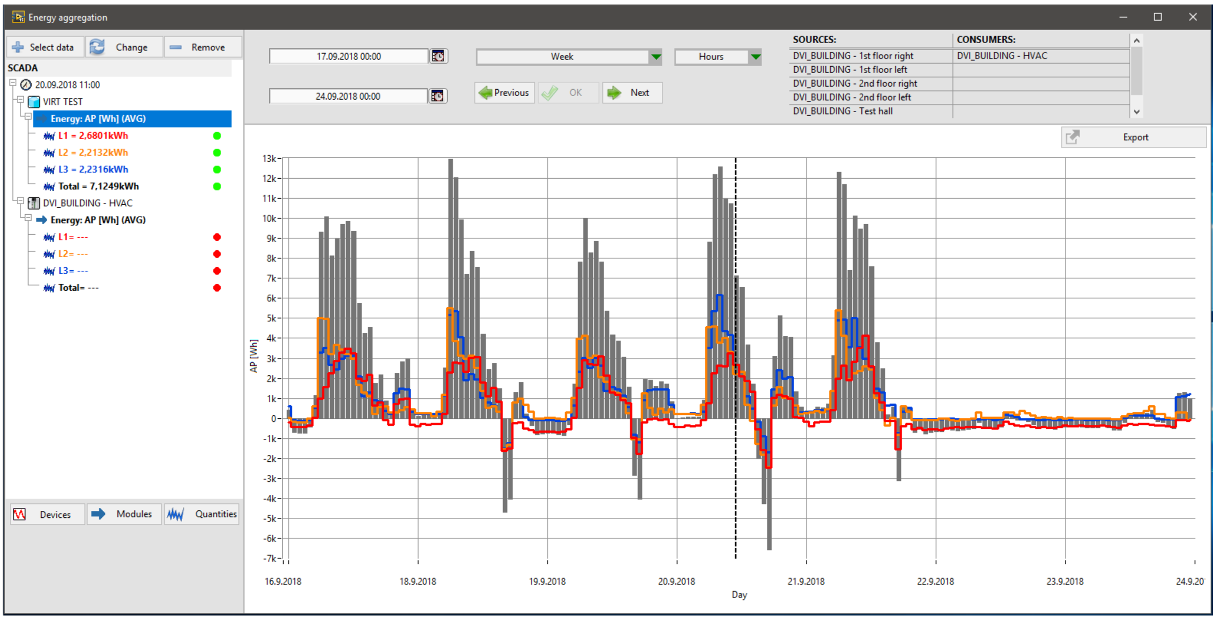
Technical Reference MANUAL

V1.5



SCADA
20.09.2018 11:00
VIRT TEST
Energy: AP [Wh] (AVG)
L1 = 2,6801kWh ●
L2 = 2,2132kWh ●
L3 = 2,2316kWh ●
Total = 7,1249kWh ●
DVI_BUILDING - HVAC
Energy: AP [Wh] (AVG)
L1= --- ●
L2= --- ●
L3= --- ●
Total= --- ●

17.09.2018 00:00
24.09.2018 00:00
Week
Hours

SOURCES:	CONSUMERS:
DVI_BUILDING - 1st floor right	DVI_BUILDING - HVAC
DVI_BUILDING - 1st floor left	
DVI_BUILDING - 2nd floor right	
DVI_BUILDING - 2nd floor left	
DVI_BUILDING - Test hall	

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Table of Contents

Thank you!

Thank you very much for your investment in our unique instrument. These are top-quality instruments which are designed to provide you years of reliable service. This guide has been prepared to help you get the most from your investment, starting from the day you take it out of the box, and extending for years into the future.

Support

When you are working with our products we want to provide you with the greatest possible benefits. If you need any support, we are her to assist you.

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1 Introduction

In this technical reference manual we would like to offer you a deep dive into the technological world of NEO Messtechnik. This manual is intended to discuss the fundamental knowledge of power and power quality measurement and goes into great detail on the data analysis according to well-known and established norms and standards of the industry.

Furthermore, we would like to offer you a hands-on approach by combining this essential information with application examples using the right NEO hardware and software solutions. Throughout this document we will refer to other NEO manuals like the Software Manual or the Current Sensors Manual as well. In order to get the full picture of effortless power quality measurement and analysis we can only strongly advise you to take a closer look on these manuals as well. All the necessary information and links can be found in the last chapter of this manual.

Measuring and analyzing in the power and power quality industry has never been easier, more mobile and effortless, and we would like to take you on our journey!

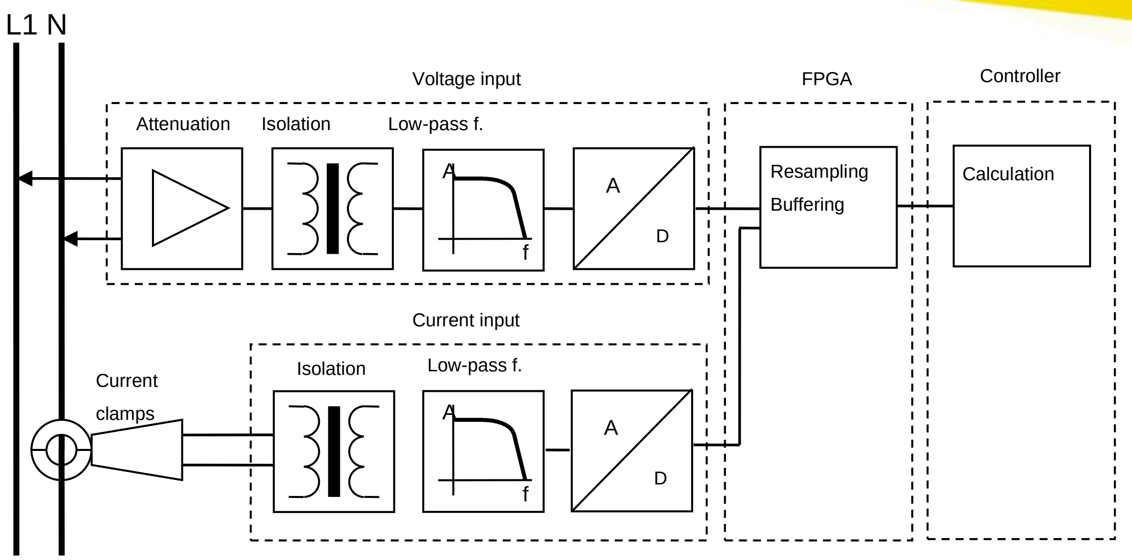
2 Computer-based Power Quality Analyzer

NEO Messtechnik power quality measurement instrument are used to measure and analyze electrical power network parameters and quality according to international standards IEC 61000-4-7, IEC 61000-4-15, EN 50160, and IEC61000-4-30. The analyzers fully comply with the IEC 61000-4-30 standard, class A.

2.1 Basic Principle and A/D Conversion

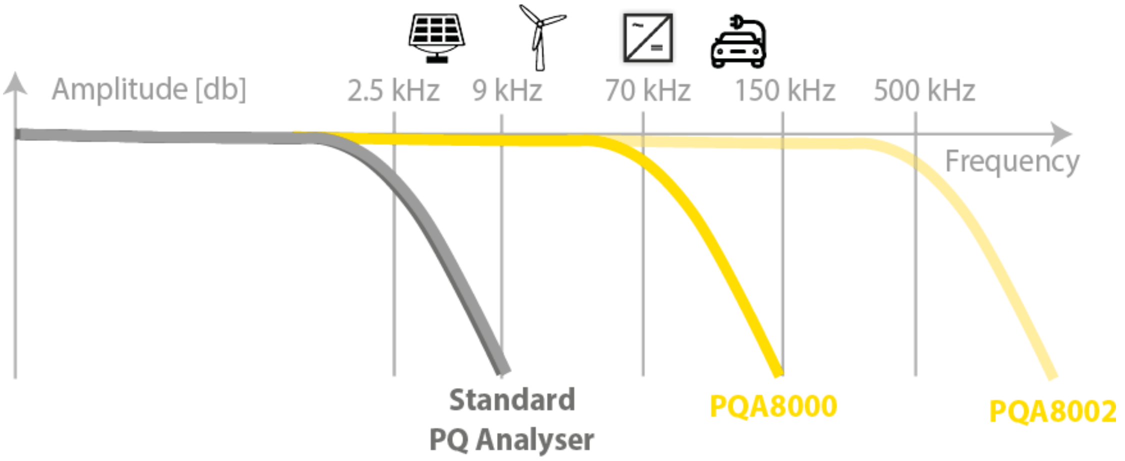
The performance of the hardware, including bandwidth, accuracy and resolution, has increased dramatically over the past 10 years to the point where the performance of computer-based digitizers is comparable to traditional instruments. Today, virtually all common measurements and complex applications, such as FFTs and signal processing routines, can be done in less time and at a lower cost due to the declining prices of measurement components. Moreover, these components are tightly integrated with the software. It is easy to reconfigure the computer-based system to follow the user’s changing demands.

Currently, the analyzer is implemented on several HW platforms. The following points are common for any HW platform: The computer is equipped with the plug-in data-acquisition (DAQ) board. The DAQ process of instrument’s SW uses a basic sampling frequency up to 1 MS/s per channel. Modules for signal conditioning of voltage and current signals provide attenuation/amplification, isolation and anti-aliasing filtering. Modules for signal conditioning are programmable via digital lines and allow a wide input range selection and an anti-aliasing cut-off frequency set-up.



2.1.1 Sampling Rate and Bandwidth and Anti-Aliasing Filter

Conventional PQ Analyzers, even if they are Class A certified, are not sufficient for modern measurement applications. We use the best available components to ensure the highest safety category and also the highest accuracy. NEO instruments offer high bandwidth (up to 1 MHz) and correct the frequency dependent behavior of current & voltage sensors as well as integrated electronics to achieve the best possible measurement results.



The instrument uses analog and digital filters. Independent from the chosen sampling rate an automatic anti-aliasing filter will be applied. For example, if you set the sampling rate to 124 kS/s, the aliasing free bandwidth (-3dB) will be 70kHz. For more information about sampling rate, filter and bandwidth of your instrument please refer to the technical specification at the end of the product manual.

2.1.2 Amplifier – isolated and non-isolated

All High-Voltage inputs of the NEO Instruments are isolated. Current Inputs (via Low-Voltage inputs) are usually non-isolated, as isolation is provided by the used current sensors.

Differences between isolated and non-isolated amplifiers

While single-ended amplifiers are easy to use due as their second pin is connected to ground, they are only suitable for measuring floating voltage sources and thereby have two disadvantages – the influence of ground loops and the missing isolation. Differential amplifiers using inputs separated from ground avoid the aforementioned ground loops, although deal with the problem of common mode voltage.

Benefits of isolation

Isolated amplifiers eliminate all these disadvantages like ground loops, common mode voltage as they are isolated from the housing and the main board of the measuring device and are therefore a safe and reliable solution handling voltage peaks, faults and other disturbances.

2.1.3 Safety Categories - Leading in Safety

Over voltages from power lines down to factories can be higher than normal operating voltages. To avoid any kind of electrical accident, NEO Messtechnik emphasizes the importance of a safe instrument design. As a matter of fact, the High-Voltage inputs of the PQA 8000 instrument (CAT IV 600V) are isolated up to 6kVp – and this while maintaining high precision (0.05%) and high sampling (up to 2MS/s). This is world-leading technology.

Safety categories

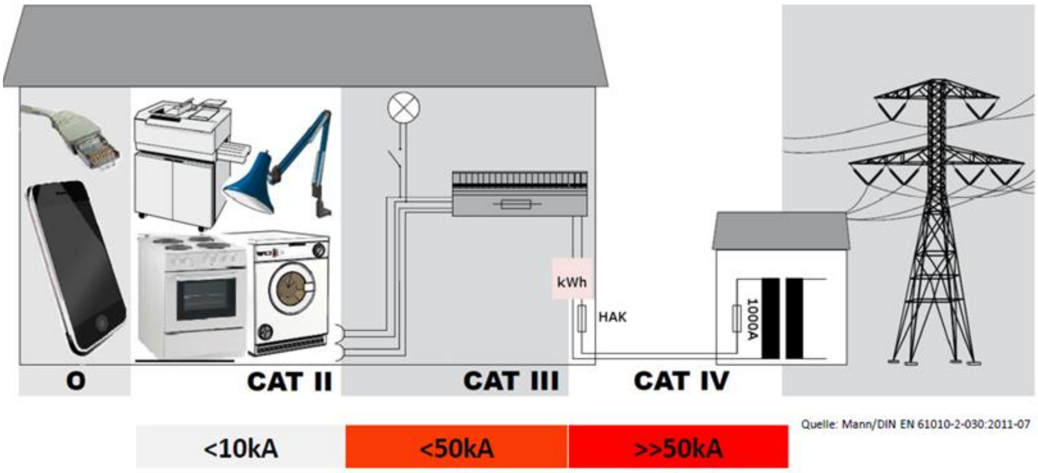
- **CAT I:**

  This category is for measurements of voltages from specially protected secondary circuits. Such voltage measurements include signal levels, special equipment, limited-energy parts of equipment, circuits powered by regulated low-voltage sources, and electronics.
- **CAT II:**

  This category refers to local-level electrical distribution, such as that provided by a standard wall outlet or plug in loads (for example, 115 AC voltage for U.S. or 200 AC voltage for Europe). Examples of Measurement Category II are measurements performed on household appliances, portable tools, and similar modules.
- **CAT III (1000V):**

This category refers to measurements on hard-wired equipment in fixed installations, distribution boards, and circuit breakers. Other examples are wiring, including cables, bus bars, junction boxes, switches, socket outlets in the fixed installation, and stationary motors with permanent connections to fixed installations.
Any kind of measurements at electric vehicles also needs specifications of CAT III.

- **CAT IV (600V):**
  This category refers to origin of installation or utility level measurements on primary over-current protection devices and on ripple control units.



Quelle: Mann/DIN EN 61010-2-030:2011-07

Expected short-circuit current (1kV normalized)

2.1.4 Measurement Range

Selecting the right measurement range for input channels is vital for the further conditioning and analysis of signals. Configurable amplifiers allow the user to select the right measurement range via the software.

At this point we would like to take a closer look at how the selected range is vital for the accuracy and reliable results.

- Choosing a range that is smaller than the expected input signal, the signal will exceed the input range and this results in a channel overload.
- Choosing a range that is too big, the inaccuracy within this measurement range will result in a high uncertainty of the read-off signal value. It is not possible to make correct readings.

The most precise and reliable measurement is achieved with a carefully selected DAQ amplifier range that meets the expected signal range.

Measurement range and resolution with a 24-bit converter

With the following table we would like to talk about the importance of choosing the right amplifier range for voltage input signals by using a 24-bit converter.

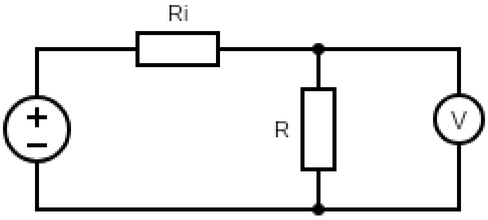
Number of bits	Discrete steps	Smallest resolution for input range of		
		+/- 1V	+/- 5V	+/- 10V
8	256	7.813 mV	39.1 mV	78.1 mV
12	4096	0.488 mV	2.441 mV	4.883 mV
14	16384	0.122 mV	0.610 mV	1.221 mV
16	65536	0.031 mV	0.153 mV	0.305 mV
24	16777216	0.119µV	0.596 µV	1.192 µV

- This 24-bit converter we use dissolves an analog signal into 16777216 different discrete values, resulting in the highest resolution for your measurement applications.
- Choosing the right range actually means taking advantage of the best resolution that is offered by the converter.

3 Power Analysis

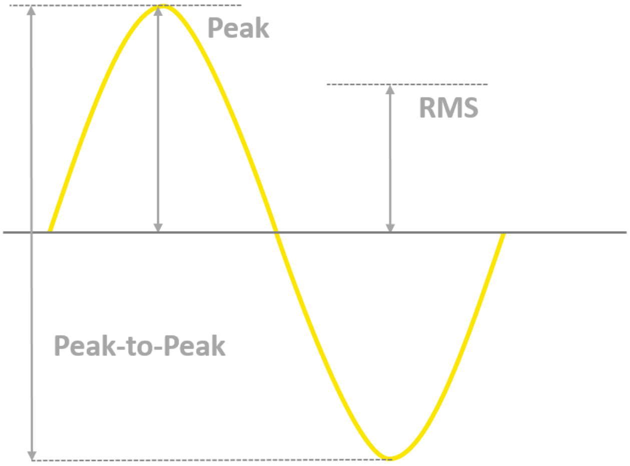
3.1 Voltage Measurement

As Voltage is defined as the electrical potential difference of two points, voltmeters are used in parallel of these two points to determine the voltage in an electric circuit. Typical input impedances of voltmeters can be stated in the MΩ area.



Measuring voltage signals with DAQ devices requires knowledge about the range of input signals (µV up to kV), using the right amplifiers, selecting the according measurement range and be aware of phenomena like ground loops, disturbances and noise signals. Choosing the right amplifier, also in terms of isolation voltage, has already been discussed in previous chapters, as it is very important for a safe and reliable measurement setup. The High-Voltage inputs of the PQA 8000 instrument (CAT IV 600V) are isolated up to 6kVp.

Peak, Average and RMS Value of a signal



- The (mathematical) **Average** value of a signal is calculated over a certain time span and equals zero for pure sinus-signals.
- The **RMS** value (Root mean square) is the square root of the arithmetic mean of the squared function values that define the continuous waveforms. It results in the same energy as the **DC** voltage at an ohmic load.

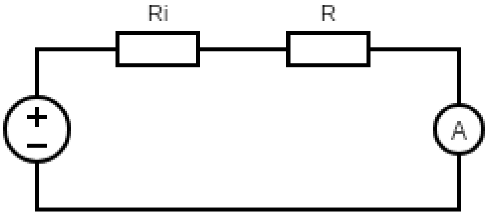
$$U_{RMS} = \sqrt{\frac{\sum_{n=0}^{N-1} u^2(n)}{N}}$$

- The **Peak** value describes the highest value of a period, and in datasheets is also stated as DC voltage of an input. Dividing the peak value by the square root of 2 results in the RMS value of a sine wave signal.
- The **Peak to Peak** value sums up the positive and negative peak of a period.
- The Crest factor is the peak amplitude divided by the RMS value of the waveform.

$$C = \frac{|x|_{peak}}{x_{rms}}$$

3.2 Current Measurement

Electric current basically flows when an electric circuit is closed and the potential difference of an energy source, e.g. battery, can be equalized. For measuring current on a basic level Ampere meters are used in series to the electric circuit, which has to be opened therefore. The input impedance of Ampere meters must be as low as possible to not affect the actual circuit too much.



Moving on from this very basic approach to applications in the power and energy field using DAQ amplifiers, electric current can be measured directly as well as indirectly.

- The **direct** method involves opening the circuit/conductor to connect a sensor in series. The sensor is a **Shunt resistor**, a resistor with a highly accurate and very low resistance value. The actual current value is determined by the means of the voltage drop off over the Shunt and Ohm’s Law.
- The **indirect** methods allow current measurements via the magnetic field, without the need of opening the circuit and thereby galvanic isolation of the sensor from the conductor. Current sensor that work on these indirect principles include Rogowski coils, Hall compensated clamps or zero flux transducers among others.

A more in-depth discussion of these principles and NEO current sensors can be found in the *Current Sensor Manual* on our website.

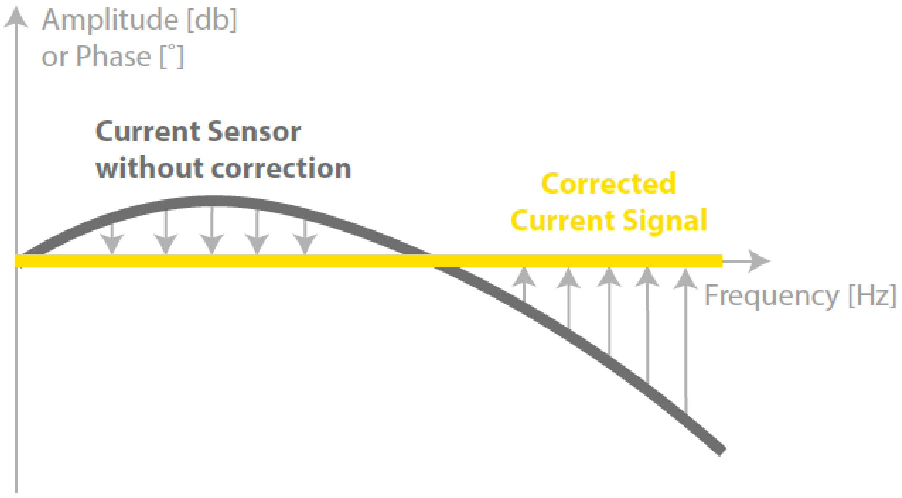
3.3 NEO Sensor calibration and correction

All current sensors offered by NEO Messtechnik are industry proven for different applications. We use best available sensors but also improve them by frequency dependent and measurement range dependent calibration and correction.

FREQUENCY DEPENDENT CALIBRATION

The NEO sensor integration calibrates each sensor over a wide frequency bandwidth and corrects frequency dependent

phase shift and amplitude damping. This allows for high precision from DC to high-frequency measurements.



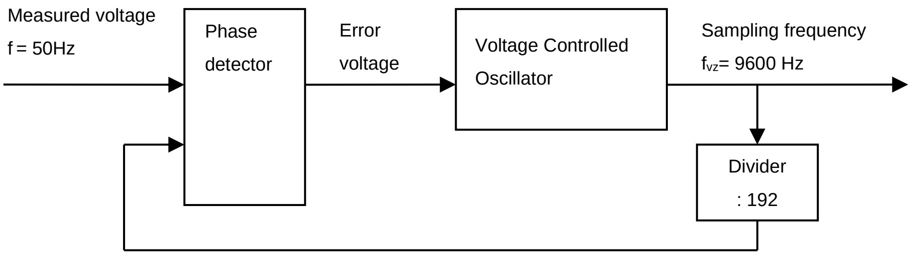
MEASUREMENT RANGE DEPENDENT CALIBRATION

In addition, the sensors will calibrated for each measurement range using multiple points. The calibration will typically cover points from 1% to 100% of the nominal measurement range. This will improve the accuracy and precision, especially at low current (e.g., 1% of nominal measurement range).

All sensors will be delivered with a standard calibration, which improves the accuracy compared to nominal specifications,whereas the NEO calibration will be performed on each individual sensor and needs to be ordered separately.

3.4 Frequency Measurement

The Phase Lock Loop (PLL) is used to synchronize the sampling rate with the frequency of measured voltage signals and is described in the following picture. According to the IEC61000-4-30, the basic time window is 10 cycles (200ms for 50Hz signal).

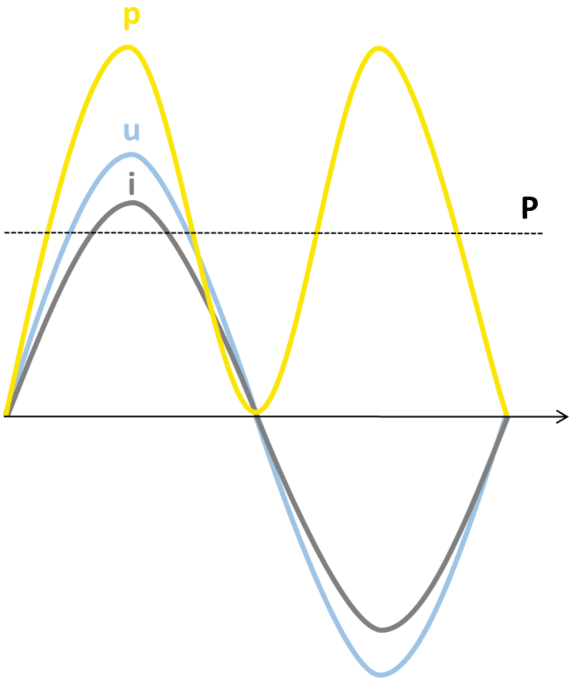


The principle of Phase Lock Loop

3.5 Power Calculation

Electric power is the product of current and voltage in every occurring moment, which is equal to the mathematical sum using the integral over the cycle time T. Its unit is Watt [W].

$$P(t) = \frac{1}{T}\int_{t}^{t+T} u(t)\cdot i(t)dt$$



On the other hand it can also be understood as the energy flow in a certain period of time, as power over a certain time results in energy.

$$E = \int P(t)dt$$

The power calculation is based on the aforementioned formula, although the correct calculation and meaningful interpretation of these results depends on the consideration of various challenging factors. These include characteristics of the measured systems (AC or DC), the number of systems and phases (single line or 3 phase) or the influence of inverters etc.

In the following pages we will talk about power measurement and calculation of different systems (DC, single-phase or three phase systems) and for different applications.

Power calculation with NEO Messtechnik

The determination is done in the frequency domain on the basis of the period time. Carrying out a FFT analysis of the electric voltage and current, for 10 cycles and a certain sample rate, the **voltage/current amplitude and cos phi of every single harmonic**.

It is thereby possible to consider amplifier or transducer shifts (amplitude or phase) over the whole frequency range distorting the measured quantities and automatically correcting them. Doing this determination in the frequency domain also completely synchronize all PQ parameters with the fundamental frequency of the measured system.

Once the FFT values are corrected, the RMS values of each voltage/current harmonics sum up to the respective total RMS voltage/current value according to:

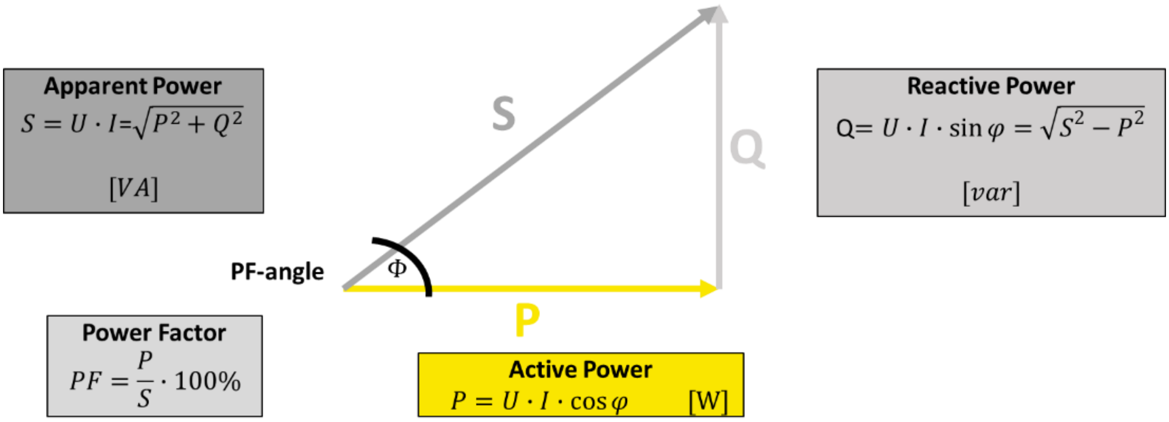
$$U_{rms_{total}} = \sqrt{U_0^2 + U_1^2 + U_2^2 + \ldots + U_n^2}$$

$$I_{rms_{total}} = \sqrt{I_0^2 + I_1^2 + I_2^2 + \ldots + I_n^2}$$

In the next steps the main three power quantities are calculated accordingly:

Power	certain harmonic h	Total value
Apparent	$S_h = U_h \cdot I_h$	$S = U_{rms,total} \cdot I_{rms,total}$
Active	$P_h = U_h \cdot I_h \cdot \cos\varphi_h$	$P = \sum_{h=1}^{H} P_h$
Reactive	$Q_h = U_h \cdot I_h \cdot \sin\varphi_h$	$Q = \sqrt{S^2 - P^2}$ or $Q = \sum_{h=1}^{H} Q_h$

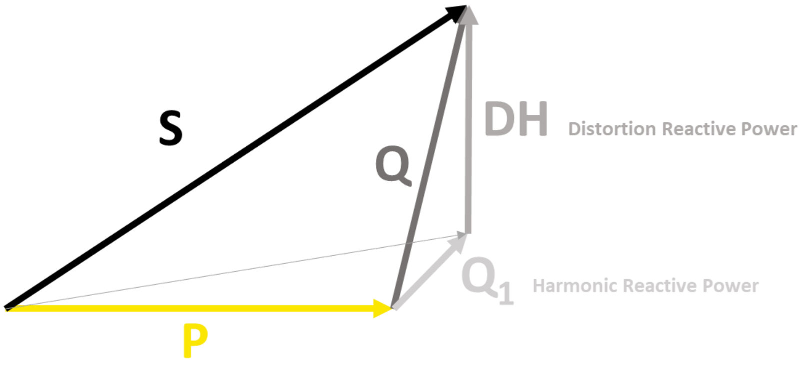
Types of power by means of the classic power triangle



- **Active Power P** is transferred to the electric consumer/load and can be “used”, which means transferred to mechanical energy, for example.
- **Reactive Power Q** is a natural part of the electric grid as it is needed/provided for magnetic fields (motors, generators) of generators or capacitors. It is a crucial part of the grid and also influences it as well as the transfer capacity. Q displayed on the imaginary axis vertically and can be positive as well as negative.
- The higher the **Power Factor**, the lower current flow and therefore losses in the system, equals to a reduced transmission efficiency, which can be seen in the formula above.
- The **cos-phi** gives the phase angle between the voltage and current of a certain harmonic. In contrast to the power factor, the cos-phi is calculated for each harmonic, while the power factor takes the whole system into consideration.

Types of power by means of the new power triangle

Inverters among other non-linear loads and especially renewable energy generation units (wind, PV) bring two new parameters into the Power-Quality industry, leading to the following new power triangle.



- **Harmonic Reactive Power $Q_{1,2,...}$** of a single harmonics result from phase shifts between the current and voltage of each harmonics and are summed up to the
- **Harmonic Reactive Power QH**

$$QH = \sum_{h=1}^{H} Q_h$$

- **Distortion Reactive Power DH** combining voltage and current quantities from different harmonics

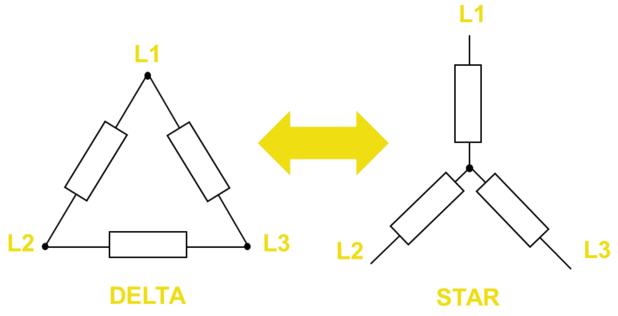
$$DH = \sqrt{Q^2 - QH^2}$$

- **Distortion D** considering all the parts **except** the first harmonic**:**

$$D = \sqrt{Q^2 - Q_{h=1}^2}$$

3.6 Star-Delta Calculation and Wiring

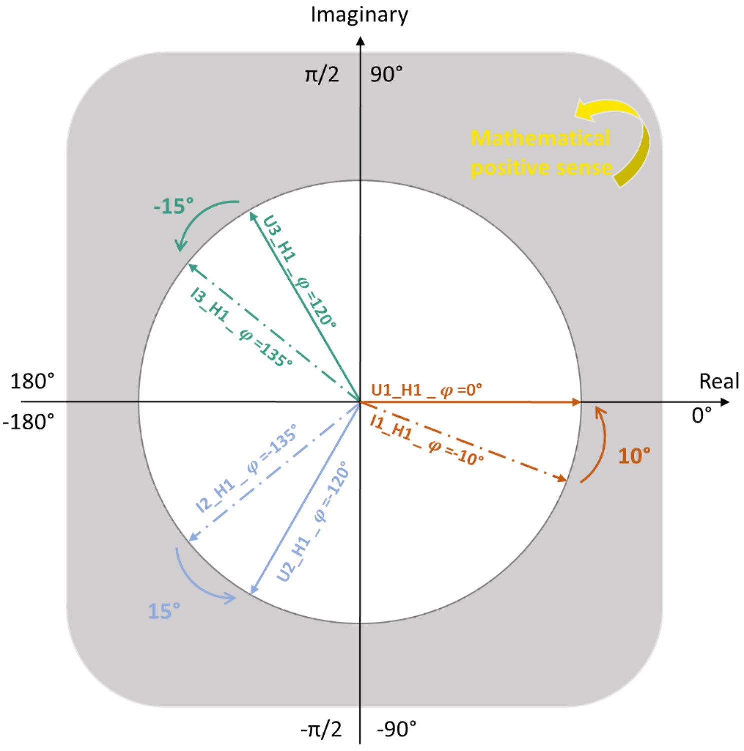
The following table shows the relation of star and delta parameters making it straight forward to easily calculate the other values.



Star-Delta calculation	Delta-Star Calculation
$\boldsymbol{u_{12} = u_1 - u_2}$	$u_1 = \frac{1}{3}(u_{12} - u_{31})$
$\boldsymbol{u_{23} = u_2 - u_3}$	$u_2 = \frac{1}{3}(u_{23} - u_{12})$
$\boldsymbol{u_{23} = u_2 - u_3}$	$u_3 = \frac{1}{3}(u_{31} - u_{23})$

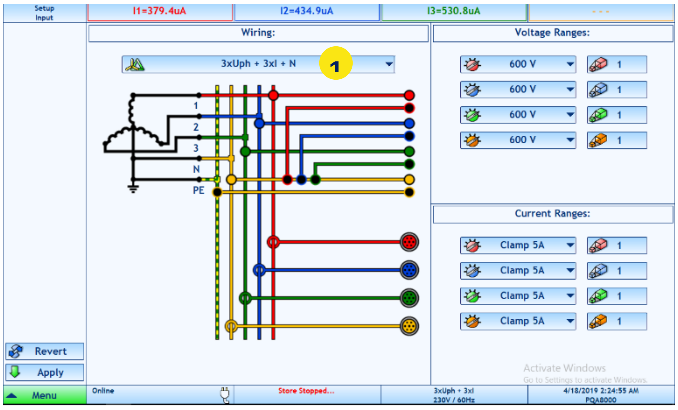
Phase angle definition

The voltage of U_L1 is defined with 0°, being in line with the real axis, serving as **the reference point to all phase angles**.



Star (Y) Connection

Select '3xUph + 3xl + N' in the wiring setup and connect the cables according to the picture.



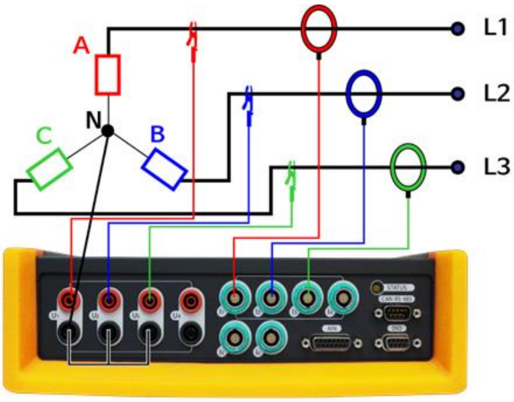
I1=379.4uA | I2=434.9uA | I3=530.8uA

Wiring: 3xUph + 3xl + N

Voltage Ranges: 600 V, 1 / 600 V, 1 / 600 V, 1 / 600 V, 1

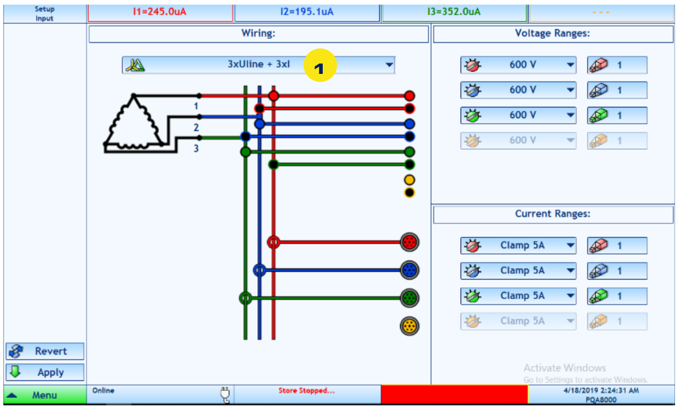
Current Ranges: Clamp 5A, 1 / Clamp 5A, 1 / Clamp 5A, 1 / Clamp 5A, 1

Online | Store Stopped... | 3xUph + 3xl 230V / 60Hz | 4/18/2019 2:24:55 AM PQA8000



Delta Connection

Select '3xUline + 3xl ' in the wiring setup and connect the cables like below picture.



I1=245.0uA | I2=195.1uA | I3=352.0uA

Wiring: 3xUline + 3xl

Voltage Ranges: 600 V, 1 / 600 V, 1 / 600 V, 1 / 600 V, 1

Current Ranges: Clamp 5A, 1 / Clamp 5A, 1 / Clamp 5A, 1 / Clamp 5A, 1

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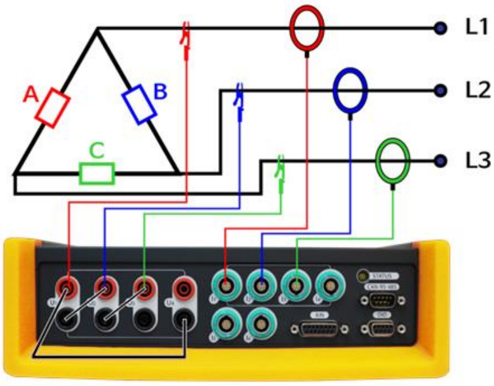
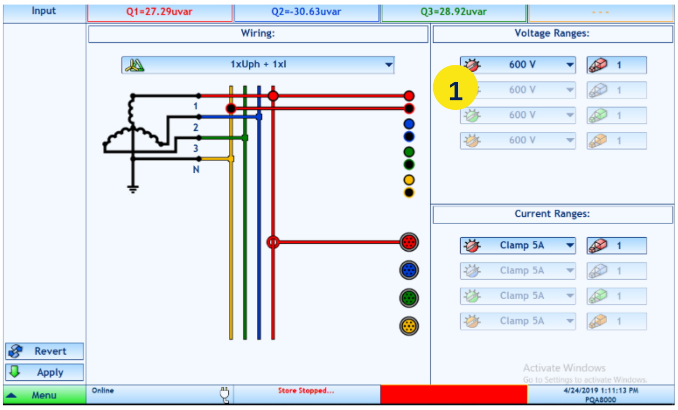


Single Phase Connection

Select ‘1xUph + 1xl' in the wiring setup and connect the cables like below picture.



Q1=27.29uvar | Q2=-30.63uvar | Q3=28.92uvar

Wiring: 1xUph + 1xl

Voltage Ranges: 600 V, 1 / 600 V, 1 / 600 V, 1 / 600 V, 1

Current Ranges: Clamp 5A, 1 / Clamp 5A, 1 / Clamp 5A, 1 / Clamp 5A, 1

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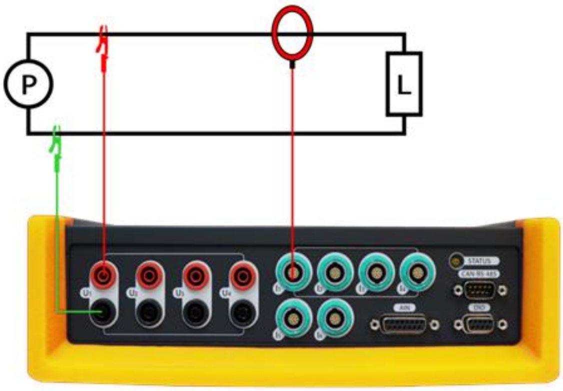


3.7 Energy & Efficiency Calculation

The calculation of energy consumption or delivery can be done easily with the following calculations. The sign of the power flow determines the positive or negative energy value and also leads to the meaning of consumed energy (positive value) or delivered energy (negative value).

Various applications for assessing load profiles of industries or even private households or systems in general with a certain amount of generators and consumers work on this basic principle for making conclusive statements about the energy flow.

The same can be said about efficiency calculation which takes the power & energy assessment a step further. The energy calculation is basically the integration of power values over a defined period of time, which means that positive as well as negative values are integrated. The electric power is measured and calculated in Watt [W], while the energy unit is Watthours [Wh].

Description	Function
Energy (total)	$E = \int_{t=0}^{T} p(t)dt$
Positive Energy $P_{mot}(t) > 0$	$E_{motor} = \int_{t=0}^{T} p_{mot}(t)dt$
Negative Energy $P_{mot}(t) < 0$	$E_{recuperation} = \int_{t=0}^{T} p_{mot}(t)dt$

Efficiency is generally defined as the ration between output and input values of a system, whether it is power or energy efficiency. Efficiencies are always given in per cent [%].

$$\eta = \frac{P_{motor}}{P_{grid}} \cdot 100$$

3.8 Time Aggregation of Power Quality data

According to IEC61000-4-30 the following aggregation is provided for Class A:

- Time intervals: The basic measurement time interval for parameter magnitudes (supply voltage, harmonics, interharmonics and unbalance) shall be a 10-cycle time interval for a 50 Hz power system or 12-cycle time interval for a 60 Hz power system.
- Aggregation: Measured time intervals are aggregated over 3 different time intervals. The aggregation time intervals are:
    - 150/180 cycle interval (150 cycles for 50 Hz nominal or 180 cycles for 60 Hz nominal)
    - 10-min interval
    - 2-h interval

4 Power Quality Measurement

4.1 The evolution of the power grid

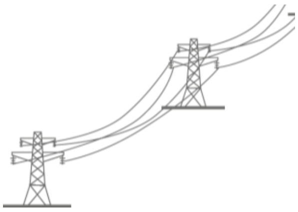
From Power Generation via Transmission and Distribution Grids to changes in electrical equipment and energy consumption, the electrical power grid is constantly evolving.

Changes in Power Generation:

- Large conventional plants are being replaced with a high number of small units (connected to Low-Voltage grids)
- There is a shift to non-dispatchable renewable energy
- Synchronous machines are being replaced by power-electronic interfaces

Changes in Transmission and Distribution:

- Advancements are being made in Power Electronic Equipment (Filters, STATCOM, etc.)
- Two-Way Power Flow are being introduced due to distributed generation
- HV AC cables and HVDC systems are being re-innovated
- There is an increased use in Power-Line communication



Changes in Consumption:

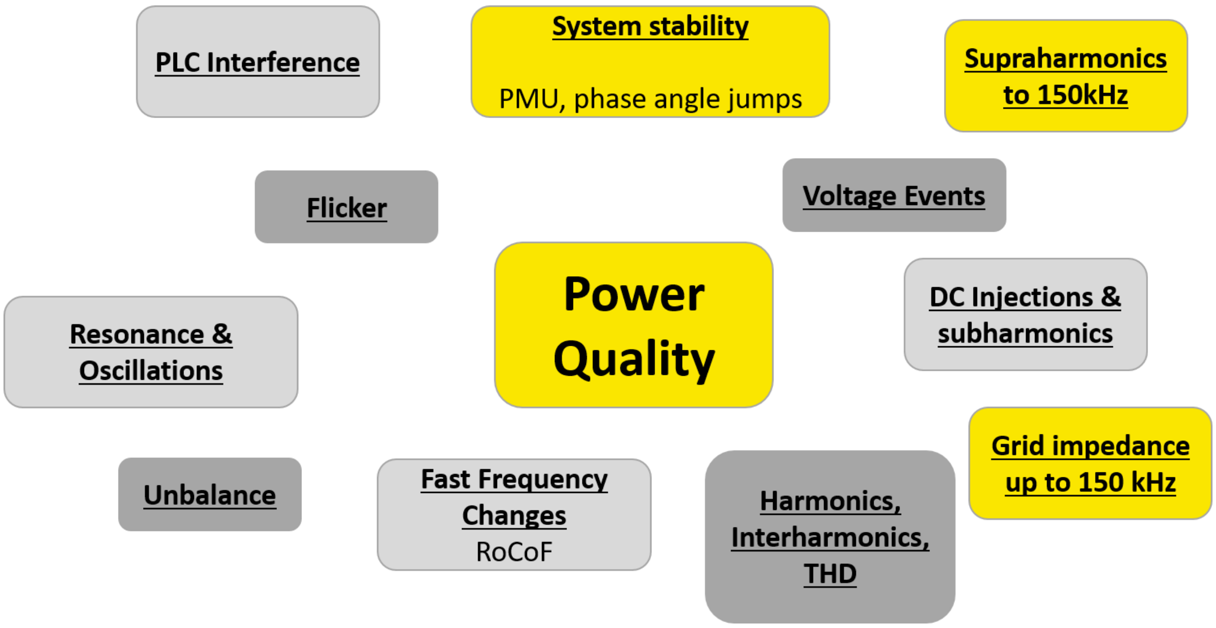
- Energy-efficient device usage is increasing
- There is an overwhelming proliferation of small devices on the grid
- There is an increase in Electric-Vehicles and Heat pumps
- There is almost a complete shift to active Power Electronics (motors, pumps, lighting...)

These changes require new technologies such as Microgrids, Demand Side management (DSM), Distributed Generation (DER), Distributed control (U, P), Feeder Reconfiguration, etc. The decrease in short-circuit power and destabilization of the grid require that the distributed generation units also need to provide services to the power grid. This services are defined in Grid Codes (international and national regulations).

4.2 The future of Power Quality

Power Quality phenomena arise from electric wave signals deviating from the ideal sinus waveform. Today classical Power Quality Analysis according to EN50160, including reports defined by the measurements of Voltage variations, Frequency, Harmonics (50th order), Flicker and Unbalance, is no longer sufficient.

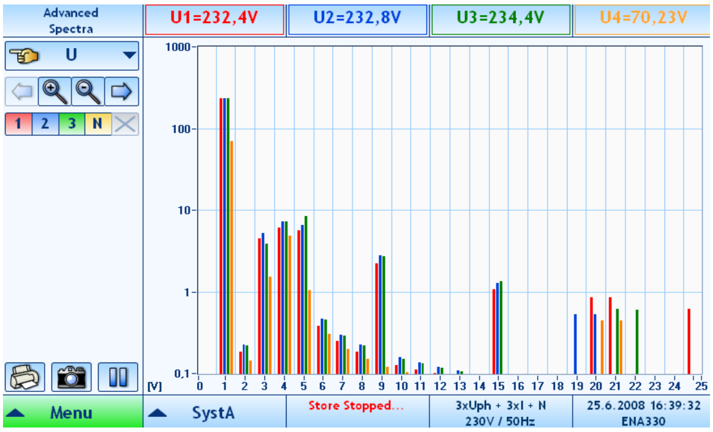
Power Quality Analysis must adapt to the ever-evolving power grid which requires additional measurements that are depicted in the following graph and discussed in the next subchapters.



4.3 Harmonics, Interharmonics, THD

Pure sinus waveform signals only consists of the fundamental frequency, which is well known to be 50Hz, 60Hz or 16 2/3 Hz for electric grids around the world. Even a small deviation of the pure sinus waveform, even though it can hardly be seen or detected in the time domain, the results are better illustrated in the frequency domain.

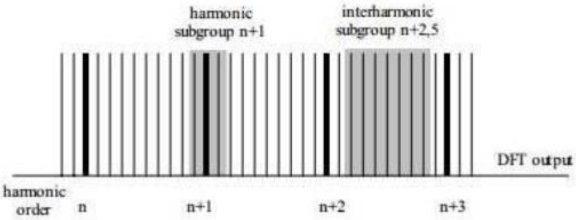
As seen in the following picture, the integer multiples of the fundamental frequency are causing the distortion in the original waveform. These are called harmonics.



Effects of Harmonics

Harmonics don't only influence the signal shapes, but operation and the life span of electrical devices and equipment. Harmonic frequencies in motors and generators can result a various mechanical phenomena that all have efficiency reduction as end result. Among these are higher audible noise, faster aging of the shaft, insulation and mechanical parts. Furthermore pulsating or reduced torque as well as increased heat development.

Harmonics and Interharmonics



FFT analysis provides frequency analysis of 4 voltages and 4 current signals up to the 50th harmonic, based on IEC61000-4-7, and operates in two modes:

- **Harmonic Analysis** where the frequency resolution is 50Hz (60Hz) or
- **Interharmonic Analysis** where the frequency resolution is 25Hz (30Hz).

FFT output has a step size of 5Hz due to the basic time frame of 200ms. According to the IEC 61000-4-30 the standard IEC61000-4-7 shall be used to determine a 10/12-cycle, a gapless harmonic subgroup measurement, denoted Gsg,n in IEC 61000-4-7:2002. The harmonic subgroup measurement defines how the 5Hz spectral lines should be grouped to obtain harmonic lines with a frequency step size of 50Hz.

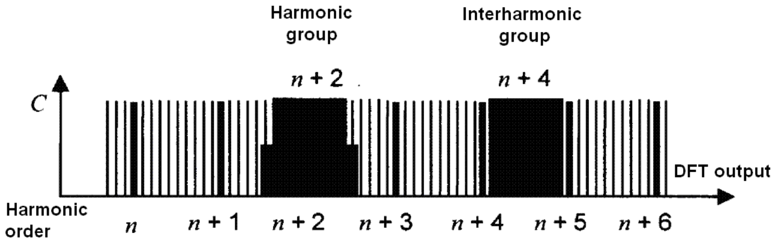
$$C_{sg,n}^2 = \sum_{i=-1}^{1} C_{k+i}^2 \quad \{\text{harmonic subgroup}\}$$

IEC61000-4-7 shall be used to determine a 10/12-cycle gapless centered interharmonic subgroup measurement, denoted Cisg,n in IEC 61000-4-7:2002. The harmonic centered interharmonic subgroup measurement defines how the 5Hz spectral lines should be grouped to obtain interharmonic lines with a frequency step size of 50Hz.

$$C_{ig,n}^{2} = \sum_{i=1}^{9} C_{k+i}^{2} \quad \left\{\text{centered interharmonic subgroup, power network 50 Hz}\right\}$$

In case the FFT is running on harmonic only mode, 5Hz spectral lines must be grouped in a different way (IEC 61000-4-7:2002) to complete the signal energy in the frequency domain with a 50Hz step size, see the following figure.

$$G_{sg,n}^{2} = \frac{C_{k-5}^{2}}{2} + \sum_{i=-4}^{4} C_{k+i}^{2} + \frac{C_{k+5}^{2}}{2} \quad \left\{\text{harmonic group, power network 50 Hz}\right\}$$



Example:

$$G_{g,n}^{2} = \frac{C_{k-5}^{2}}{2} + \sum_{i=-4}^{4} C_{k+i}^{2} + \frac{C_{k+5}^{2}}{2} \quad \left\{\text{síť 50 Hz}\right\}$$

$$G_{g,n}^{2} = \frac{C_{k-6}^{2}}{2} + \sum_{i=-5}^{5} C_{k+i}^{2} + \frac{C_{k+6}^{2}}{2} \quad \left\{\text{síť 60 Hz}\right\}$$

Harmonics calculations in the Neo Messtechnik Software

FFT analysis provides the amplitude and phase spectra, thus the U, I, P, Q spectra can be provided. In power spectra, the power flow can easily be recognized on a particular harmonic that can be useful to identify sources of disturbances.

Channel name	Description	Formula/Calculation
S_L1_H1	**Apparent, active and reactive power** for one harmonic frequency (e.g. L3 and h=5)	$S_h = U_h \cdot I_h$
P_L1_H1		$P_h = U_h \cdot I_h \cdot \cos(\varphi_h)$
Q_L1_H1		$Q_h = U_h \cdot I_h \cdot \sin(\varphi_h) = \sqrt{(S_h^2 - P_h^2)}$ or Q = $\sum_{h=1}^{H} Q_h$
S_L1	**Apparent, active and reactive power** for the whole waveform (e.g. L3)	$S = U_1 rms \cdot I_1 rms$
P_L1		$P = \sum_{h=1}^{H} P_h$
Q_L1		$Q = \sqrt{(S^2 - P^2)}$
Z_L1	**Impedance** of the whole waveform (e.g. L3)	$Z_{L1} = \frac{U}{I}$
Z_L1_H1	**Impedance** of one harmonic (e.g. L3 and H1)	$Z_{L1} = \frac{U_H}{I_H}$
PF_L1	**P-factor** (e.g. for L3)	$PF = \frac{P}{S}$
D_L1	**Distortion power** of all harmonic reactive power parts (e.g. for L3)	$D = \sqrt{(Q^2 - Q_{h=1}^2)}$
QH_L1	**Reactive power** of all harmonics (e.g. for L3)	$QH = \sum_{h=1}^{H} Q_h$
DH_L1	**Distortion power** of all harmonic reactive power parts (e.g. for L3)	$DH = \sqrt{(Q^2 - QH^2)}$

Total Harmonic Distortion – THD (50/60 Hz)

The THD is defined as the sum of all harmonics (RMS) to the fundamental (RMS) and calculated up to the **40th or 50th harmonics** according to the following formula.

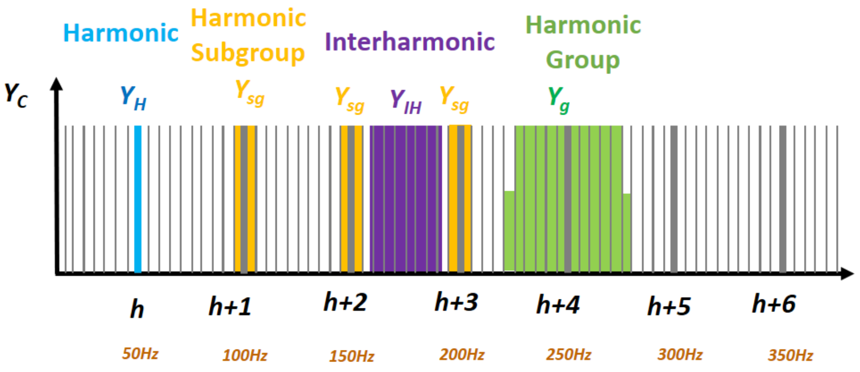
$$THD \quad = \frac{\sqrt{\left(\sum_{n=2}^{n}(G_n)^2\right)}}{G_1}$$

Note: THD vs. THDG

The THD calculation covers only the harmonic FFT lines (G_n) and does not cover the grouped harmonic value (G_{gn}). The calculation is implemented according to IEC61000-4-7. The THD value covering the harmonic group (G_{gn}) is defined as THDG according to IEC61000-4-7 and can be activated in the software optionally.

$$THDG \quad = \frac{\sqrt{\left(\sum_{n=2}^{n}(G_{gn})^2\right)}}{G_1}$$

The following picture shows the difference between THD, THDG and THDS in the spectra and as formula:



$$\boxed{THD_Y = \sqrt{\sum_{h=2}^{h_{\max}}\left(\frac{Y_{\mathrm{H},h}}{Y_{\mathrm{H},1}}\right)^2}}$$

Klasse A

$$\boxed{THDG_Y = \sqrt{\sum_{h=h_{\min}}^{h_{\max}}\left(\frac{Y_{\mathrm{g},h}}{Y_{\mathrm{g},1}}\right)^2}}$$

$$\boxed{THDS_Y = \sqrt{\sum_{h=h_{\min}}^{h_{\max}}\left(\frac{Y_{\mathrm{sg},h}}{Y_{\mathrm{sg},1}}\right)^2}}$$

Klasse S

Total Harmonic Distortion – Higher Frequency THD (200 Hz)

The THD is defined as the sum of all higher frequency harmonics (RMS / 200Hz bands) to the fundamental (RMS) and calculated up to 9 kHz according to the following formula.

$$THD \quad = \sqrt{\sum_{h=1}^{h}\left(\frac{Y_{hf,h}}{Y_{hf,1}}\right)^2}$$

Total Harmonic Distortion – Supraharmonics THD (2 kHz)

The THD is defined as the sum of all supraharmonics (RMS / 2kHz bands) to the fundamental (RMS) and calculated up to 150 kHz according to the following formula.

$$THD \quad = \sqrt{\sum_{h=1}^{h}\left(\frac{Y_{shf,h}}{Y_{shf,1}}\right)^2}$$

PWHD (Partial weighted harmonic distortion)

The PWHD is defined as the sum of selected group of harmonics (RMS) to the fundamental

(RMS) and calculated according to the following formula.

$$PWHD = \sqrt{\left(\sum_{n=min}^{max} n\left(\frac{G_n}{G_1}\right)^2\right)}$$

The PWHD harmonics in NEO Software are defined according to EN12015. The minimal harmonic is 14 and the maximal is 40. This limits can be customized on the instrument.

TDD (Total Demand Distortion)

The TDD is defined as the sum of all harmonics (RMS) to the nominal load current (RMS) and calculated according to the following formula.

$$TDD \quad = \frac{\sqrt{\left(\sum_{n=2}^{n}(I_n)^2\right)}}{I_{nom}}$$

In NEO Software the nominal load for TDD calculation can be selected in Report tool and doesn’t need to be defined in advance of a measurement.

Note: In some countries the TDD is also defined as THD_{IA} (Example Austria TOR regulation)

Channel name	Description	Formula/Calculation
THD_U_L1, ...	**THD of the voltage**	$THD_U = \frac{\sqrt{(\sum_{h=2}^{n}(U_h)^2)}}{U_1}$
THDOdd_U_L1, ...	**THD of the voltage** for odd and even harmonics	$THD_{Uodd} = \frac{\sqrt{(\sum_{h=1}^{n}(U_{2h+1})^2)}}{U_1}$
THDEven_U_L1, ...		$THD_{Ueven} = \frac{\sqrt{(\sum_{h=1}^{n}(U_{2h})^2)}}{U_1}$
THD_I_L1, ...	**THD of the current**	$THD_I = \frac{\sqrt{(\sum_{h=2}^{n}(I_h)^2)}}{I_1}$
THDOdd_I_L1, ...	**THD of the current** for odd and even harmonics	$THD_{Iodd} = \frac{\sqrt{(\sum_{h=1}^{n}(I_{2h+1})^2)}}{I_1}$
THDEven_I_L1, …		$THD_{Ieven} = \frac{\sqrt{(\sum_{h=1}^{n}(I_{2h})^2)}}{I_1}$
TIHD_U_L1, ...	**Total Interharmonic Distortion** of the voltage/current	$TIHD_U = \frac{\sqrt{(\sum_{k=1}^{n}(U_k)^2)}}{U_1}$
TIHD_I_L1, ...		$TIHD_I = \frac{\sqrt{(\sum_{k=1}^{n}(I_k)^2)}}{I_1}$
K_U_L1	**K-factor** for voltage and current refers to the full-spectrum, the THD only to the fundamental voltage	$THD_U = \frac{\sqrt{(\sum_{h=2}^{n}(U_h)^2)}}{U}$
K_I_L1		$THD_I = \frac{\sqrt{(\sum_{h=2}^{n}(I_h)^2)}}{I}$
PWHD_U	**PWHD of voltage**	$PWHD = \sqrt{(\sum_{n=min}^{max} n(\frac{U_n}{U_1})^2)}$
PWHD_I	**PWHD of current**	$PWHD = \sqrt{(\sum_{n=min}^{max} n(\frac{I_n}{I_1})^2)}$
TDD	**TDD of current**	$TDD = \frac{\sqrt{(\sum_{n=2}^{n}(I_n)^2)}}{I_{nom}}$

4.4 Higher Frequencies and Supraharmonics

Introduction

The increase of Power electronics and inverters will increase the demand of Higher Frequency and Supraharmonics measurement. Emissions in the frequency range from 9 kHz to 150 kHz are source of electromagnetic interference to other electrical equipment in the power grid and therefore the need of measurement of disturbances is increasing.

The following list shows types and sources of higher frequency emissions up to 150kHz.

- **Inverters**: any kind of AC/AC, AC/DC, DC/AC converter.
  Typical examples: Inverters for variable speed drives (VSD) and PV or wind power plants.
- **Switched-Mode Power supply:** for any kind of electronics (consumer, PC, etc.)
- **Lighting equipment:** LED’s, dimmer, fluorescent lamps
- **Household equipment & tools:** Induction cooking, washing machines, lawn mowers, power drills, etc.
- **Smart Meters:** use PLC transmission
- **Industrial machinery:** welding machines
- **High-Voltage equipment:** Static VAr compensators etc.

This emission can have effects to other electrical equipment and can cause failures like this:

- **Interference and disturbances of Smart Meters** like displaying wrong values, connection problems or reading wrong data (AMR-PLC)
- **Malfunction and unintentional switching** of electronic controlled equipment (coffee machine, alarm systems, dimmer lamps, street lighting, ceramic hobs etc.
- **Communication system disturbances:** CRC errors or loss of link (Ethernet, etc.)
- **Audible Noise** in TV receivers, Radio and Telephone systems
- **Electronic Clocks deviation** (too fast)
- **Malfunction of Notebooks** like disturbed cursor positions
- **Navigation systems problem** like loss of position
- **Malfunction** of contactless magnetic card readers, credit cards

NEO Messtechnik Benefit

The NEO instruments provide market-leading accuracy from 0 to 150kHz for voltage and current measurements. The correction of frequency dependent amplitude and phase shift together with measurement range correction allows measuring very low currents (<1mA) to very high currents (150kA) from DC to 150kHz with very high accuracy.

Higher Frequencies Calculation Method

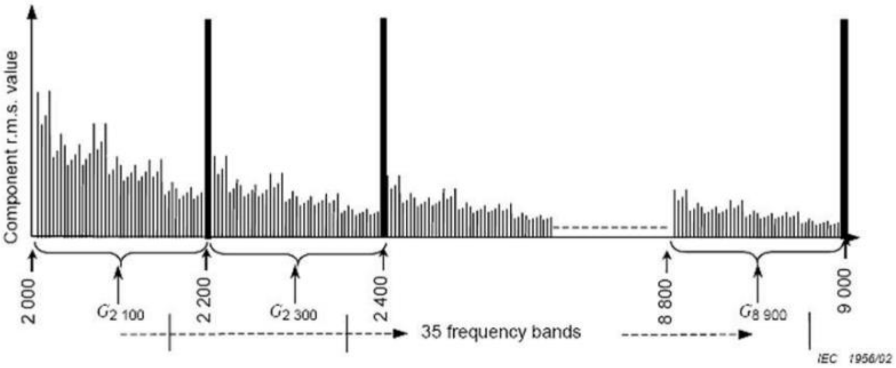
According to IEC 61000-4-7, higher frequencies are grouped in 200 Hz bands and in 2kHz bands up to 150 kHz.

The standards (IEC61000-4-7, IEC61000-4-30, IEC61400-21) requires:

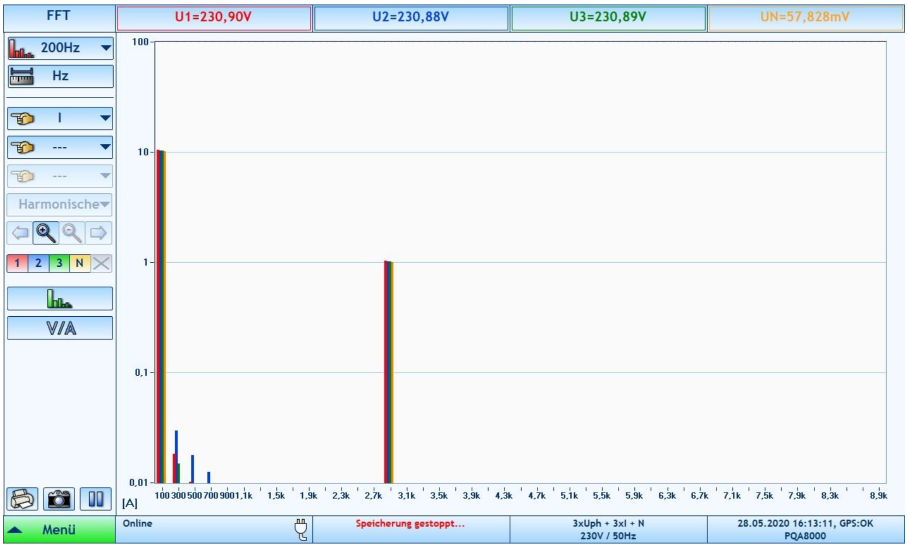
- grouping in 200 Hz bands called ***“Higher Frequencies”*** from **2-9kHz**
- grouping in 2 kHz bands called ***“Suparharmonics”*** from **8-150kHz**

  (Note: The calculation of Supraharmonics might be changed in future due to ongoing discussions in different work groups)

It is very important to consider that according to the aforementioned standard, frequency groups start at -95 Hz until +100 Hz around the middle frequency. For a middle frequency of 2.5 kHz, the frequency band is defined from 2.405 kHz to 2.3 kHz.



The following picture shows the Higher Frequencies (2-9kHz) in the NEO Messtechnik software solution. The values can be show as a FFT chart, table or Heatmap visualisation (Analyse).



U1=230,90V
U2=230,88V
U3=230,89V
UN=57,828mV

Online
Speicherung gestoppt...
3xUph + 3xI + N
230V / 50Hz
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PQA8000

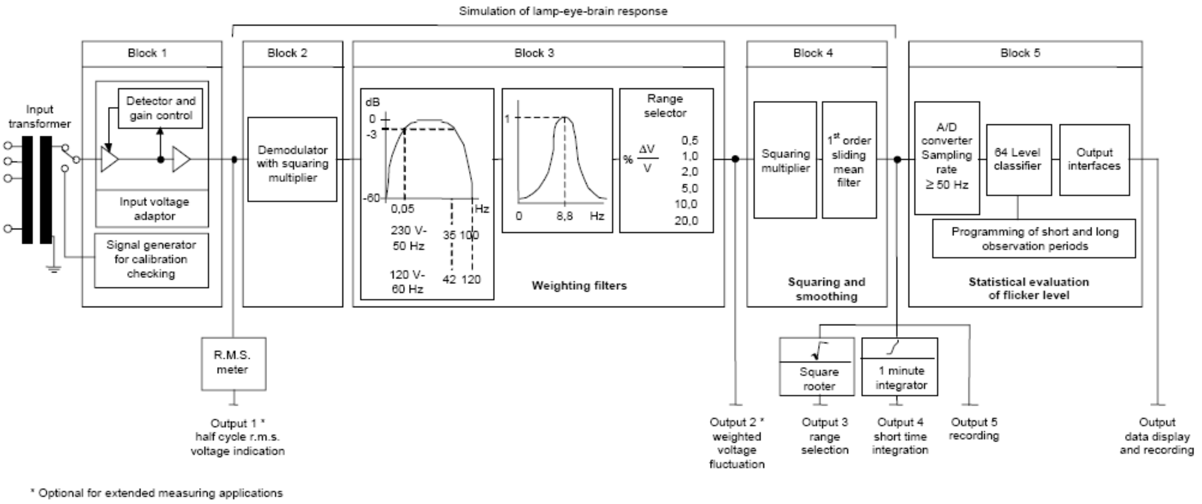
4.5 Flicker and Rapid Voltage Changes

Flicker

Commonly emerging at power grids with a low short-circuit resistance and due to repeated connection/separation of loads, Flicker leads to fluctuating voltage. Flashing lightbulbs are often cited to explain this phenomena and to underline the perception of a high Flicker level to be harmful and irritating to people.

The Flicker meter is implemented according to IEC 61000-4-15. It provides a function and design specification for flicker measuring apparatuses intended to indicate the correct flicker perception level for all practical voltage fluctuation waveforms.

The block diagram of the flickermeter can be seen in the following picture. Based on the simulation of the lamp-eye-brain chain, the flicker signal is statistically evaluated and calculated in the normed parameters. Creating a reference signal in Block 1, the next three Blocks simulate the human perception of it. The Flicker parameters are calculated in Block 5.



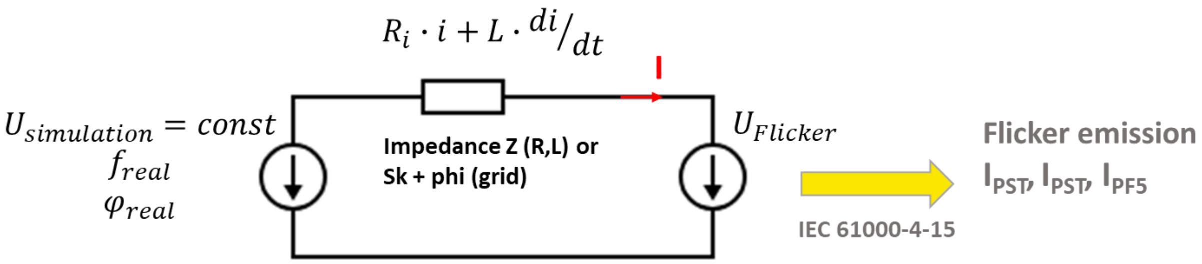
Flickermeter block diagram according to IEC61000-4-15

The Flicker meter provides one P_{st} value every 10minutes for voltage inputs. Every 2 hours, one Pit value is calculated from 12 P_{st} values. The Voltage quality monitor is in accordance with EN50160 and IEC61000-4-30.

Flicker parameters according to IEC 61000-4-15	
Channel Name	Descriptions
PF5_L1	P_{inst} from IEC 61000-4-15
Pst_L1	Short time flicker
Plt_L1	Long time flicker
I_PF5_L1	P_{inst} from IEC 61000-4-15 for current
I_Pst_L1	Short time flicker current
I_Plt_L1	Long time flicker current
I_PF5_L1_30; **I_Pst_L1_30;** **I_Plt_L1_30**	Flicker values from a specific phase angle

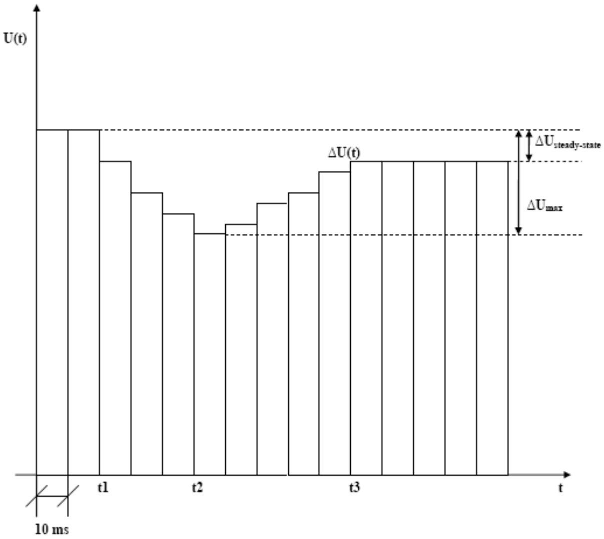
Current Flicker – Flicker emission

IEC 61400-21 defines the calculation of Flicker emission, caused by renewables like wind power plants. Producers as well as consumers are the originators of this Flicker that is effecting the power grid. The internal voltage drip that can be seen in the following picture is calculated on the basis of the grid impedance and the current flow.



Rapid Voltage Changes

In EN 50160, rapid voltage changes are defined as: “A single rapid variation of the rms value of a voltage between two consecutive levels which are sustained for definite but unspecified durations.” A voltage change characteristic is defined in IEC 61000-3-3: “the time function of the RMS voltage change is evaluated as a single value for each successive half period between the zero-crossings of the source voltage and the time intervals in which the voltage is in a steady-state condition for at least 1 s.”



U(t)	voltage change characteristic
ΔU_{max}	maximum voltage change
$\Delta U_{steadystate}$	steady-state voltage change

Representative voltage change characteristic with statement of rapid voltage changes

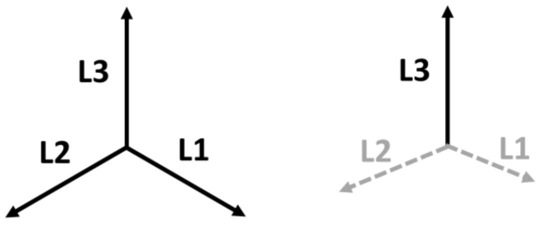
In IEC61000-4-30, rapid voltage changes are defined as: A quick transition in RMS voltage between two steady-state conditions. To measure rapid voltage change, thresholds must be defined for each of the following:

- Minimum rate of change
- Minimum duration of the steady-state conditions
- Minimum difference in voltage between the two steady-state conditions
- Steadiness of the steady- state conditions

The voltage during a rapid voltage change must not exceed the voltage dip and/or the voltage swell threshold, as it would otherwise be considered as a voltage dip or swell. The characteristic parameter of rapid voltage change is the difference between the steady state value reached after the change and the initial steady-state value.

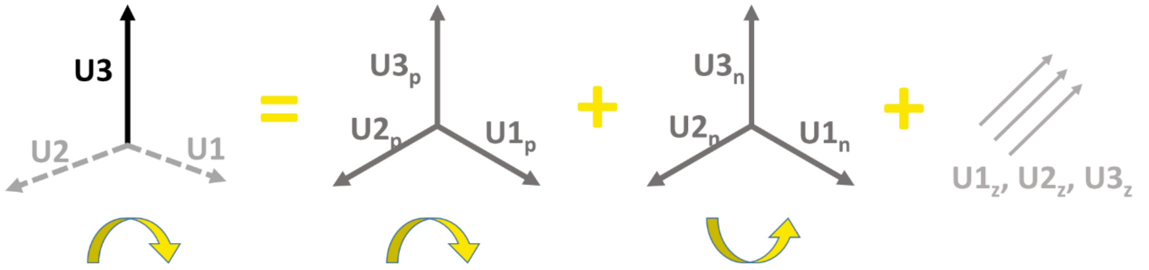
4.6 Symmetrical Components and Unbalance

Disturbances or short circuits among others result in an unbalanced system.



Balanced system **Unbalanced system**

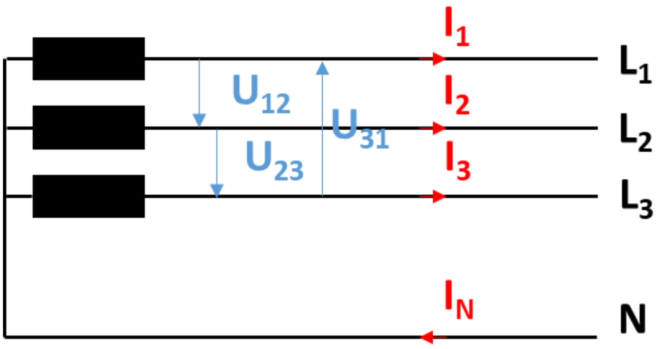
The concept of symmetrical components enables the transformation of any desired unbalanced 3-phase system (unbalanced electric grid system influenced by a number of factors) into three separated symmetrical components.



Positive sequence **Negative sequence** **Zero sequence**

With the help of the following transformation an assessment of the influencing factors can be done according to standards like the IE 64000. (In the end, phase voltages and currents can be calculated out of the symmetrical components in the end.)

In general a 3-phase system can be displayed with the following RMS values:



$$\underline{U}_{L1} = U_{\mathrm{L1,RMS}} \mathrm{e}^{j\varphi_{UL1}} \qquad \underline{I}_{L1} = I_{\mathrm{L1,RMS}} \mathrm{e}^{j\varphi_{IL1}}$$

$$\underline{U}_{L2} = U_{\mathrm{L2,RMS}} \mathrm{e}^{j\varphi_{UL2}} \qquad \underline{I}_{L2} = I_{\mathrm{L2,RMS}} \mathrm{e}^{j\varphi_{IL2}}$$

$$\underline{U}_{L3} = U_{\mathrm{L3,RMS}} \mathrm{e}^{j\varphi_{UL3}} \qquad \underline{I}_{L3} = I_{\mathrm{L3,RMS}} \mathrm{e}^{j\varphi_{IL3}}$$

In case of a typical three phase grid the voltages do have phase shift of 120° to each other. Because of that the unit vector a is defined as operator causing this phase-shift of 120° mathematically, resulting into this notation:

$$a = \mathrm{e}^{120°} = \mathrm{e}^{\frac{j2\pi}{3}}$$

Line Voltages	Complex Notation	Radian Notation
U_L1	$\underline{U}_{L1} = U_{\mathrm{L1,RMS}}\mathrm{e}^{j0°}$	U
U_L2	$\underline{U}_{L2} = U_{\mathrm{L2,RMS}}\mathrm{e}^{j240°\,(or-120°)}$	a² U
U_L3	$\underline{U}_{L3} = U_{\mathrm{L3,RMS}}\mathrm{e}^{j120°}$	a U

Zero sequence system

In a symmetrical system, without any disturbances, the phase voltages sum up to zero.

U_L1 + U_L2 + U_L3 = 0

This rather symmetrical state cannot be found in real-life grids. The zero sequence results due to disturbances and from current flow in the neutral line U_N, that is driven by the following voltage difference:

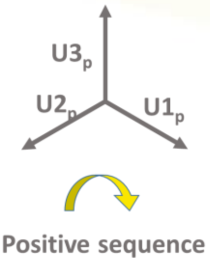
U_L1 + U_L2 + U_L3 = $\underline{\Delta}$u

This voltage difference divided by three is the zero-sequence system:

U_0 = 1/3 * $\underline{\Delta}$u = u10 = u20 = u30

- As it can be seen in the picture as well, that zero sequence has the same amplitude and phase for all of three phases (u10, u20, u30).
- This is the reason usually only one value, U_0, can be found in literature or in the NEO Messtechnik software.

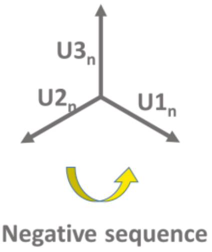
- The calculation of the current zero-sequence is analogue to this procedure.
- Multiplying the zero-sequence system of the current by 3 (3 x I_0) equals the current over the neutral line U_N.



Positive sequence system

This part rotates in the same direction as the given system (e.g. grid or electric motor/generator) and is a symmetric system for itself. This means the amplitude for all three positive phases is the same and only having a 120° phase shift to each other. This is where the unit vector a comes in to simplify the formulas.

$$\begin{aligned}
\underline{v}_{1\mathrm{m}} &= \frac{1}{3}\left(\underline{v}_1+\underline{a}\,\underline{v}_2+\underline{a}^2\underline{v}_3\right)\\
\underline{v}_{2\mathrm{m}} &= \underline{a}^2\,\underline{v}_{1\mathrm{m}}=\frac{1}{3}\left(\underline{v}_1+\underline{a}\,\underline{v}_2+\underline{a}^2\underline{v}_3\right)\cdot\underline{a}^2\\
\underline{v}_{3\mathrm{m}} &= \underline{a}\,\underline{v}_{1\mathrm{m}}=\frac{1}{3}\left(\underline{v}_1+\underline{a}\,\underline{v}_2+\underline{a}^2\underline{v}_3\right)\cdot\underline{a}
\end{aligned}$$



Negative sequence system

This part rotates in the opposite direction as the real system (e.g. grid or electric motor/generator) and is a symmetric system for itself. Like the positive system, the phase values are the same with a 120° phase shift to each other.

$$\begin{aligned}
\underline{v}_{1\mathrm{g}} &= \frac{1}{3}\left(\underline{v}_1+\underline{a}^2\underline{v}_2+\underline{a}\,\underline{v}_3\right)\\
\underline{v}_{2\mathrm{g}} &= \frac{1}{3}\left(\underline{a}\,\underline{v}_1+\underline{v}_2+\underline{a}^2\underline{v}_3\right)=\underline{a}\,\underline{v}_{1\mathrm{g}}\\
\underline{v}_{3\mathrm{g}} &= \frac{1}{3}\left(\underline{a}^2\underline{v}_1+\underline{a}\,\underline{v}_2+\underline{v}_3\right)=\underline{a}^2\underline{v}_{1\mathrm{g}}
\end{aligned}$$

Matrix of symmetrical components

The three symmetrical components for voltage and current are often seen in the following matrix notation, giving a clear overview on the whole system and the relation of the operator a.

Channel Name	Matrix Notation
U0, U1, U2	$\begin{bmatrix}\underline{U}^0\\\underline{U}^1\\\underline{U}^2\end{bmatrix}=\frac{1}{3}\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\cdot\begin{bmatrix}\underline{U}_{L1}\\\underline{U}_{L2}\\\underline{U}_{L3}\end{bmatrix}$
I0, I1, I2	$\begin{bmatrix}\underline{I}^0\\\underline{I}^1\\\underline{I}^2\end{bmatrix}=\frac{1}{3}\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\cdot\begin{bmatrix}\underline{I}_{L1}\\\underline{I}_{L2}\\\underline{I}_{L3}\end{bmatrix}$

Calculation of the phase voltages and currents

By using the formulas we have discussed, it is always possible to calculate the phase voltages and current flow of your 3-phase system with the help of the symmetrical components. For example, the current flow on Phase 2 can be easily calculated by

$$I\_L1 = I\_0 + a\ I\_1 + a^2\ I\_2$$

EN 50160 Parameters in the Neo Messtechnik software

In the EN 50160 zero- and negative sequence components are always put into relation to the positive sequence system for the total and fundamental harmonics. These key indicators can be found in the Neo Messtechnik software under the following channel names:

Channel name	Description	Formula/Calculation
	Negative sequence component – of the voltage/current – of all harmonics Note: This parameter is regulated in the EN50160	$u_2 = \frac{\underline{U}^2}{\underline{U}^1} \cdot 100\% i_2 = \frac{\underline{I}^2}{\underline{I}^1} \cdot 100\%$
	Zero sequence component – of the voltage/current – of all harmonics	$u_0 = \frac{\underline{U}^0}{\underline{U}^1} \cdot 100\% i_0 = \frac{\underline{I}^0}{\underline{I}^1} \cdot 100\%$
	Negative sequence component – of the fundamental voltage/current in per cent – unbalance factor according to EN50160	$u_{2\_1} = \frac{\underline{U}_{H1}^2}{\underline{U}_{H1}^1} \cdot 100\% i_{2\_1} = \frac{\underline{I}_{H1}^2}{\underline{I}_{H1}^1} \cdot 100\%$
	Zero sequence component – of the fundamental voltage/current in per cent	$u_{0\_1} = \frac{\underline{U}_{H1}^0}{\underline{U}_{H1}^1} \cdot 100\% i_{0\_1} = \frac{\underline{I}_{H1}^0}{\underline{I}_{H1}^1} \cdot 100\%$

IEC 61400 Extended Parameters of the positive sequence

According to Annex C of IEC 61400-21, the Fourier coefficients (cos- and sin-parts) of both measured phase voltages and currents are calculated over one fundamental cycle T.

$$u_a, \cos = \frac{2}{T}\int_{t-T}^{t} u_a(t)\cos(2\pi f_1 t)dt \qquad u_a, \sin = \frac{2}{T}\int_{t-T}^{t} u_a(t)\sin(2\pi f_1 t)dt$$

These formulas are the coefficients for phase 1 (L1 or Ua). The coefficients for L2 (ub) and L3 (uc) as well as the coeffiecients for the currents (ia, ib, ic) are calculated exactly the same. Furthermore f1 is the frequency of the fundamental. With the help of the Fourier coefficients the RMS-value of the Phase-1 fundamental voltage can be calculated as following:

$$U_{a1} = \sqrt{\frac{u_{a,\cos}^2 + u_{a,\sin}^2}{2}}$$

Channel name	Description	Formula/Calculation
	Voltage and current vector components of the positive sequence for the fundamental	$U_{1+,\cos} = \frac{1}{6}[2u_{a,\cos} - u_{b,\cos} - u_{c,\cos} - \sqrt{3}(u_{c,\sin} - u_{b,\sin})]$
		$U_{1+,\sin} = \frac{1}{6}[2u_{a,\sin} - u_{b,\sin} - u_{c,\sin} - \sqrt{3}(u_{c,\cos} - u_{b,\cos})]$
		$i_{1+,\cos} = \frac{1}{6}[2i_{a,\cos} - i_{b,\cos} - i_{c,\cos} - \sqrt{3}(i_{c,\sin} - i_{b,\sin})]$
		$i_{1+,\sin} = \frac{1}{6}[2i_{a,\sin} - i_{b,\sin} - i_{c,\sin} - \sqrt{3}(i_{b,\cos} - i_{c,\cos})]$
	Active and reactive power from the fundamental positive sequence	$P_{1+} = \frac{3}{2}(u_{1+,\cos}i_{1+,\cos} - u_{1+,\sin}i_{1+,\sin})$
		$Q_{1+} = \frac{3}{2}(u_{1+,\cos}i_{1+,\sin} - u_{1+,\sin}i_{1+,\cos})$
	RMS value of the line voltage of the fundamental positive sequence	$U_{1+} = \sqrt{\frac{3}{2}(U_{1+,\sin}^2 + U_{1+,\cos}^2)}$
	RMS values of the active and reactive current from the fundamental positive sequence	$I_{P1+} = \frac{P_{1+}}{\sqrt{3}U_{1+}}$
		$I_{Q1+} = \frac{Q_{1+}}{\sqrt{3}U_{1+}}$
	Power factor of the fundamental positive sequence	$\cos\varphi_{1+} = \frac{P_{1+}}{\sqrt{P_{1+}^{(2)} + Q_{1+}^{(2)}}}$
		$S_{1+} = \sqrt{P_{1+}^{(2)} + Q_{1+}^{(2)}}$
		$i_{1+} = \frac{S_{1+}}{\sqrt{3}U_{1+}}$

IEC 61400 Extended Parameters of the negative sequence

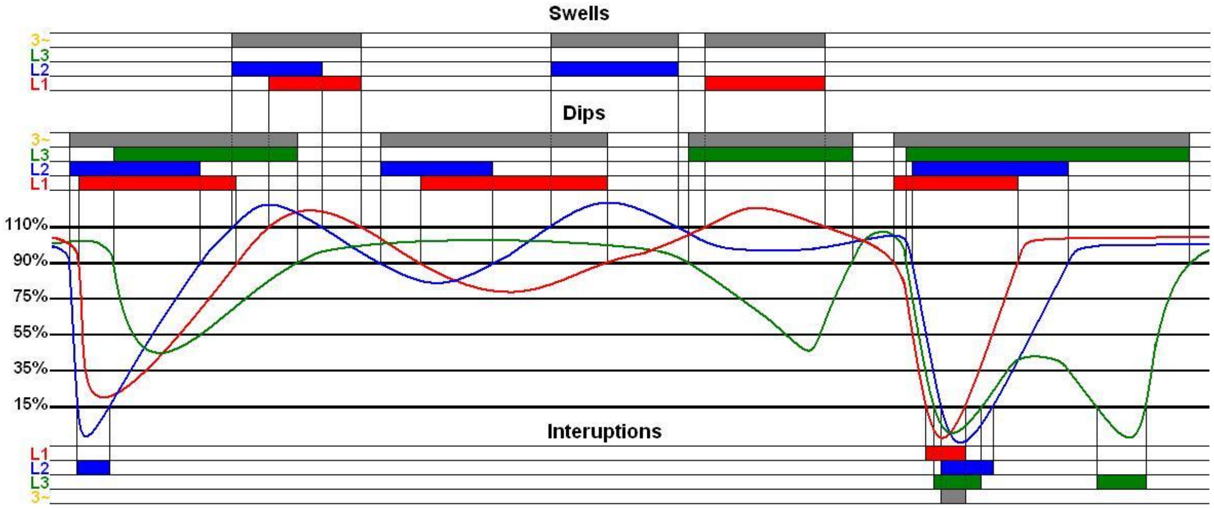
Channel name	Description	Formula/Calculation
	Voltage and current vector components of the negative sequence for the fundamental	$U_{1-,\cos} = \frac{1}{6}[2u_{a,\cos} - u_{b,\cos} - u_{c,\cos} + \sqrt{3}(u_{c,\sin} - u_{b,\sin})]$
		$U_{1-,\sin} = \frac{1}{6}[2u_{a,\sin} - u_{b,\sin} - u_{c,\sin} + \sqrt{3}(u_{b,\cos} - u_{c,\cos})]$
		$i_{1-,\cos} = \frac{1}{6}[2i_{a,\cos} - i_{b,\cos} - i_{c,\cos} + \sqrt{3}(i_{c,\sin} - i_{b,\sin})]$
		$i_{1-,\sin} = \frac{1}{6}[2i_{a,\sin} - i_{b,\sin} - i_{c,\sin} + \sqrt{3}(i_{b,\cos} - i_{c,\cos})]$
	Active and reactive power from the fundamental negative sequence	$P_{1\text{-}} = \frac{3}{2}(u_{1-,\cos}i_{1-,\cos} - u_{1-,\sin}i_{1-,\sin})$
		$Q_{1\text{-}} = \frac{3}{2}(u_{1-,\cos}i_{1-,\sin} - u_{1-,\sin}i_{1-,\cos})$
	RMS value of the line voltage of the fundamental negative sequence	$U_{1\text{-}} = \sqrt{\frac{3}{2}(U_{1-,\sin}^2 + U_{1-,\cos}^2)}$
		$S_{1\text{-}} = \sqrt{P_{1\text{-}}^{(2)} + Q_{1\text{-}}^{(2)}}$
		$i_{1\text{-}} = \frac{S_{1\text{-}}}{\sqrt{3}U_{1\text{-}}}$

IEC 61400 Extended Parameters of the zero sequence

Channel name	Description	Formula/Calculation
	Voltage and current vector components of the zero sequence for the fundamental	$U_{1z,\cos} = \frac{1}{3}[u_{a,\cos} + u_{b,\cos} + u_{c,\cos}]$
		$U_{1z,\sin} = \frac{1}{3}[u_{a,\sin} + u_{b,\sin} + u_{c,\sin}]$
		$i_{1z,\cos} = \frac{1}{3}[i_{a,\cos} + i_{b,\cos} + i_{c,\cos}]$
		$i_{1z,\sin} = \frac{1}{3}[i_{a,\sin} + i_{b,\sin} + i_{c,\sin}]$
	Active and reactive power from the fundamental zero sequence	$P_{1z} = \frac{3}{2}(u_{1z,\cos}i_{1z,\cos} - u_{1z,\sin}i_{1z,\sin})$
		$Q_{1z} = \frac{3}{2}(u_{1z,\cos}i_{1z,\sin} - u_{1z,\sin}i_{1z,\cos})$
	RMS value of the line voltage of the fundamental zero sequence	$U_{1z} = \sqrt{\frac{3}{2}(U_{1z,\sin}^2 + U_{1z,\cos}^2)}$
		$S_{1z} = \sqrt{P_{1z}^{(2)} + Q_{1z}^{(2)}}$
		$i_{1z} = \frac{S_{1z}}{\sqrt{3}U_{1z}}$

4.7 Voltage Events and Flagging

For voltage dips, swells and interruptions, the RMS voltage must be evaluated over 1 cycle (on base of sliding ½ period values estimation), commencing at a fundamental zero crossing, and refreshed every half-cycle. Voltage dips, swells or interruptions are detected if the voltage leaves the pre-defined range (usually ±10% of Un). Single phase or three-phase events are evaluated in a different way according to IEC61000-4-30, see the following diagram.



Voltage dips swells and interruptions

Flagging

Voltage monitor data must be stored as ‘flagged’. During a dip, swell, or interruption, the measurement algorithm for other parameters (for example, frequency measurement) might produce an unreliable value. The flagging concept therefore avoids counting a single event more than once in different parameters (for example, counting a single dip as both a dip and a frequency variation) and indicates that an aggregated value might be unreliable.

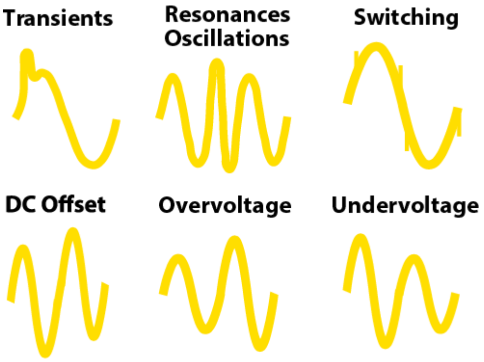
Flagging is only triggered by dips, swells, and interruptions. The detection of dips and swells is dependent on the threshold selected by the user, and this selection will influence which data has been ‘flagged.’

4.8 Transient Recording

One main strength of the NEO Messtechnik products is to record any kind of waveform deviation with best possible accuracy and high sampling rate.

The instrument offers a lot of different trigger conditions to capture Transients. The available options cover 99% of the use-cases.

If you need any additional one… just let us know. We will implement it.



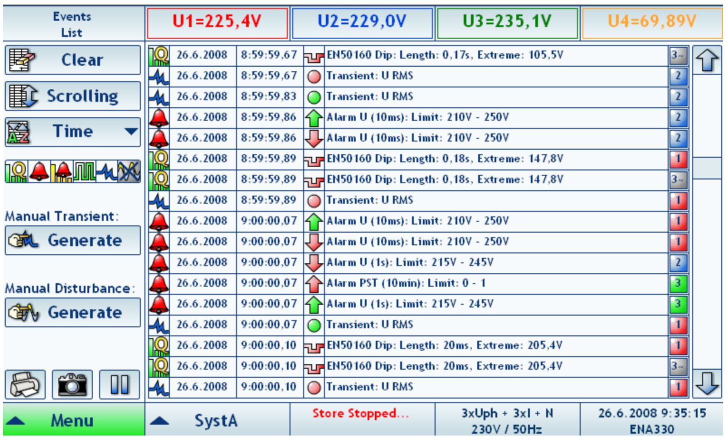
Available Trigger conditions for Transient and Disturbance recording

The following table shows the different trigger types and their calculation base.

Type	Time Base
RMS (U, I)	½ Period RMS values
Harmonic (U, I, THD, etc.)	200ms values (10/12 period-values)
P, Q, S, PF, phi	200ms values (10/12 period-values)
Frequency	1 Periodenwert
Delta Frequency	Delta between period-values
MAX (U, I)	Waveform (Sampled values)
Delta	Delta between period values based on ½ period-values (sliding window)
dX/dt (dU, dI)	Waveform (Sampled values)

This trigger conditions also can be combined by AND respective OR condition.

Transient Recording in addition with Disturbance recording allows recording any kind of waveform deviation or disturbance within the power grid. All records will be classified by type of event and are nicely shown in a table:



U1=225,4V | U2=229,0V | U3=235,1V | U4=69,89V

26.6.2008	8:59:59,67	EN50160 Dip: Length: 0,17s, Extreme: 105,5V	3~
26.6.2008	8:59:59,67	Transient: U RMS	2
26.6.2008	8:59:59,83	Transient: U RMS	2
26.6.2008	8:59:59,86	Alarm U (10ms): Limit: 210V - 250V	2
26.6.2008	8:59:59,86	Alarm U (10ms): Limit: 210V - 250V	2
26.6.2008	8:59:59,89	EN50160 Dip: Length: 0,18s, Extreme: 147,8V	1
26.6.2008	8:59:59,89	EN50160 Dip: Length: 0,18s, Extreme: 147,8V	3~
26.6.2008	8:59:59,89	Transient: U RMS	1
26.6.2008	9:00:00,07	Alarm U (10ms): Limit: 210V - 250V	1
26.6.2008	9:00:00,07	Alarm U (10ms): Limit: 210V - 250V	1
26.6.2008	9:00:00,07	Alarm U (1s): Limit: 215V - 245V	2
26.6.2008	9:00:00,07	Alarm PST (10min): Limit: 0 - 1	3
26.6.2008	9:00:00,07	Alarm U (1s): Limit: 215V - 245V	3
26.6.2008	9:00:00,07	Transient: U RMS	1
26.6.2008	9:00:00,10	EN50160 Dip: Length: 20ms, Extreme: 205,4V	1
26.6.2008	9:00:00,10	EN50160 Dip: Length: 20ms, Extreme: 205,4V	3~
26.6.2008	9:00:00,10	Transient: U RMS	1

Store Stopped... | 3xUph + 3xI + N 230V / 50Hz | 26.6.2008 9:35:15 ENA330

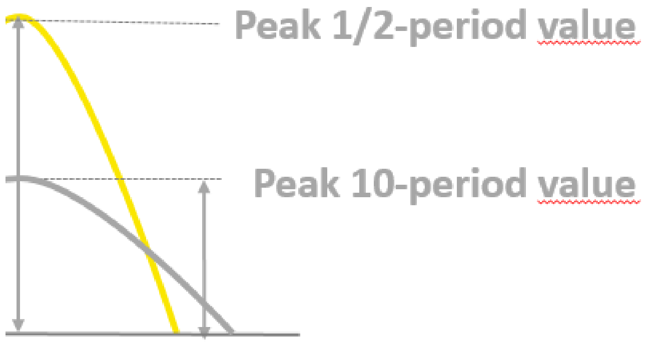
4.9 Disturbances and ½ Period Values

The Disturbance recorder allows the user to store half-period values of U, I, P, Q, S, phi, Symmetrical components, fundamentals, etc.

Recording disturbances is from vital importance as a lot of information about the disturbance can be recorded and analyzed.

Voltage and Current ½ Period Values (RMS and fundamental)

Recording and Analyzing 10-period values (or longer averaging intervals) often can show disturbances. Nevertheless, often this averaging period is too long to make short-time interruptions visible. In addition, the 10-period value will only show a reduced peak value of disturbances, as it is averaged over a couple of periods.



The peak of ½ period values (real value) can be a couple of times higher than the measured 10-period value.

P, Q, S, phi, symmetrical components

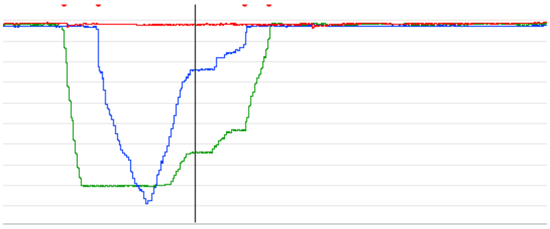
Recording of additional parameters like active, reactive, apparent power, cos phi, and symmetrical components of period values (e.g. positive system reactive power) makes it possible to analyze disturbances in perfect way and easier investigations to find the cause of the disturbance.

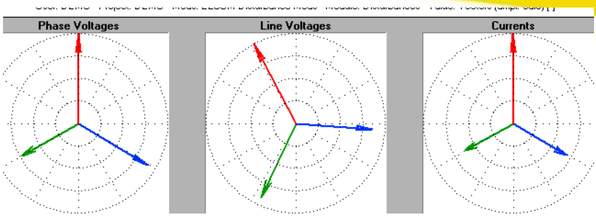
Pre-and Post Trigger time

The length of stored disturbance can range from 1min up to 10min. To get the best picture of recorded disturbance, the user can define the pre-trigger up to 60sec.

The length of stored disturbance recorded data ranges from 1 min up to 10 mins.

An example of disturbance data postprocessing can be seen in the following pictures:



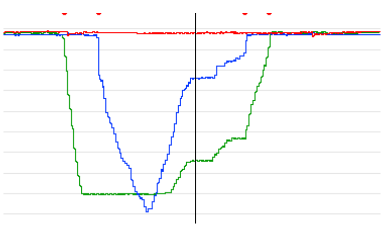


The possibilities of recorded disturbance is even broader if many three-phases systems are monitored by one instrument. In this case, up to five synchronized disturbance monitors are running simultaneously while waiting for each system for an independent set of conditions until the trigger conditions are met.

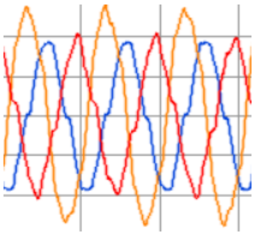
4.10 Transient Recording versus Disturbance recording

On one hand, the lack of information about each sample slightly restricts off-line analysis possibilities of the disturbance recorder data, on the other hand it significantly decreases the amount of data and allows the user to store data over a longer time interval.
For a lot of situations in the power grid disturbance recording shows all needed information to identify the disturbance and the cause. Anyway, there are situations in the grid which only can be analyzed in detail if Raw sampling data (Transient record) are available, like Switching operations, Resonances, etc.

Practically, a combination of both storing options will be used. This combines the benefits of both recording options and allows recording of any kind of disturbance or waveform deviation in the grid, while using optimized data storage. The computer-based systems of NEO Messtechnik allows recording a high number of Transients and Disturbances with long recording time.

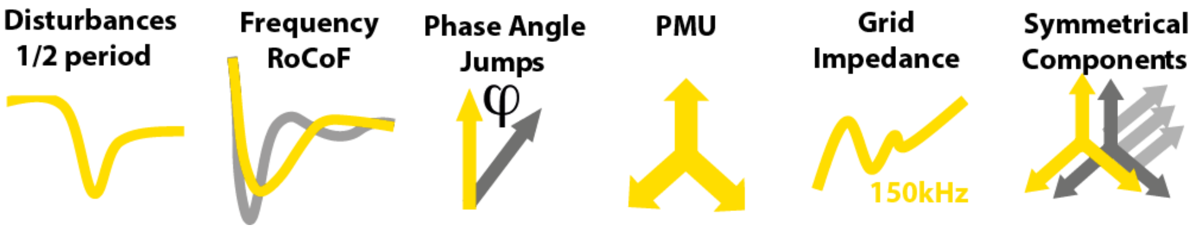


&



½ Period Values ***Raw Data***

4.11 System Dynamics



New applications like Microgrids, Distributed generation (DER), Distributed Control will bring higher dynamics and wider range of interactions.

During connection & reconnection of Microgrids and DER an increased number of Phase Angle jumps, frequency variations (RoCoF), voltage dips/swells and switching transients will appear. Increasing number of inverters & power electronics will increase significance of Grid Impedance measurements, Resonances and oscillations measurements and analysis.

One main focus of NEO Messtechnik products is to investigate System dynamics and help to design a stable grid – as much as possible. The instrument measures all kind of sytem disturbances and dynamics with best quality records.

4.12 Phase Measure Unit

PMU – The Phasor Measurement Unit is a device for accurate synchrophasor measurements. The measurement results are used for the online detection of the electrical grid status. This principle is based on comparing the phase angles of the fundamental harmonic measured at different points of the distribution or transmission network using several devices at synchronized points in time.

Modern PMUs allow to measure phase currents along transmission lines, phase voltages on generator buses and substation buses, current frequency, as well as active and reactive power flows. Unlike traditionally used telecontrol systems, PMU provides the ability to measure modules and angles of voltages and currents. This makes it is possible to eliminate the lack of information about transients and to identify the energy system.

Solving the problem of the energy system identification online on the base of synchronized phasor measurements makes it possible in real time to form adequate linear and nonlinear mathematical models suitable for analysis of stability and dynamical (according to the full nonlinear model) stability respectively, determination of their stocks, as well as the synthesis of vector control of synchronous machines, system stabilizers, networked energy storage devices and static reactive power compensator, including the invariant and emergency management.

High-Accurate GPS Receiver

The meter has to be equipped by the internal/external GPS for receiving synchronous timestamps.

Additional Sensor and Range calibration

The additional sensor and measurement range calibration (see chapter sensor calibration) allows for highly accurate measurement results.

IEEE C37.118

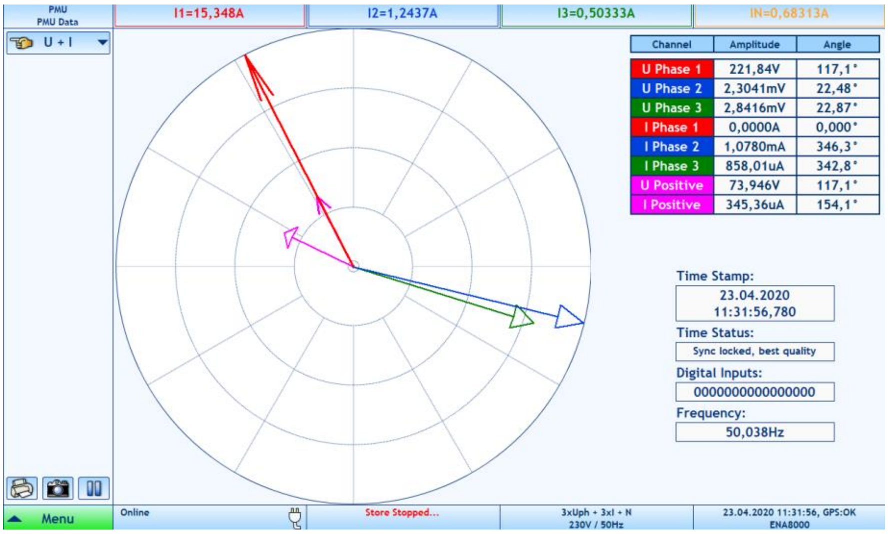
The PMU firmware measures voltage and current phasors, frequency, and calculates the positive symmetrical components of voltages and currents. The measured data is sent to the superior system according to the IEEE C37.118 communication protocol. By default, the device fully complies with the requirements of IEEE C37.118, which defines the PMU accuracy in stabilized state and a communication protocol for real-time phasor transmission.

Highest Precision Synchrophasor Measurement

The PQA8000 instrument offers a built-in GPS receiver together with highly-accurate voltage inputs and

– Total Vector Error 0.01% (typ.)

– Angle Accuracy 0.003° (typ.)



I1=15,348A | I2=1,2437A | I3=0,50333A | IN=0,68313A

Channel	Amplitude	Angle
U Phase 1	221,84V	117,1°
U Phase 2	2,3041mV	22,48°
U Phase 3	2,8416mV	22,87°
I Phase 1	0,0000A	0,000°
I Phase 2	1,0780mA	346,3°
I Phase 3	858,01uA	342,8°
U Positive	73,946V	117,1°
I Positive	345,36uA	154,1°

Time Stamp: 23.04.2020 11:31:56,780

Time Status: Sync locked, best quality

Digital Inputs: 0000000000000000

Frequency: 50,038Hz

Wide Area Monitoring System

Phasor angle differences between various parts of the transmission grid are an indicator of grid health and can provide early warning in the case of developing power system disturbances that can lead to grid separation known as islanding, or even blackout. The accurate measurement of the phasor angles across the grid is made possible by the use of GPS-synchronized phasor-sampling clocks. Nationwide networks of time-synchronized phasor measurement units (PMUs) are called Wide Area Monitoring Systems (WAMS).

The main features of the WAMS systems are the visualization and monitoring of phasors , islanding detection, resynchronization and black start detection, oscillations detection, stability and voltage monitoring. The results can also be passed to SCADA or other systems.

The WAMS, as a complex for power system performance data recording, transmission, processing and analysis software and trained personnel monitoring, is widely used in power systems both to verify power system digital models and to solve issues pertaining to information support for power system operation control. Its appearance allowed elimination of shortages of information regarding electromechanical transients. This information is essential for an adequate analysis of the power system dynamic performance.

4.13 RoCoF

Rate of change of frequency RoCoF is the time derivative of the power system frequency (df/dt). Large df/dt values may endanger secure system operation. RoCoF measurements are becoming more important to system operators as the number of distributed energy resources (DER) increases and at the same time big synchronous generators are disconnected from the power grid. Large df/dt values may endanger secure system operation because of mechanical limitations of individual synchronous machines (inherent capability), protection devices triggered by a particular RoCoF threshold value or timing issues related to load shedding schemes.

- ROCOF is used in loss of mains relays which protect distributed generation against disconnection from the synchronous network.
- ROCOF can be used in fast frequency response and “synthetic inertia” control schemes which attempt to provide active power response to frequency changes.
- ROCOF can be a metric for under-frequency load shedding, where some customers allow their loads to be disconnected to protect the energy balance.
- ROCOF is becoming more important to system operators as the number of distributed energy resources (DER) increases.

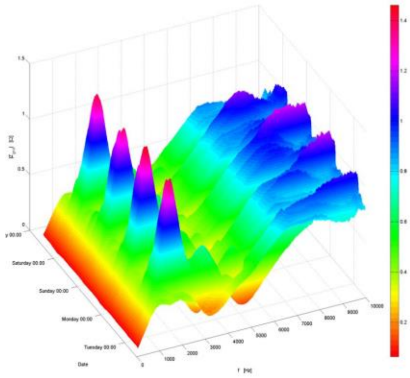
Typically, synchronous power generating modules can at least withstand frequency changes of 2.5Hz/s (100ms) and wind turbines up to 4Hz/s. RoCoF measured at any point in time as an average of the previous 500 ms, is the most reasonable proposal for the minimum RoCoF withstand capability. The ENTSO-E recommends 2Hz/s as minimal rate of change value which has to be withstood.

NEO Messtechnik offers highest precision RoCoF measurement instruments. The extremely low noise floor of the amplifiers together with a smart measurement algorithmn, which reflects influences like Harmonics, Interharmonics, Flicker, etc., allows highest accurate measurements with very low latency.

4.14 Grid Impedance Measurement up to 150kHz

With an increasing amount of power electronic converters connected to the power grid and the increasing modulation frequency of those converters also the disturbances between the power quality frequency range and the EMI range namely 2 kHz to 150 kHz are increasing.

On the one side knowledge of the frequency depending grid impedance is necessary for adequate grid integration, including setting of standards, of renewable energy sources. It is also essential for the design of power converters for renewable energy sources. The grid codes require special features from renewable energy generators as voltage stabilization by reactive power feed in, limited harmonics and fault ride through capability. In all cases the grid impedance is of high importance.



On the other side, due to higher efficiency and better controllability, loads like electric machines but also consumer electronics applications are more often connected to the grid via power electronics

The grid impedance at the point of connection (PoC) is basically only calculated for the fundamental grid frequency based on short–circuit power of the relevant grid. Nevertheless, for future grid operation and grid integration of renewables this calculated value is insufficient. The actual grid impedance is varying with time and is *variable over the frequency*. High differences in commonly modeled and the actual measured grid impedance can be found (Jessen et al., Uni Kiel).

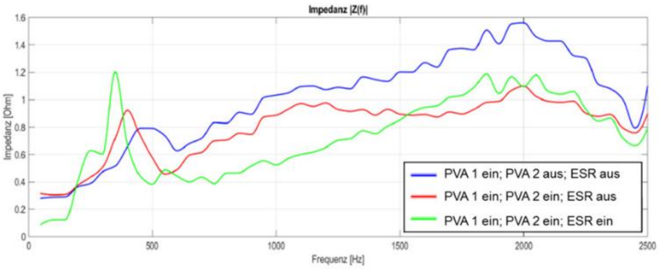
In a low frequency range it can be calculated based on short circuit network calculation. Therefore, loads and generators in the distribution system are usually neglected. Unfortunately, this method is not valid to calculate the grid impedance at higher frequencies. This is because loads and generators close to the PoC influence the grid impedance.

Additionally, loads and generators affect resonances in the grid impedance that challenge system stability. Due to resonances in the frequency and time depending grid impedance, a resistive–inductive grid model is insufficient for meaningful stability analysis

Grid Impedance Measurement up to 150kHz

NEO Messtechnik offers together with a partner company a state-of-the-art grid impedance analysis measurement system. It is a compact system which can be easily carried and installed, which allows measurement and calculation of the following parameters:

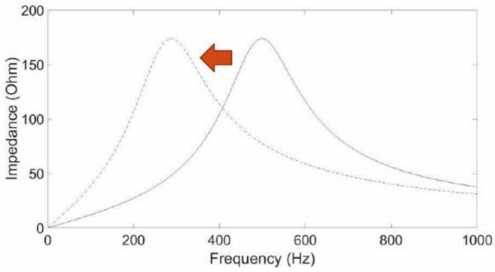
- Grid Impedance Measurement (Z, phi, Re, Im, R, X / Zero-, Postivie- Negative Sequence)
- Fundamental Frequency Impedance (50Hz / 60Hz /…)
- Grid Impedance up to 10 kHz (Higher Frequencies)
- Grid Impedance up to 150 kHz (Supraharmonics)
- Inverter Interaction Analysis



4.15 Resonances / Oscillations

Electrical resonance occurs in an electric circuit at a particular resonant frequency when the impedances or admittances of circuit elements cancel each other.

The electric power system is experiencing a number of changes as part of the transition to a more sustainable energy system. This includes a large-scale integration of ***renewable energy sources***, changes in ***load composition*** (e.g. due to a switch to energy-saving appliances) and ***changes in the grid itself***, such as replacement of overhead lines by underground cables. As a consequence, a reduction in resonance frequencies at all voltage levels, from low voltage to high voltage take effect.



As more capacitance is introduced to the grid, along with a general weakening of the power system due to the replacement of conventional generation sources, resonance frequencies are expected to decrease to lower frequencies (down to 150Hz). This shift in resonance frequencies could have a large impact on the spread of harmonics (amplification of lower harmonics), temporary overvoltages and destabilization of the grid by active contribution of inverters to resonances.

Type of Resonances

- Internally in the Inverter
- Series Resonances
- Parallel Resonances between Inverters

Resonances are analyzed out of Waveform data together with FFT data. The NEO Messtechnik instruments allows to record resonances as Transients using the different trigger possibilities. The FFT and Harmonics from 0 to 150kHz can be recorded in definable time intervals starting from 200ms.

4.16 PLC Interference

Using Power Electronic Interface for connection loads and generation offers a couple of benefits like increased efficiency.

But as power electronic equipment generates perturbations in form of harmonics rejected to the grid, we are facing new power quality issues as well as EMC interferences between converters and control signals transmitted over the supply lines (PLC). Due to the latest progress in technology, the harmonics generated by converters have moved from a very low frequency range to tenths of kHz. Until now EMC standards have been successful in limiting interferences in the frequency domain below 2 kHz. Limits for the frequency range from 2 – 150 kHz is currently discussed in several working groups.

The classical approach has been to set limits for harmonics emission of a single piece of equipment and to define immunity for the same piece of equipment to a higher interference level, corresponding to the emission of numerous devices.

Till there are no obligatory limitations of emission to 150kHz, there are several conflicts and EMC problems within this range.

Possible problems of PLC communication are:

- The communication signal drowns in the disturbance and the communication does not succeed (e.g. enduser equipment creates voltage or current distortion ad communication frequency)

- Only a small signal of the communication signal arrives at the received and the communication does not succeed (e.g. enduser equipment creates low-impedance path at communication frequency)
- Reduction in life-length and incorrect operation of equipment (e.g. the communication signal results in large currents through the end-user equipment)
- Non-linear end-user equipment exposed to the communication signal results in currents at other frequencies
- Distortion of the voltage waveform due to communication signal

NEO Messtechnik allows analyzing disturbances using the FFT Analysis together with the Transient Recording function. For detailed analysis the grid impedance measurements up to 150kHz completes the analysis capabilities.

4.17 Subharmonics and DC components

The number of AC to DC and DC to AC conversions in the power landscape is steadily increasing. More and more loads and energy generation units are connected via power electronic interfaces (inverters) to the grid. The number of batteries is increasing and DC power is also used for long-distance power transfer (HVDC). The measurement of AC and DC parts of the voltage and current signals is getting mandatory.

4.18 Power Quality Mitigation and Spreading

Mitigation of some Power Quality parameters very often increases the penetration of other Power Quality parameters. Typical example is using higher switching frequencies of inverters while reducing lower number harmonics often increases emission at higher frequencies.
The spreading analysis of Power Quality parameters is done for electrical equipment which is used in high amount or with high power. Examples are multiple Electric Vehicle (EV) Charging stations or heatpumps.

This types of analysis require synchronous measurements of multipe input channels and instruments. The NEO Messtechnik instruments can be synchronised directly or via GPS with highest time precision.

5 Further Manuals and Links

There are a couple of additional manuals and information available for our products.
All information can be found on our webpage in the download section.

www.neo-messtechnik.com

- **Product Manual**
  Describes hardware and software features and usage of the products.
- **Accessories Manual**
  Shows technical data of all sensors. For all current sensors detailed technical information are found as well as accuracy specifications for different applications and use-cases.
- **Classical Report Tool Manual**
  Detailed information for the classical report tool, detailed description to all analysis and data visualization functionalities.
- **NEO Messtechnik Brochure**
  Showing all products and accessories available.
- **Quick Start Manual**
  This quick start manual is available online and as PDF.

6 Services and Training

6.1 Regular calibration

The Instrument must be calibrated at regular intervals as determined by the accuracy requirements of the application. For most applications a one-year cycle is appropriate. Accuracy specifications are only guaranteed if adjustments are made at regular calibration intervals. Accuracy specifications are not guaranteed unless a one-year calibration cycle is followed. Calibration cycles beyond 2 years are not recommended for any application.
Regardless of which calibration cycle you choose, it is always a good to perform a complete readjustment at each calibration cycle. This keeps the instrument within specification for the next calibration cycle and provides the best stability in the long run. Before your instrument is delivered, it is calibrated. Detailed calibration reports can be requested.

6.2 Services

Service & Repair

The team of NEO Messtechnik performs any kinds of service and repairs to your system to assure a safe and proper operation in the future. Contact us for more information. Maintenance work should be done by NEO Messtechnik only.

Training

We offer various training options (In-House, On-Site, Remote). Contact your local distributor or NEO Messtechnik directly.

Measurement Service

We are happy to execute measurement services for our clients. From supporting measurement setups, data analysis to complete measurements with measurement reports we offer the full scope of services.

6.3 Revision History

12.03.2020	V1.0	Initial Version
20.08.2021	V1.1	Supraharmonics
01.02.2021	V1.3	Detailed THD, TDD, PWHD, THDG description
15.04.2021	V1.4	Chart for THD, THDG, THDS
17.08.2023	V1.5	THD description added

6.4 Contact

When you are working with our products we want to provide you with the greatest possible benefits. If you need any support, we are her to assist you.

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