{MAX} = \pm \frac{1}{f_{signal}} \tag{1.6}$$

If the signal's frequency is 50 Hz, then the maximum uncertainty is equal to ± (1/50) = ±20 ms. This error is also fixed and depends only on the signal's frequency.

You can minimize the influence in the measurement accuracy, by selecting a higher duration.

If the selected cycle time is 30 ms, the energy measurement durations is 5 s and the signal's frequency is 50 Hz, with the formula in (1.13) the total and maximum time uncertainty is then:

$$Time\ Uncertainty_{MAX} = \pm \frac{50}{10^6} * 5 \pm 30 * 10^{-3} \pm \frac{1}{50} = \ \pm 0.05\, s$$

The uncertainty of the energy measurement is:

$$\Delta E = \pm(t * \Delta P + P * \Delta t) = \pm(5\,s\; 0.7725\,Watt\; + 1\,150\,Watt * 0.05\,s)$$

$$\Rightarrow \Delta E = \pm 61.36\,Ws = \pm 0.017\,Wh$$

The relative energy error is:

$$Relative\ Error = \frac{\Delta E}{E} = \frac{61.36\,Ws}{5\,750\,Ws} = 1.06\,\%$$

If the energy measurement duration is 60 s, 1 min, the energy is equal to 69 kWs and the results are:

$$Time\ Uncertainty_{MAX} = \pm\frac{50}{10^6} * 60 \pm 30 * 10^{-3} \pm \frac{1}{50} = \pm 0.053\,s$$

$$\Delta E = \pm(t * \Delta P + P * \Delta t) = \pm(60\,s * 0.7725\,Watt\; + 1\,150\,Watt * 0.053\,s)$$

$$\Rightarrow \Delta E = \pm 107.3\,Ws = \pm 0.03\,Wh$$

$$Relative\ Error = \frac{\Delta E}{E} = \frac{107.3\,Ws}{69\,000\,Ws} = 0.15\,\%!$$

If the desired duration is equal to e.g. 155ms, the LMG duration is e.g. 150ms and the energy reading on LMG is equal to e.g. 100Ws. If the signal is constant (which is very often the case, especially for calibration), then the energy value without error can be calculated by applying a simple analogue method:

Energy = Energy Reading *(Desired Duration/LMG Duration) = 103.3 Ws

2. Applications

There are various applications requiring the measurement of energy. Each one of these applications has different requirements and challenges. In the section below are described the calibration of energy meters and the optimized measurement of energy on devices with fluctuating current, such as fridges, chargers and more.

2.1 Calibration of Energy Meters

Energy meters are devices that measure the energy consumption of the connected loads. Loads could be home appliances, power grids, power generators, photovoltaics and more.

Energy meters have usually the following characteristics:

- Energy meters have a pulse output, S_0. The frequency of the pulses indicates the power demand and the number of the pulses the energy.
- Each pulse represents an amount of energy passing through the meter. Usually energy meters transmit from 1 to 1000 pulses representing 1 kWh energy.
- The minimum pulse duration is 30 ms and the minimum time between two successive pulses is 30 ms, the transition time should not be more than 5ms.
- For calibration purposes and to avoid very long measurement time, energy meters have sometimes an additional pulse output. This output sends pulses with higher frequency (more pulses per kWh).

The calibration of energy meters is similar with the calibration of other devices under test and is based in the following steps:

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- The same signal is applied and measured on LMG (Reference) and on the Energy Meter (Equipment under Test).
- The tolerance of the reference (LMG) and the tolerance of the EUT (Energy Meter) are calculated.
- The results of the two devices are compared and the measurement error is calculated.

	Energy Reading Reference	Reference Tolerance	Lower Limit	Upper Limit	Energy Reading EUT	EUT Tolerance	Difference
Applied Signals							

Table 1: Calibration Steps

But, there are some challenges: the Energy Meter outputs pulses, while the Power Analyzer displays energy. How will the user compare the results? How can we ensure that we measure energy synchronously on LMG and Energy Meter? Are there any time delays?

2.1.1 Testing Methods

There are different ways and methods to calibrate energy meters with LMG600. Every method has advantages and disadvantages.

Method1

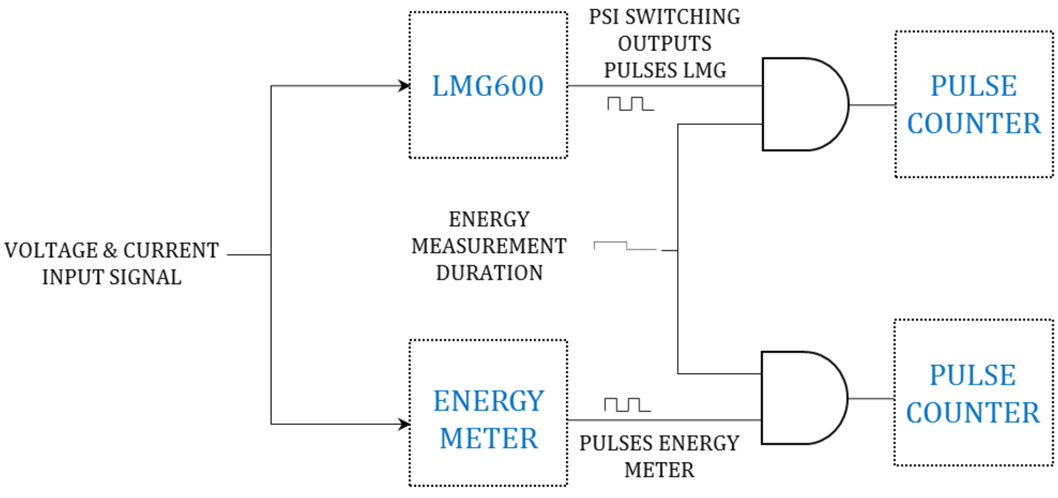

Figure 3: Method 1

LMG can be equipped with a Process Signal Interface (PSI). The PSI has up to 8 switching outputs via a female 25 pin D-SUB connector.

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LMG can be programmed via the script editor to output pulses (set digital output to 0 or 1) based on the energy measurement. The script runs once per cycle, the digital output changes once per cycle and a pulse depending on the reading of the energy measurement is the output.

```
def {
$step = 1.
$limit = $step
$count = 1
}
Energy= [ep1111?]
SetPSIDigitalOut(1,0)
if(Energy>=$limit){
SetPSIDigitalOut(1,1)
$count = $count + 1
$limit = $step * $count
}
```

In the above script, the digital output 1 of the PSI is equal to 0 (low). If 1Wh of energy is measured, then the digital output of PSI is set to 1 (high) and the limit changes to 2 Wh. The next cycle the digital output is at first 0 again. If one pulse should be sent for every e.g. 500 Wh, then the user should only change the value of $step.

Then, the pulse output of the LMG should be set as an input to a logic AND Gate. The other input of the logic gate is a signal indicating the duration of the energy measurement (1 if the measurement runs and 0 if not). The output of the AND gate is based on the following table.

INPUT A	INPUT B	OUTPUT
0	0	0
0	1	0
1	0	0
1	1	1

Table 2: Logic AND Gate

Therefore the output of the gate will be 0, when the energy measurement integration is 0 and will be equal to the switching output of LMG, when the energy measurement integration is 1.
The pulse output of the energy meter is an input to another logic gate. Purpose of this is that the duration of the energy measurement and the reading of the pulses is synchronized between the two devices. Two pulse counters count the total number of pulses on each device and the user compares the number of pulses.

The lowest cycle time on LMG600 is 30 ms. The maximum number of cycles per second is therefore 33 and the maximum number of pulses per second is 16.5. There is a restriction on the number of pulses per second LMG can create and this is why this method may result in long measurement time.

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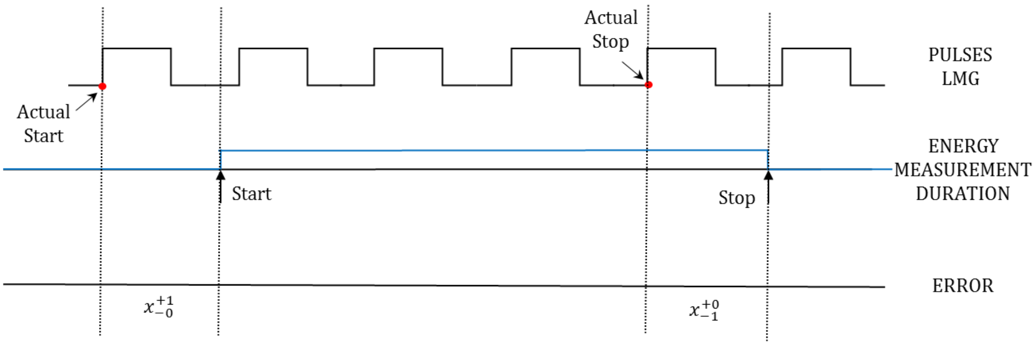

Figure 4: Pulses Error during Energy Measurement

When LMG outputs pulses, there is an additional error, maximum equal to ±1 pulse (start and stop of energy measurement) as it is illustrated in the Figure 4.

The same error applies on the energy meter and the total error of this method is equal to ±2 pulses.

Method 2

LMG is equipped with a 15 pin D-SUB male synchronization connector. One pin of the synchronization connector, Sync_Energy_I/O, is used for the integration of the energy measurement. If it is set as an output and the integration is stopped, a low level output is produced (0) and if the integration is running, a high level output (1). If it is selected as an input, the energy measurement can be externally controlled and the integration will run during the time the input is set to high.

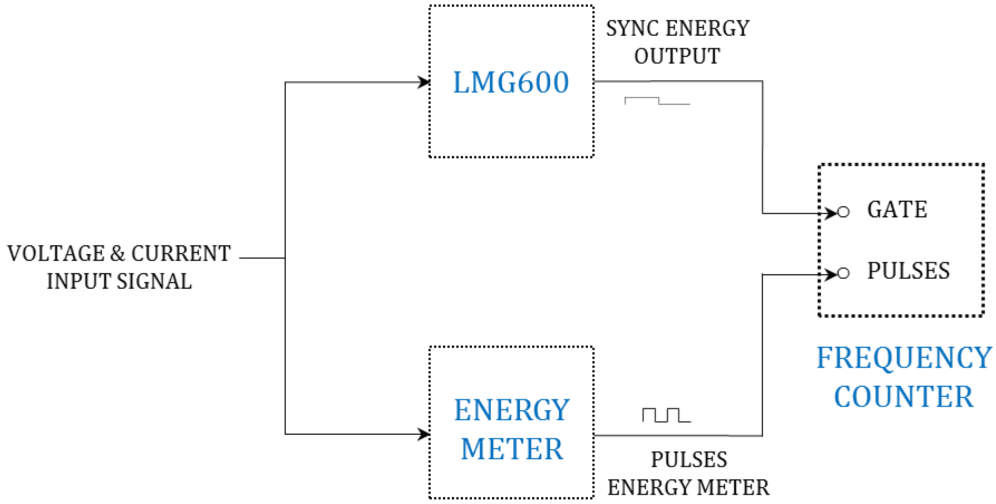

Figure 5: Method 2

If the Sync_Energy_I/O is set as an output, it shows the status of the energy measurement. This signal is connected to the gate time of a frequency counter. The information regarding the duration of the energy measurement is then transferred from the LMG to the counter.

The pulses of the energy meter should be set as an input to the pulses input of the frequency counter. The pulses of the energy meter are measured for the time defined by the gate signal and the energy is calculated in Wh from the pulses. The result is compared with the energy measurement displayed on LMG's screen.

The error of this method is equal to ±1 pulse, due to the pulse output of the energy meter. The Sync_Energy_I/O pin of LMG doesn't have any time delays.

Method 3

In the previous methods, additional equipment is needed to measure the pulses of the energy meter. With method 3, LMG measures the pulses of the energy meter and all the results can be displayed on a custom screen. To set the pulses of the energy meter as input on LMG, the Process Signal Interface (PSI) is used.

The total error of this method is equal to ±1 pulse in the pulse output of the energy meter. There are no any additional time delays on LMG.

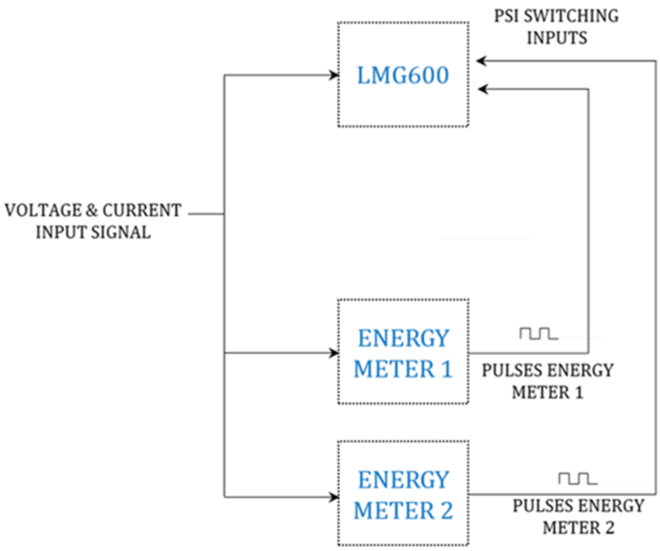

Figure 6: Method 3

The PSI has up to 8 switching inputs, accessible at one 25 pin D-SUB connector. Switching inputs detect the current state of digital signals and the number of the input pulses is displayed on LMG screen under the *PSI - Switch In* menu.

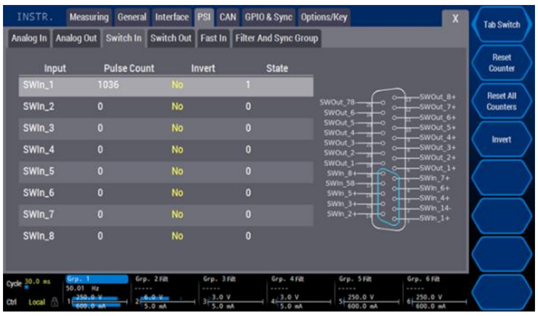

Figure 7: PSI Pulse Count

The input signal of a switching input should have the following characteristics:
State = 0 (Low) is detected for voltage 1.4 V @ max. 10 µA
State = 1 (High) is detected for voltage 2.3 V @ max. 0.5 mA.
Overload: ±33 V

PSI - Pulse Count has a sub cycle resolution and the maximum frequency is equal to 10 kHz. *Pulse Count* counts continuously the pulses received on the respective pin. By pressing *Reset Counter*, the counter can be reset and the pulse count starts again from zero.

When the user will start the energy measurement, the pulse counting is automatically reset and therefore the energy measurement of LMG and the pulse counting are synchronized.
Via the script editor and by using the following formula, the energy of the energy meter can be calculated:

Energy of Energy Meter = ((Number of Pulses)/ (Pulses per kWh)), kWh (1.8)

All the results can be displayed on a custom screen. Another benefit of this method is that up to 8 digital inputs are available and therefore up to 8 energy meters can be calibrated at the same time.

Overview

	METHOD 1	METHOD 2	METHOD 3
COMPARISON	PULSES VS PULSES	PULSES VS ENERGY	PULSES VS ENERGY
ERROR LMG	± 1 PULSE	0	0
ERROR EUT	± 1 PULSE	± 1 PULSE	± 1 PULSE
PSI NEEDED	YES	NO	YES
EXTERNAL EQUIPMENT NEEDED	YES	YES	N0
MAX NO. OF EUTs	n/a	1	8
ONE SCREEN DISPLAY	NO	NO	YES

Table 3: Comparison of the methods

2.2 Optimize the Energy Measurement – Example with household appliances

There are applications where the equipment under test has various power stages. A typical example is the measurement of energy consumption of household appliances.

In the description below, we will use as an example a refrigerator. There are the following stages, in reference to Figure 8:

1. Operation-Inrush Current: in the beginning of the operation and when the refrigerator is energized, the power is equal to about 1000 W, due to the inrush current of the compressor. The duration of this stage is from a few ms up to for instance 1s.
2. Normal Operation: after a while the current will fall in normal levels and the device will be in normal operation. The total power is equal to about 100 W and the duration is 3 min.
3. Standby: when the refrigerator has cooled down, but it is connected to the grid, it consumes a low amount of power, known as standby power. Standby power can be found in the specification of every device. We assume that it is 1 W and the duration is 30min.

Real Energy of Stage 1 = 1000 W * 100 ms = 100 Ws

Real Energy of Stage 2= 100W*3 min= 18000 Ws

Real Energy of Stage 3 = 1W*30 min= 1800 Ws

Total Energy = 19900 Ws

Total Duration = 1980.01 s

Average Power = Total Energy/Total Duration = 10.05 W

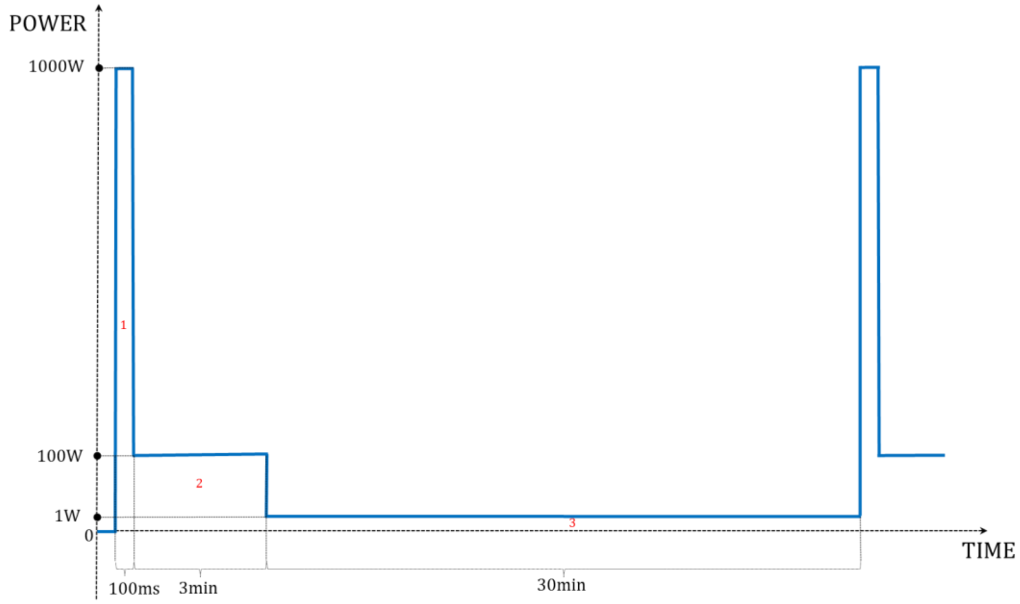

Figure 8: Power Stages of Household Appliances

Stage 1 consists of 0.5 % of the total energy, stage 2 of 90.5 % and stage 3 of 9 %. When a device has various power stages, it is important to select a range that minimizes the uncertainty and gives optimal results.

Set the Auto Range to Manual

On LMG in the *CHANNEL* menu, the user can select if the voltage and current range will be set manually or automatically. If *Auto Range* is on, the instantaneous value of the current might exceed the maximum value of the ADC (Analogue to Digital Converter). The instrument detects this situation and stops the running measuring cycle. Already sampled values are discarded. Then the instrument switches to the next higher range of the measuring channel. Implicitly with that comes a gain change of the internal amplifiers and filters which requires a signal settling time. All values recorded during this period which takes about 30 ms must be discarded. After that the instrument has to synchronise itself to the signal before a new cycle is started. At the end of this cycle new valid values are available. If the instrument has to switch up several ranges, this algorithm is performed several times consecutively.

With a few words, an automatic range selection causes measuring gaps. Short peaks could fall into such a gap.

Optimized Manual Range Selection

We assume that the power factor is equal to 1 to simplify the calculations. Voltage is equal to 230 V and current is equal to 4.35 A (5 A range, 15 Apeak), 0.435 A (0.6 Arange, 1.87 Apeak) and 4.35 mA (5 mA range, 14 mApeak) for stage 1, 2 and 3 respectively. Based on LMGs' specifications, the power peak value for 1000 W is 6000 W, for 100 W is 750 W and for 1 W is 5.6 W.

Although it is assumed for simplicity reasons that the current and the power of e.g. the stage 1 are rectangular, the actual current is as it is described in Figure 9.

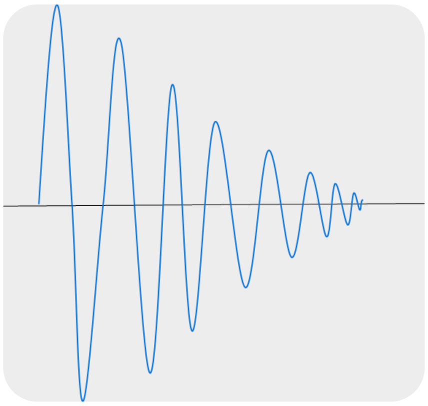

Figure 9: Current Graph

While the measured voltage remains the same, the current is changing. The question is therefore which current range should the user manually select?

The user selects 15 A peak current range (400 Vpeak, 6000 Wpeak):
This peak value is necessary for the initial inrush current.

STAGE	t (s)	P (W)	P_m (W)	E (Ws)	P_{pk} (W)	ΔP_{spec} (W)	ΔP_{syst} (W)	ΔE_{spec} (Ws)	ΔE_{syst} (Ws)	ΔE_{tot} (Ws)
1	0.1	1000	1000	100	6000	0.75	0	0.075	0	0.075
2	180	100	100	18000	6000	0.62	0	110.7	0	110.7
3	1800	1	1	1800	6000	0.60	0	1080.3	0	1080.3
SUM										1191

P_m = Measured Power
ΔP_{spec} @ 50 Hz = 0.015 %*P_m + 0.01 %*P_{pk}
$\Delta P_{syst} = P_m - P$
$\Delta E_{spec} = \Delta P_{spec} * t$
$\Delta E_{tot} = \Delta E_{spec} + \Delta E_{syst}$

The user selects 7.5 A peak current range (400 Vpeak, 3000 Wpeak):

STAGE	t (s)	P (W)	P_m (W)	E (Ws)	P_{pk} (W)	ΔP_{spec} (W)	ΔP_{syst} (W)	ΔE_{spec} (Ws)	ΔE_{syst} (Ws)	ΔE_{tot} (Ws)
1	0.1	1000	1000	100	3000	0.45	0	0.045	0	0.045
2	180	100	100	18000	3000	0.315	0	56.7	0	56.7
3	1800	1	1	1800	3000	0.200	0	540.27	0	540.27
SUM										597.02

Although the range is lower, a current equal to 4.35 A can still be measured and the power is equal to 1000 W.

The user selects 3.75 A peak current range (400 Vpeak, 1500 Wpeak):

STAGE	t (s)	P (W)	P_m (W)	E (Ws)	P_{pk} (W)	ΔP_{spec} (W)	ΔP_{syst} (W)	ΔE_{spec} (Ws)	ΔE_{syst} (Ws)	ΔE_{tot} (Ws)
1	0.1	1000	267*	27.6	1500	0.191	-724	0.0191	72.4	72.419
2	180	100	100	18000	1500	0.165	0	29.7	0	29.7
3	1800	1	1	1800	1500	0.150	0	270.27	0	270.27
SUM										372.39

*When the current peak value is equal to 3.75 Apeak, LMG measures 1.2 A instead of 4.35 A. The measured power is equal to 1.2*230=276 W only, but the sum of all the ΔEtot is smaller!

The user selects 1.875 Apeak current range (400 Vpeak, 750 Wpeak):

STAGE	t (s)	P (W)	P_m (W)	E (Ws)	P_{pk} (W)	ΔP_{spec} (W)	ΔP_{syst} (W)	ΔE_{spec} (Ws)	ΔE_{syst} (Ws)	ΔE_{tot} (Ws)
1	0.1	1000	138	13.8	750	0.096	-862	0.009	86.2	86.21
2	180	100	100	18000	750	0.09	0	16.2	0	16.2
3	1800	1	1	1800	750	0.075	0	135.27	0	135.27
SUM										237.68

The user selects 0.938 A peak current range (400 Vpeak, 375.2 Wpeak):

STAGE	t (s)	P (W)	P_m (W)	E (Ws)	P_{pk} (W)	ΔP_{spec} (W)	ΔP_{syst} (W)	ΔE_{spec} (Ws)	ΔE_{syst} (Ws)	ΔE_{tot} (Ws)
1	0.1	1000	69	6.9	375.2	0.048	-931	0.005	93.1	93.105
2	180	100	69	12420	375.2	0.048	-31	8.612	5580	5588.6
3	1800	1	1	1800	375.2	0.038	0	67.806	0	67.806
SUM										5749.5

We can now notice the following:

- The optimal range selection is different for every power stage. A different range selection results to a different measurement error for every stage and for all the stages.
- Minimizing the measurement uncertainty of the stage 2 (90.5 % of the total energy) will result in a lowest total energy error, while changes on the measurement error of the stage 1 (0.5 % of the total energy) don't affect a lot the total measurement uncertainty.

Please note:

- The formulas described under the section 1, describe the calculation of the measurement uncertainty for the total energy measurement (including start and stop) and can't be used for every level in the middle.
- Although the energy error can be reduced by selecting a lower range, it is not recommended to do so, as it is not a good practice to measure with over ranged ranges. The recommended manual range selection in the example above is 15 A peak current range.

Hybrid method:

There is a method to combine the auto and manual range selection and optimize the results.

The same signal is applied to two different power channels of LMG600. The channels should be of the same category (A, B or C). In the first power channel an auto range is selected, while in the second power channel a sufficient range is manually selected.

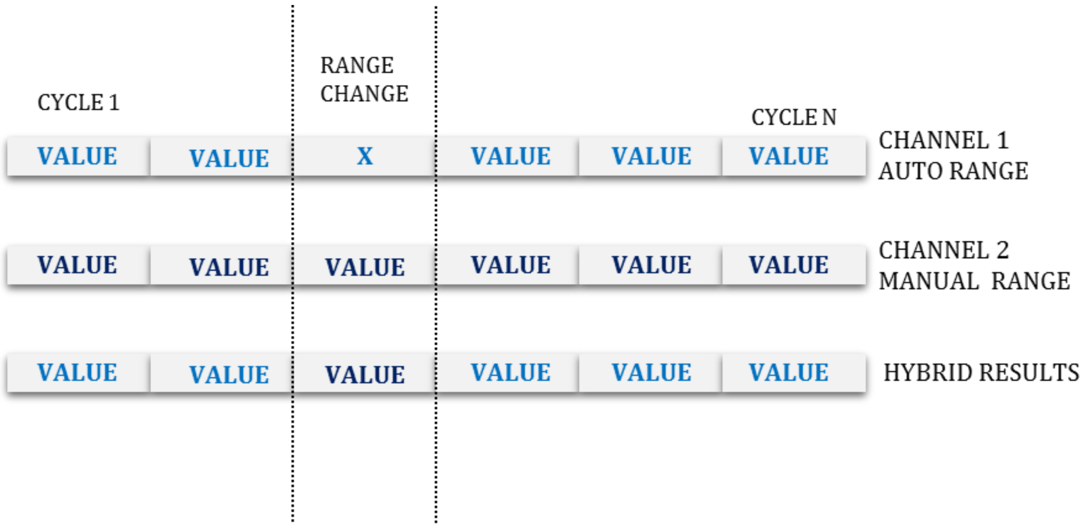

Figure 10: Hybrid Method

The results of the power channel 1 are used, since the auto range selection minimizes the measurement error. Every time the range is changing and a measuring gap is caused, the results of the power channel 2 are used. Thus the uncertainty for this cycle might be higher than with the optimum range, the final result is much better than discarding the results.

The user can obtain all the measurands (current, voltage, power, time, range, invalid values flag, UIP Sampling values and more) via interface and calculate the energy and the total error. This can be done via an external script or program (e.g. Matlab). The results of the two channels are combined and the final values can be stored on e.g. an Excel file.

Useful Accessories
L6-ACC-SYNC: LMG600 sync cable

LMG-DSUBIO25M: D-SUB25f to terminal block adapter (screw type), incl. 1.8 m cable for connecting adapter to LMG600 process signal interface

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