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Trustfull testing leads to working products – working products lead to more recognition on the market – more recognition leads to more sales – more sales leads to more service demands – more service demands leads to more testing. Testing is the first and last thing we do, to ensure customer happiness.

Power measurement in general / Setup

1. Set the correct wiring of the power analyzer

Before we can start with the configuration of the unit we need to wire the unit to our specimen. Depending on what kind of object we wire the unit up, we need to give the power analyzer a hint how it is wired.

In general there is one of four types of wiring to choose:
- 1P3W: 1 Phase measurement with 3 wires - for example a coffee maker
- 3P3W: 3 Phase measurement with 3 Wires - for example two-watt meter method for any 3-phase system
- 3P4W: 3 Phase measurement with or without star point connection - for example electrical motor in star configuration
- 3V3A: 3 Phase measurement with 3 wires – for example power lines or delta configured electrical motors

2. Synchronization on the fundamental period time

When setting up a power meter for measurement, several things have to be checked.

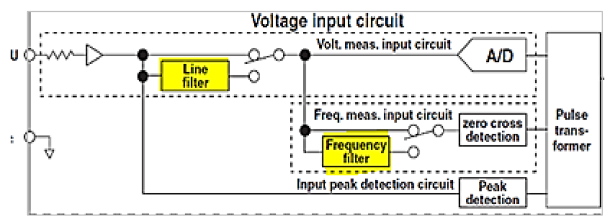
Most important factor beside the correct wiring is to make sure the measurement will synchronize to the correct period time and to the correct phase.

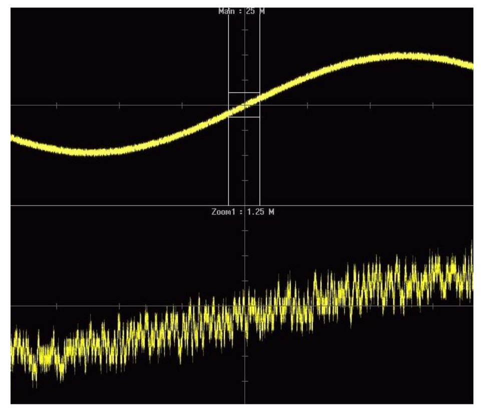
That the power analyzer is able to find the correct period time three settings have to be done in general.
- **Setting synchronization source** (which phase element)
- **Choose the source** in which one the period time is easier to see, the more sine wave the better (motors = current)
- **Setting the frequency filter** on the synchronization source element of choice
- Setting Bandwidth filters: If needed, but rarely up to never used because of cutting off the harmonic parts (bad influence)

Difference of frequency - filters(measurement support) and line - filters (bandwidth filters)

If looking at the block diagram of an power analyzers input section you will usually find a so called **line filter** and a separate **frequency filter**.

The difference on these two is that the **frequency filter is in parallel to the measurement path**. In this case the filter does not influence the measurement negatively (no cut off of harmonic parts). The filter will filter a separated signal to determinate the fundamental frequency more precise, even if it is very heavily distorted like shown in the picture on the right. (about 20 zero-crossings in the zoom, where does the period start?)





Be aware that if you are doing ramp-up tests (changing frequency of drives or inverters), that the frequency filter has to be set to off after a while to correctly capture the fundamental above 1kHz when exceeding 1kHz of fundamental frequency.

3. Setting the update rate of the power analyzer

The update rate of a power meter is the measurement period and also the output interval of measurement values.
It usually can be set from 5ms up to 20 seconds. To correctly measure the power or even any other value on the display, the update rate has to be set to longer then 1 Period of the measurement signal.

Example:
Measurement of 1Hz fundamental: the update rate must be > 1 second ; 1/1Hz = 1s
Measurement of 50Hz fundamental: the update rate must be > 20ms ; 1/50Hz = 20ms

4. Synchronize the phase-lock-loop for correct harmonics analysis

Some systems have integrated phase-lock-loop circuits also called PLL to enable proper, fast and stable harmonics analysis.
These circuits have to be synchronized to a reference signal which should be measured.
More about PLL in the below section „harmonics measurement methods“.

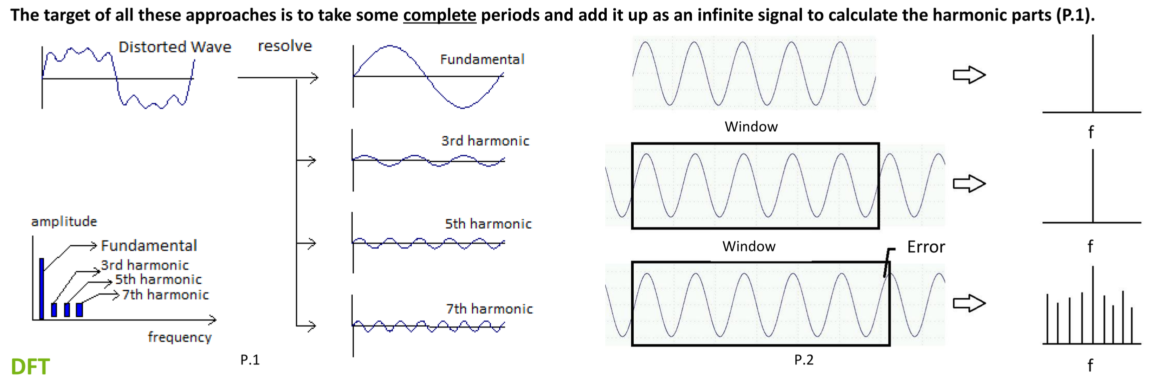
Harmonics measurement methods

Advantages and disadvantages of different methods

There are 3 different approaches to measure harmonics on the market but only two are sufficient to perform real harmonics measurements.

- **DFT:** Discrete Fourier Transformation
- **FFT:** Fast Fourier Transformation
- **FFT with PLL:** Fast Fourier Transformation with Phase-Lock-Loop Technology

The target of all these approaches is to take some complete periods and add it up as an infinite signal to calculate the harmonic parts (P.1).



DFT

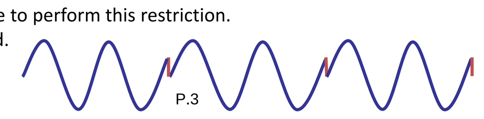
This approach is the oldest theory of splitting up a waveform into single parts of sinewaves. The DFT is the most proper way to do harmonics analysis. Although the DFT is the correct way to do the analysis, it has many disadvantages. Because the DFT is a very heavy mathematical formula it needs incredibly much calculating power to process the data within a useful limit of time.
Mainly to decrease this calculation time, the maximum number of points used in DFT are set to a very low level.
In most units there are used 1000 points for doing the DFT calculation. Unfortunately these 1000 points may only cover 1 or 2 periods of your signal. Special behavior will not be seen on the screen because it may did not happen when capturing the periods.
Therefore the DFT is very limited to do proper analysis is real world conditions.

FFT

The **fast fourier transformation** is a shortcut developed by Mr. Fourier to solve the timing and calculating issue from the DFT.
The FFT is able to process much more points in the same time.
Therefore the FFT is in praxis much more meaningful to use then the DFT, in case of the analyzed number of points.
Like this we can perform the FFT with up to 100‘000point.

Unfortunately there is also a penalty in the FFT formula from Mr. Fourier.
To process the data correctly we need to capture **an integer count of points** (2^x points e.g. 1024, 2048,... points), unfortunately there will also be the need that the first point captured is exactly the start of the period and the 1024th exactly the end of the period.

As FFT is gathering it‘s points from the window size of your unit, it will not be able to perform this restriction.
This problem leads to **an infinite signal with an abrupted end (P.3)** in each period.
→ **this will create not existing harmonic parts on not existent frequencies (P.2)**



To soften this behavior there are several filters in oscilloscopes or power measurement units, witch soften this problem.
The filters try to make the end points the same value as the start point to make it infinite. Also they use different algorithms to soften the abrupted tails.
Unfortunately non of these filters give really satisfying results because we change the shape of our waveform by filtering.
One is good for amplitude but bad for frequency resolution, the other bad in gain but good on frequency resolution,…

FFT with PLL (Phase-Lock-Loop)

Because DFT is too slow and FFT has this restriction, next step was to use a phase-lock-loop. This oscillator-circuit is synchronizing to the fundamental wave and will create a new multiple sampling frequency of the fundamental to capture the exact frame of single or multiple full periods. In this case the PLL technology ensures that always the start and the end of full periods are captured within an integer amount of points in the storage.

This technology offers the same accuracy of DFT with up to 100‘000 points of your waveform instead of 1000 points.
In addition the FFT with PLL enables to have accuracy figures on each harmonic part.

Accuracy of the power measurement / calculation

Basic understanding of range uncertainty

The total accuracy of the system is what matters, the single power analyzer or the single uncertainty specification does not say anything about the total accuracy of the system.

All the uncertainties have to be taken into account and have to be added up when a uncertainty calculation should be done.

The accuracy of an input is usually given as:
±% of reading value
±% of range value (rms range, peak range, maximum measurable value or full scale*)

The % of range is the most complicated one to use in the calculation. It matters much if it is referring to the rms value, the peak value or to the f.s / full scale value.

*Especially full scale can either be 100% of range (rms or pk), 130% of range (max. measurable) or even worse 300% of range (max. input before broken)

Depending which one is used the accuracy can be very good or extremely horrible, even if both power analyzers show the same value in the datasheets.
In case of referring to peak dependent ranging or to full scale ranging the rms-ranged most often is the more accurate one.

Example: ±0.1% reading + **±0.1% of range rms** / ±0.05% reading + **±0.05% of range peak**

Other uncertainty specifications types

The uncertainty calculation gets even more complicated, if there is no uncertainty on power in the datasheet. Some models only specify the voltage and current input.

For each model the uncertainty calculation procedure can be found in the manual. Be aware that nearly all manufacturers use their own way of doing it (formula). Some of them are very complicated, but only if referring to the calculation and to the ranges you can find out which unit is more accurate.

As well the figures in the datasheets can have a different meaning:
- **Guaranteed values** (guaranteed accuracy range is a hint, e.g. **specification valid between 1-130% of range**)
- **Typical values** (meaning that may be 6 out of 10 are as good)
- **Best ever** (specification made up on the best unit they ever produced)
- **No indication** (hope to be good)

Also take into account other influences to the uncertainty, these can contribute the uncertainty even more and are hidden.
- Add uncertainty of **ambient temperature** influence to the temperature the unit was calibrated (most critical)
- Add uncertainty of **external input or different probing inputs influence** (different inputs lead to different uncertainties)
- Add uncertainty of **self generated heat influence** over time
- Add uncertainty of **special setting of the meter influence** (some settings in combination or functions may have influence)
- …

Uncertainty specifications are difficult to read, lots of parameters have to be checked before calculating.

Uncertainty calculation 60° phase shift, 1kHz

U= 230Vrms, I =8Arms, cos Phi = 0.5, tan = 1.73, S = 1840VA, Pread = 920W, f = 1kHz

WT3000 guaranteed specification, 66≤ f ≤1kHz **cosφ=0.5 at 1kHz**	⇒ ± (0.05% of reading + 0.05% of range) ⇒ ± ($\delta_{(WT3000,\ 1kHz)} \cdot 100 \cdot \tan\varphi$)% of reading
Uncertainty at cosφ=0 and 1kHz	= ($\delta_{(WT3000,\ 1kHz)} \cdot 100$)% of S = (0.03 + 0.05 · f in kHz)% of S
Absolute unc. at cosφ = 1	= ± (0.0005 · 920)+(0.0005 · 3000 · 920/1840)= = ±(0.46 + 0.75) = ± 1.21 [W]
Absolute unc. Addition because of cosφ=0.5 error at 1kHz = 1, to be given in kHz (contribution of Lambda, frequency dependent)	= ± $\delta_{(WT3000,\ 1kHz)}$ **tanφ x reading** = ± (0.03 + 0.05 · 1)% · **1.732 x 920** [W] = ± (0.0008 · 1.732 · 920) = ± 1.275 [W]
Total Absolute uncertainty	= 1.21[W] + 1.275[W] = 2.485 [W]
P-reading absolute values	= 920 [W] ± 2.485 [W]
Relative Uncertainty	= 0.135 % of Apparent Power S 0.27 % of Power Reading P 0.083 % of Power Range

Setup for motor efficiency testing

What needs to be measured?

When measuring an electrical motor and inverter there is mainly the need to know about:
- Efficiency of the inverter and motor drive (input / output power) IEC60034-xx-x
- Harmonics compability IEC61000-3-2
- Power losses in inverter and electrical to mechanical power conversion
- Waveform shape analysis of PWM voltage and current
- Symmetry of coils, voltages and currents as well as their individual values
- Inrush behavior and start up behavior of the motor

Proper full system measurement

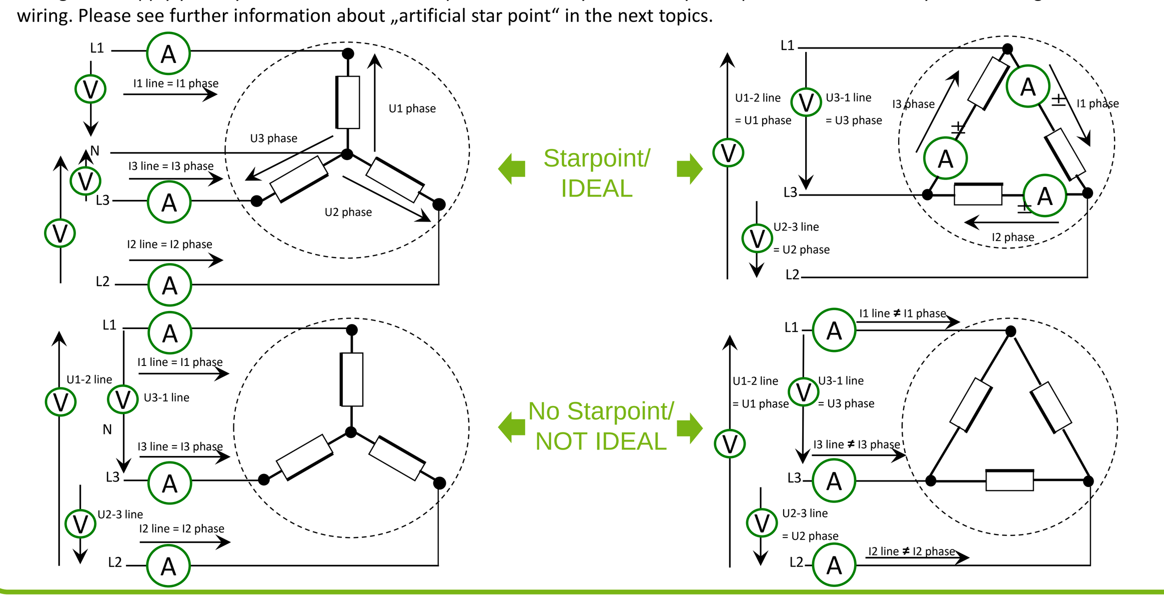
To handle all these needs, the analyzer must have up to 6 power elements, torque and speed input for mechanical power, harmonics analysis and a bunch of mathematical functions as well as visibility functions for symmetry and waveforms, as well as a wide bandwidth and fast sampling. To ensure that a motor and an inverter are working in harmony it is necessary to measure them as a package.
3-phase in, 3-phase out, harmonics at input and at the output as well as mechanical power at one glance.

Harmonics: why test further then the IEC standard says?

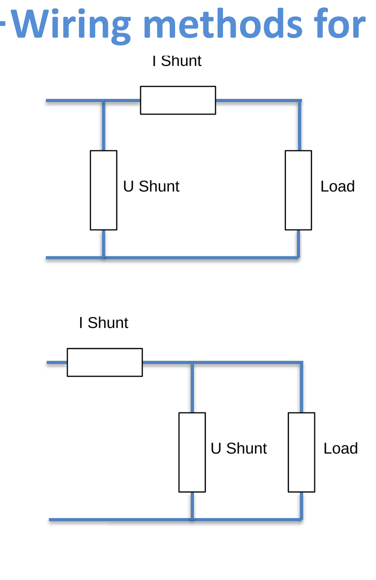
The IEC standards are interested in covering the first 40th orders of harmonics. Unfortunately for motors we should be interested in far higher harmonic parts. Fundamentals from some Hz up to 4000Hz, as well as PWM tact frequencies from 10kHz to 40kHz enforces us to have a wider view then the 40th order. With a fundamental of 400 Hz and a PWM tact of 10kHz we are not even able to see any harmonic part of the inverter harmonics (40x 400Hz = 16kHz, 2nd harmonic of PWM=20kHz). Unfortunately is a non matched inverter with power leading harmonics the usual reason why the motor either does not rotate and the axis breaks in a few months or is inefficient.
To cover the need in R&D as well as production validation, we need to cover at least 200 harmonics on 400Hz fundamental frequency.
So we could see at least up to the 7th harmonic of the PWM tact of the inverter. Better would be up to the 20th = 500th order of 400Hz.

Wiring of the power analyzer for proper measurement

To measure a motor there are several wirings that could be used to get at least the power correct. Unfortunately only the above IDEAL wirings also supply you any other value within the specified accuracy of the analyzer. If possible wire the analyzer according IDEAL wiring. Please see further information about „artificial star point“ in the next topics.



Wiring methods for different loads



Measurement on low current loads

If measuring low current loads, the primary accuracy is laid on the current.
In this case we measure the true current trough the load and take into account that we will have an influence on the accuracy on the voltage measurement, caused by the additional small voltage drop over the current shunt (I Shunt)

Specially for standby power measurements the other configuration will lead to an ineligible current offset (maybe about 3mArms, depending on the consumption of the voltage shunt)

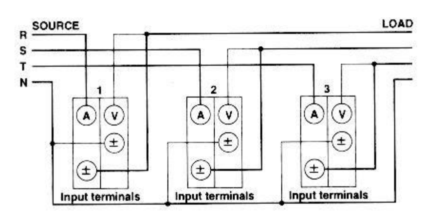
Measurement on high current loads

For high current loads the influence of additional 3mArms consumed by the Voltage Shunt (U Shunt) will be negligible. In this case we take more care to measure the voltage correctly.

In this case we measure the voltage after the current, that the current of the voltage shunt is measured in the load current as well, but not to have high voltage drop over the current shunt like we would have with the above low current load setting.

1st is to think of which parameter is more interesting, and what impedance the load will have, which is directly related to the current consuming level of the load.

Wiring 3-phase / measurement with artificial star point



Connection for 3-phase with star point connection

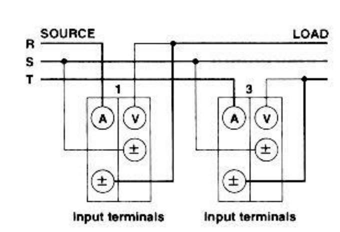
To correctly measure a 3-phase system for all measured values the star point connection is needed. Even if working with star point adapters or other helping tools, the real star point can not be displaced.

Except the power values, no other measured value is trustful and measured 100% within specification except you have the star point connected.

Connection for 3-phase with artificial star point

The artificial star point can be created by short cutting the negative connectors of the voltage shunts, because they are fully isolated. The internal shunts can be used as **fully specified „star point adapter“** .

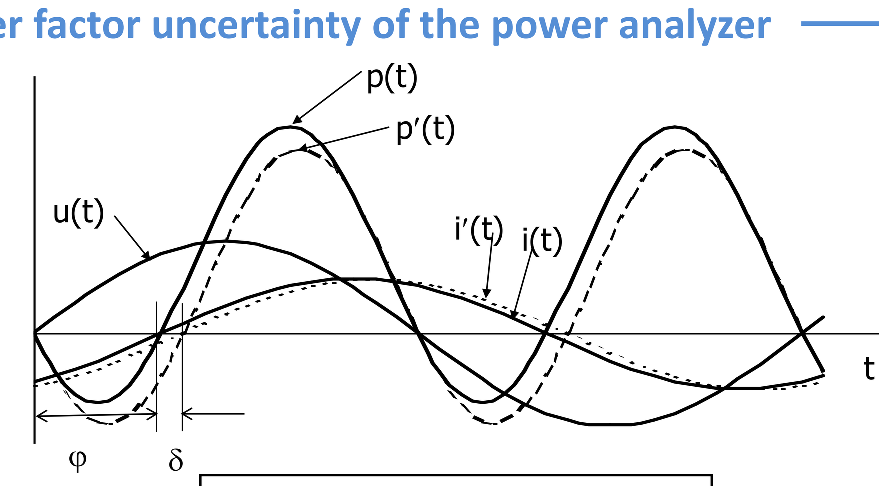
Be aware that extra sold star point adapters do most often not have any specification. Therefore you have no information how it will influence your measurement system in case of additional capacities and inductors.
Both will change the measurement systems frequency behavior and may be even cut off the bandwidth of your system or add unknown phase shifts to certain frequencies.



Two watt meter method for 3-phase / Aron measurement circuit

The total consumed power of a 3-phase system can be measured with only two watt meters instead of three. Kirchhoff‘s law allows us to measure two phases and calculate the difference in the third phase. Often used in production for lowering the costs.
Downside: No proper symmetry check, only power values are 100% within specification.

Power factor uncertainty of the power analyzer



$(U_{rms\ unc})$ & $(I_{rms,\ unc})$ & $(\cos\varphi \neq 1_{\ unc})$

Power factor uncertainty

This kind of uncertainty does explain the basic difference of the measured value of phase shift or power factor to the real value.
The phase shift or power factor does indicate how many degrees or how much time the current is leading or lagging to the voltage within one phase.

The power factor of an 100% ohmic load would be exactly λ = 1.
In this case the power would be Urms x Irms → no phase shift.

If the power factor is 0<λ<1 there is a capacitive or an inductive behavior, which is usually found in any application.

Because of this capacitance or inductive parts the current and the voltage are timely shifted (leading or lagging).

In this case it results in a different power reading, contributed by the shift and calculated by **Urms x Irms x cos φ (power factor)**

Unfortunately the power factor is a measurement value , it also has to have it‘s own uncertainty specification (δ)
→ λ±δ : be aware that this value is also frequency dependent, if there is no “f” in the formula for calculation it is only valid for 50/60Hz.

Where does the uncertainty come from?

The input section of a power meter has a voltage shunt, as well as current shunts or external sensor inputs.
Each of these components are not 100% capacitive or inductive free ohmic resistors.

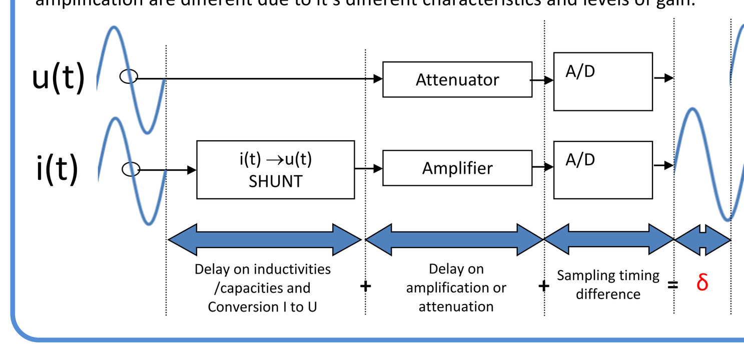
Usually shown in Input specification as :
- Voltage input: 2MOhm + 17pF
- Current Input: 100mOhm + 1uH

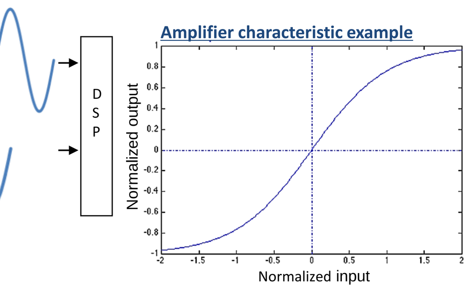
Because of this little capacities or inductor parts of the resistor, they are frequency dependent.

This means the phase shift created by the input section is different for any frequency fundamental and harmonic.

→ Therefore the **specification must offer a frequency dependent uncertainty on power factor (Lambda)** to take this uncertainty into account for several fundamentals and harmonics.

In addition the input section is also different in kind of A/D conversions because of the high attenuation of the voltage and the high amplification of the current.
Even if the same type of amplifier is used for amplification and attenuation, the frequency behavior of the attenuation and the amplification are different due to it‘s different characteristics and levels of gain.





Calibration / Adjustment & ISO17025

What values have to be calibrated?
- voltage
- current
- apperent power
- power factor (0<x<1)
- frequency

All values have to be calibrated over a high bandwith, to ensure proper measurement of fundamentals and several harmonic orders.

Calibration

The word calibration means to check the unit if it is working within the specification.
As well it is the prove that the unit is doing much better then the specification.

Adjustment

Adjustment means to bring back a unit into specification. For power meters the need of adjustments is a bad issue. Having a unit that must be adjusted every year, is not a stable unit through the year.

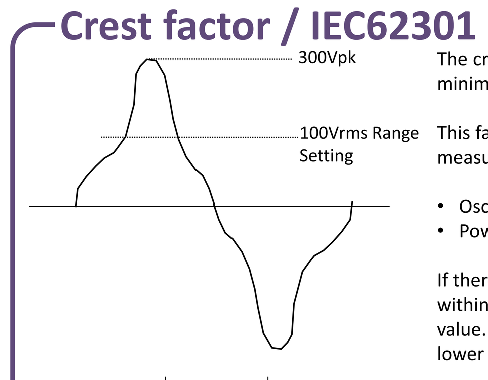
ISO17025 / ISO9001

ISO17025 proves that the unit has been calibrated to national and international standards. ISO17025 gives a maximum confidence into any measurement.

ISO9001 only says that the calibration has followed internal standards which can be set by any organization themself.

In Switzerland the ISO17025 is only available under SCS accreditation and is only valid for electrical power at 50 and 60Hz.
In case of ISO17025 have a look on the scope of calibration of your laboratory.
For power measurement on electrical motors, inverters or other specimen with high harmonics or modulation 50/60Hz is far not good enough.

Crest factor / IEC62301



$$\text{Crest Factor} = \frac{|\text{Peak value}|}{\text{RMS value}} = \frac{300Vpk}{1Vrms} = 300$$

The crest factor is the factor that says what peak value can be measured or what is the minimum rms value that can be measured in the selected range.

This factor is important on highly distorted waveforms, inrush currents or standby power measurements (high nominal currents and low standby currents)

- Oscilloscopes usualy offer crest factor up to 20
- Powermeters usualy offer crest factor 3 or 6 (does not mean bad)

If there is an uncertanty specification which **guarantees the accuracy range** for example within 1%-130% of range, the 1% measurable value can be taken as the smallest rms value. So instead of 300Vpk and 100Vrms (range) (CF=3), 1Vrms (1%) can be taken as the lower measurable limit.

This leads to much higher crest factors then 3 or 6, usualy up to 200 or 300.

IEC62301 stanby power measurement
Needs high CF rating by norm because during integration no range change is allowed.

Sensors and their hidden problems

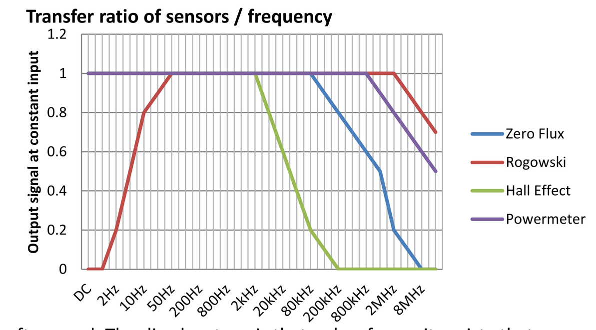
Types of Sensors

There are different Sensors on the market for power measurement. Each of these sensors has advantages, but as well disadvantages.
Basically important to know is that not every sensor can be used for any application.

Types

	Zeroflux-Sensors (DCCT)	Hall Effect Sensors	Rogowski Coils
AC	x	x	x
DC	x	x	
Accuracy	<0.1%	0.5% - 1%	0.6% - 5%
Bandwith	<1MHz	<200kHz	>30Hz - MHz

Transfer ratio of sensors / frequency



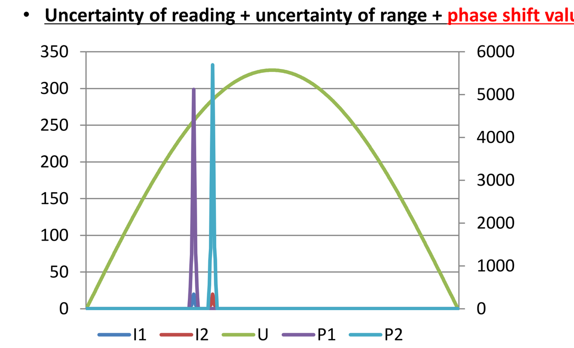
For high accuracy power measurement the zero flux sensor is most often used. The disadvantage is that only a few units exists that can be opened up and have diameter > 5cm.

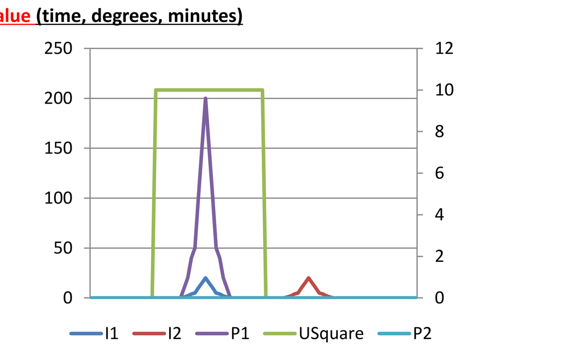
Hall effect sensors and rogowski coils usually can be opened, their main problem is the lack of accuracy.

The Accuracy figures of sensors and more important values

The same as on the power meter input the accuracy of the sensor will be added to the uncertainty of the power analyzer.
In this case we have to watch out for the same figures like on the power meter to ensure proper operation.

- **Uncertainty of reading + uncertainty of range + phase shift value (time, degrees, minutes)**





Because the sensor is the longer arm of the power meter ,all values get added up to the uncertainty of the input of the voltage as well as current shunt.

Very important for power measurement and waveform analysis:
- **Phase shift value** (time between input and output reaction) → Power factor uncertainty addition (**the smaller the better)**
- **di/dt value** (how much current change can the sensor be following in a certain time, **the bigger the better**)

Both can lead to the above showed problems:
left: to early or to late current peak, leads to more or less power
right: with a transient or with an inrush current can lead to not detect any power if the voltage and current are to much shifted

Fascinating is that the bandwidth does often indicate to be faster then the di/dt is, so do not only believe in bandwidth figure.

Two types of current probes (output)

On the market you will find two types of current probes.
- Current to current transformer with **current output**
- Current to current transformer with **voltage output**

Generally in power measurement you use **current output probes**, they are **less affected by external noise**.

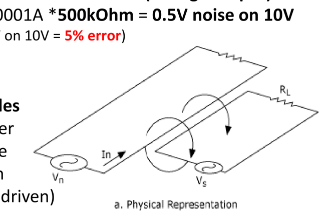
If a current is induced into the wire of the current measurement, it will be multiplied by the impedance of the measurement shunt.

Example: Output 0.2A or 10V @ 100Arms
Using current shunt as measurement shunt (current output)
I 'induced * Zshunt = 0.000001A ***1Ohm** = **0.000001V noise on 200mV**
(200mA max. Output at 100A, 1mV noise on 200mV max = **0.0005% error**)

Using voltage shunt as measurement shunt (voltage output)
I 'induced * Zshunt = 0.000001A ***500kOhm** = **0.5V noise on 10V**
(10V max. Output at 100A, 0.5V on 10V = **5% error**)

Length of cables:

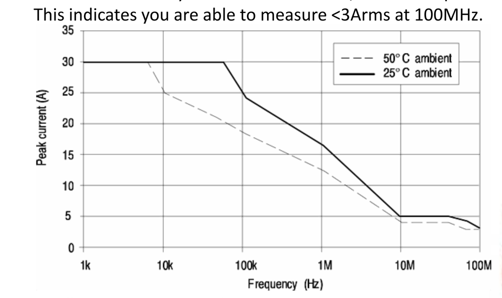
Also **the length of the cables** to the sensors can be longer Because there is no voltage drop over the cables which could be relevant (current driven)



Derating of Sensors

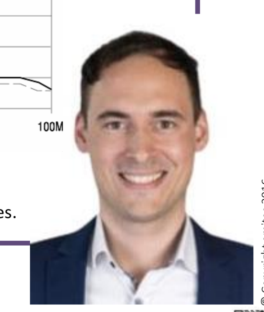
All sensors do have a derating curve in the manual. This curve indicates where the sensor will be saturated.
This means on which frequency the sensor can take how much current to not blow up, or where the measurement limit is dependent to frequency.
Only because a sensor is rated 30Arms and has a bandwidth of 100MHz, does not mean you will be able to measure 30Arms at 100MHz.

In the below table you can see a usual AC/DC current probe.
This indicates you are able to measure <3Arms at 100MHz.



Oscilloscope current probe, 30Arms 100MHz

Even worse it gets with higher ambient temperatures.



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