Power Quality Measurements – the Importance of Traceable Calibration

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Summary: Standardization has contributed significantly to comparable analysis methods for power quality parameters. However, in order to have undisputable results, the measurement values themselves should also be comparable. This can only be achieved by traceability to international measurement standards. For this reason, at VSL, the Dutch national metrology institute, a fully traceable reference setup was developed for calibration of power quality analyzers. In this paper, we show the calibration results of the critical components of the reference setup, we demonstrate its applicability by test measurements on the public low-voltage supply system for specific parameters, and show its ability to simulate and generate events that can be detected and analyzed by both the equipment under test and the reference setup.

Key words:
calibration,
power quality,
reference system,
standardization,
traceability,
harmonics,
flicker

1. INTRODUCTION

The voltage in the electricity transport and distribution systems is getting more and more disturbed by strongly varying loads and local energy generation such as photovoltaic cells and wind mills. Therefore it becomes increasingly important to monitor the state of the electricity system and detect events such as voltage dips and swells, transients or bursts of harmonics. Too large voltage distortions should be avoided since this negatively affects the correct operation of instrumentation connected to the electricity grid, and even may lead to failures and blackouts. Therefore, the first goal of grid voltage measurements is to monitor whether or not the grid power quality is within the limits set by the relevant standards. A longer term goal is to explain heavy disturbances and even blackouts by post-processing and analyzing data obtained by precise monitoring of the system state and its power quality as a function of time, marked with proper time stamps, during the disturbance. Ultimately, such an analysis should be performed real time in order to prevent these heavy disturbances and blackouts. For system operators this is extremely important in order to avoid claims from customers related to improper or failing power delivery. Furthermore, by remotely monitoring the power quality in for example substations, in case of faults, service engineers can be instructed or advised real-time to solve the problem and for example replace improperly functioning equipment.

Typical power quality parameters for electricity grid applications are frequency and magnitude of supply voltage, harmonics, dips, swells, and transients. Power quality is measured by utilities for monitoring purposes to observe and analyze trends and to maintain stable operation of the transport and distribution grid. However, power quality analyzers produced by different manufacturers came up with different results when measuring the same phenomenon. This has led to the introduction of the standard IEC 61000-4-30 [1]. This standard further restricts the possibilities the manufacturer still has when using the earlier standards IEC 61000-4-7 [2] on the measurement of harmonics and IEC 61000-4-15 [3] on the measurement of flicker severity, and extends its applicability to other power quality parameters.

Whereas the 61000-4-30 describes the measurement techniques themselves, the new upcoming standard IEC 62586 [4], [5] distinguishes between power quality monitoring devices for specific applications, such as indoor or outdoor, portable or fixed, and general or harsh EMC environment. Here, a general environment means for example power stations, medium and low voltage substations or industrial applications, whereas harsh environments for example are found in high voltage substations, arc furnaces or welding plants. Limits and conditions for power quality analyzers are put on environment, design and construction, type tests, routine tests, verification and recalibration.

At present, most high-end power quality analyzers use the IEC 61000-4-30 when analyzing the data, which has contributed significantly to comparable test methods and, therefore, to comparable results. However, apart from being carried out according to specified methods, the measurement values themselves should also be comparable in order to have undisputable measurement results. This can only be achieved by traceability to the International System of Units (SI) and to international measurement standards by means of calibrations. Traceability in this case means that the result of a calibration can be related to international measurement standards, through an unbroken chain of measurements, all having stated uncertainties. The importance of traceable calibrations has been recognized by transport and distribution system operators, who raise this issue when measurement results give rise to disputes. The upcoming introduction of the IEC 62586, in which uncertainty tests and calculations are described in detail, makes the availability of traceable calibrations of power quality analyzers even more important.

For power quality measurements, understanding of the importance of traceability of calibration equipment is not very wide-spread, although the British national metrology institute (NPL) is working on it already for years [6] and transferring their knowledge to other national metrology institutes by means of EU funded research projects. In these European research projects, the focus of the power quality measurements is on the on-site calibration of the power quality of the electricity grid, e.g. in the distribution network or in high-voltage substations.

At present, high-precision power quality recorders and analyzers used for on-site measurements have typical uncertainties of around 0.1% in voltage and current for stationary signals, whereas reference power analyzers can have significantly lower uncertainties. At VSL, the Dutch national metrology institute, a reference setup has been developed for traceable calibration of power quality analyzers according to IEC 61000-4-30, where pre-defined or user-defined test signals can be generated. These pre-defined test signals include waveforms and test parameters relevant for limiting standards like the IEC 61000-3-2 [7] that puts limits on harmonic current emissions, the IEC 61000-3-3 [8] on voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, the EN 50160 [9] on voltage characteristics of electricity supplied by public distribution systems and the earlier described upcoming IEC 62586.

In the next sections we will describe the reference setup for calibration of power quality analyzers and its possibilities, the calibration measurements to be performed for the setup to be traceable to the SI, first test measurements on the low-voltage grid to validate the analysis software and the measurement system, and initial validation measurements of the system operating when simulating events.

2. MEASUREMENT SYSTEM

2.1. Calibration Setup

To provide traceable power quality signals, we developed a setup for both generation and measurement of the desired signals. As a first step, a single-phase system has been designed, with the possibility to upgrade to a three-phase system at a later stage. The heart of the setup is a high-precision two-input analog-to-digital converter (ADC) and two-output digital-to-analog converter (DAC) combination with a resolution of 24 bits and a sampling frequency up to 200 kS/s. The DACs are used to generate a voltage waveform and a current waveform according to the customer's specification, whereas the ADCs are used to measure the same signals.

Figure 1 shows a schematic overview of the setup when calibrating a power quality analyzer. The voltage signal as generated by the first DAC is amplified 25 times using a power amplifier and amplified 10 more times using a voltage transformer. The maximum voltage is in the kV regime, but in practice a nominal value of 115 V or 230 V is used. This voltage is delivered to the voltage input of the power quality analyzer under test. In parallel to the device under test, a 100:1 resistive voltage divider scales the voltage down to voltages that can be measured using the first ADC. The current signal as generated by the second DAC (which is in fact a voltage signal at this stage), is also amplified 25 times using a power amplifier. A 3 Ω shunt resistor then converts the voltage into a current signal before it is increased to the desired level of 20 A maximum using a current transformer. This current signal is delivered to the current input of the power quality analyzer under test. The signal is fed through a 20 mΩ shunt resistor that is connected in series, over which the voltage is measured using the second ADC.

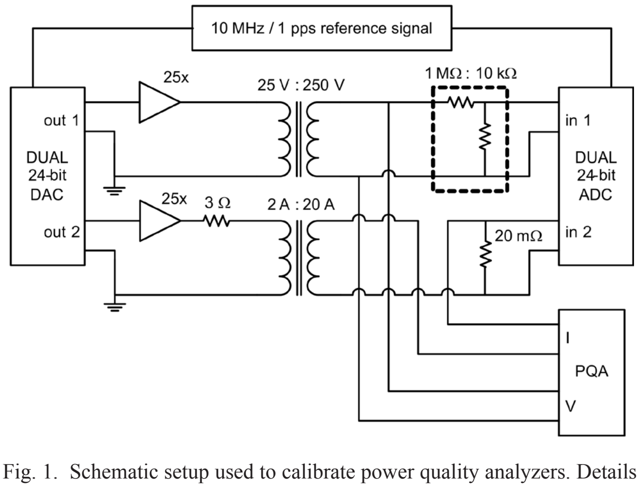

Fig. 1. Schematic setup used to calibrate power quality analyzers. Details can be found in the text.

The DACs, amplifiers and transformers are used only to generate a power quality signal that is to be measured simultaneously by the power quality analyzer under test and the reference system, i.e., the two ADCs, the current shunt and the voltage divider. Traceability of the voltage and current signals is obtained by calibrating the two ADCs, the shunt and the voltage divider at different frequencies between DC and, typically, 5 kHz.

A 1 pulse-per-second signal is used in combination with a 10 MHz reference signal derived from the atomic clock to set the time stamp of the measurements. This time stamp is necessary to reach the accuracy mentioned in the IEC 61000-4-30 for the determination of the measurement time intervals.

At present, a three-phase power quality analyzer has to be calibrated by three independent single-phase calibrations. This means that, for example, the unbalance between the three phases cannot be investigated. In the near future the setup will be upgraded to a three-phase system.

2.2. Software Analysis

The use of a high-accuracy and high-resolution data acquisition system makes us very flexible in the choice of power quality signals to be generated, and in how to analyze them. Software is written in LabView to communicate with the hardware, to generate the signals and to analyze the measurement results in full accordance with the 61000-4-7, 61000-4-15 and 61000-4-30. All sampled data are stored for further analysis at a later stage. The following features have been included so far:

- Mains frequency and timing accuracy
- Voltage calibration at 230 V or 115 V at 50 Hz or 60 Hz as is appropriate, performed using a sinusoidal signal
- Current calibration and linearity testing in all current ranges up to 20 A, performed using a sinusoidal signal
- Power accuracy test performed at for example 150 W with appropriate voltage and frequency using a distorted, non-sinusoidal, test signal
- Steady state harmonic calibration for current or voltage as desired, either user defined or reflecting the limits defined in IEC 61000-3-2 or EN 50160, for harmonics up to the 100th of the fundamental. If desired, verification tests can be performed, assessing the power quality analyzer ability to correctly report a pass or fail for certain combinations of harmonics.
- Determination of the total harmonic distortion
- Calibration of the average harmonic amplitudes when the harmonics are fluctuating [10]. If desired, excursions

above the limits under certain conditions can be tested, such as peaks of fluctuating harmonics exceeding the limit by up to 200 % for at most 10 % of the time as long as the average harmonic amplitude still obeys the limit (according to the 61000-3-2)

- Tests with bursts of harmonics [11]
- Determination of interharmonic voltage or current
- Calibration of the relative amplitude change for voltage fluctuations (dips and swells) under user defined conditions
- Flicker severity measurements with square or sinusoidal modulation, for signals with or without harmonic distortion (according to 61000-4-15 annex C); instantaneous, short-term and long-term flicker severity
- Flicker severity measurements with complex modulation, i.e., irregular modulation [12]
- Temporary power frequency overvoltages, i.e., typical duration of a few power line cycles
- Transient overvoltages, i.e. typical duration of a few milliseconds
- Mains signaling.

The software is continuously expanded, and other new features can be included if desired.

3. MEASUREMENT RESULTS

3.1. Calibration of the power quality reference system

As mentioned before, traceability of the voltage and current measurements is obtained by calibrating the critical components, i.e., the two ADCs, the shunt and the voltage divider at different frequencies. The commercial ADCs used in this setup can be calibrated by a direct comparison to a DC and AC calibrator that is traceable to thermal converter based AC-DC transfer standards and the DC Josephson voltage standard. The shunt is calibrated using AC-DC transfer standards in combination with a DC resistor traceable to the quantum Hall resistance standard.

The resistive voltage divider is calibrated as follows. First, the ADC is used to measure the DAC output voltage directly for sinusoidal signals with 10 V amplitude. The result, shown in Fig. 2, is a flat frequency response within 1.5 mV or 0.015 % of the nominal value of 10 V. This means that the ADC and DAC have the same frequency characteristic. However, since we know the frequency characteristic of the ADC from the calibration with the thermal converters, we know the frequency characteristic of the DAC. We can correct for this frequency behavior if we wish, but at 50 Hz or 60 Hz the difference with the DC value was found to be even less than 0.2 mV or 0.002 %, which is more than sufficient for the power calibration, whereas the largest differences of 0.015 % occur at the highest frequencies, where they are also more than sufficient for measurements of, for example, harmonics and transients.

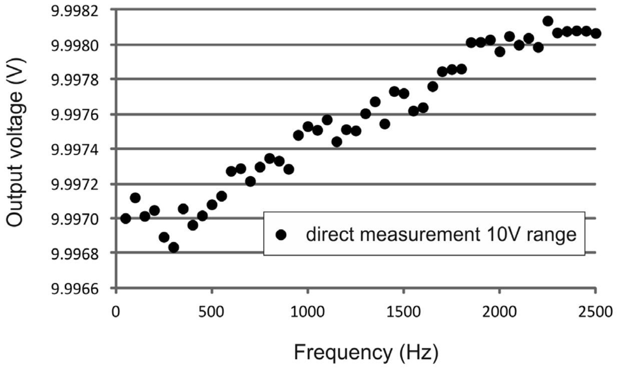

Fig. 2. Direct ADC measurement of a 10 V sinusoidal voltage signal generated by the DAC as a function of frequency.

As a second step, the DAC output is divided by 100 using the resistive divider before measuring with the same ADC. The result is shown in Fig. 3. As we can see, the divider output decreases with frequency, as we expect for the combination of the 10 kΩ output resistance in combination with the 100 pF per meter cable capacitance and the 100 pF input capacitance of the ADC (which should both be considered as integral part of the resistive divider!). We measure the 0.1 V amplitude output voltage in the 10 V range because we want to compare it to the result of the bare DAC as shown in Fig. 2. Since one might question the capabilities of the ADC when used below 1 % of the range maximum voltage, we also measured the same signal in the 1 V range, and observed the same behavior, as can also be seen in Fig. 3. Note that if necessary we can add a capacitor in parallel to either the output resistance or the input resistance of the divider to flatten the frequency response, just like an oscilloscope probe that has to be tuned to be able to observe fast transients and steps.

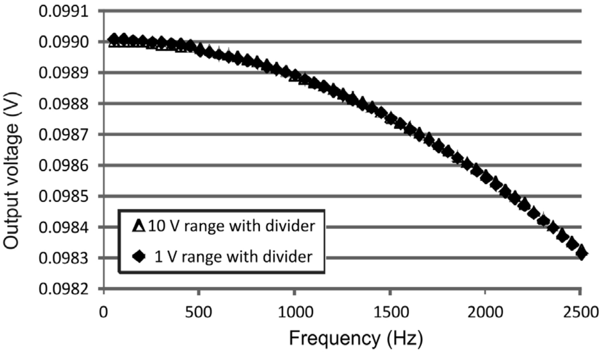

Fig. 3. Frequency dependence of the output of the 1 MΩ : 10 kΩ resistive divider (in combination with the cable capacitance and the input capacitance of the ADC) for a 10 V sinusoidal input voltage as measured in the 10 V or 1 V range, respectively, of the ADC.

3.2. Test measurements on the low-voltage grid

As an important test of the measurement part of the setup including analysis software, measurements have been performed on the low-voltage mains supply in our laboratory. To prevent hazardous situations, an isolation transformer was inserted between the supply voltage and the voltage divider. This isolation transformer has a ratio of 230:100, which means that the rms output voltage is 100 V. This voltage is further divided to 1 V by means of the resistive divider.

For this test, we recorded and stored only the voltage data during the measurement period, for the software deals with voltage data and current data in the same way. The analysis is performed afterwards, in accordance with the 61000-4-30. From Fig. 4 we can see that a typical voltage waveform shows small

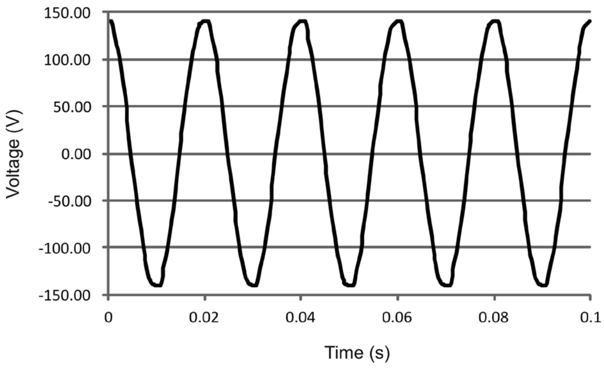

Fig. 4. Typical waveform as measured on the mains supply using an isolation transformer with a ratio of 230:100. From these waveforms several power quality parameters have been analyzed (see Figs. 5-7).

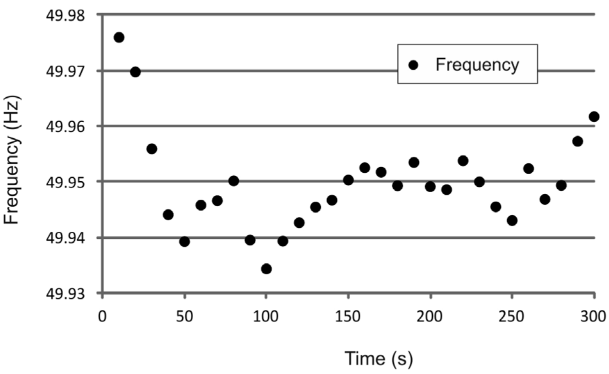

Fig. 5. Mains frequency as analyzed over subsequent periods of 10 seconds.

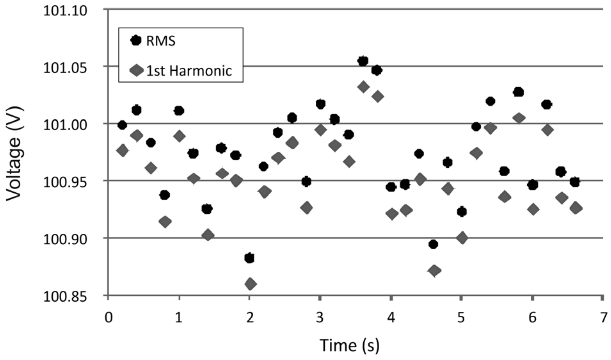

Fig. 6. Rms value of the voltage compared to the first harmonic, both analyzed over subsequent periods of 10 power line cycles.

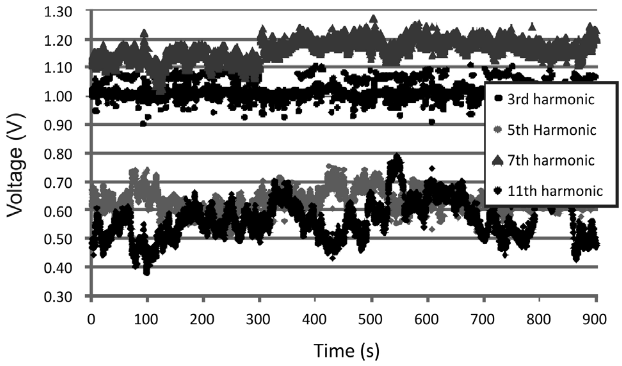

Fig. 7. Harmonic content of the third, fifth, seventh and eleventh harmonics, analyzed over subsequent periods of 10 power line cycles.

deviations from a pure sinusoidal wave. Typical results of the analysis of the frequency, the rms value as compared to the first harmonic, and the third, fifth, seventh and eleventh harmonics, respectively, during a certain test period are shown in Figs. 5–7.

The frequency is analyzed over subsequent periods of 10 seconds as described in the 61000-4-30. Small fluctuations of the order of less than 0.1% are observed for this period, as shown in Fig. 5. The absolute value of the frequency of around 49.95 Hz is well within the ± 1 % from the nominal value of 50 Hz that has been set out in the EN 50160 standard.

The values of the rms voltage and the first harmonic, calculated for every subsequent period of 10 power line cycles as described in the 61000-4-30, are almost identical. As can be seen in Fig. 6, the value of the first harmonic follows the rms value, but it is always a little bit smaller, which is due to the small part of the power that is contained in the higher harmonics. The amplitude of these higher harmonics, also calculated every 10 power line cycles, are indicated in Fig. 7. As we can see, the values of the harmonics are relatively constant over a period of 15 minutes. Furthermore, we observe that the seventh harmonic is larger than the third.

Note that the signals described above are measured on a low-voltage distribution grid for a very short period. Measurements over a longer period, for example in a substation or industrial application, might show much higher deviations from sinusoidal behavior.

3.3. Simulation and generation of events

As a second important test, events that typically occur in the electricity grid have been simulated. We can program and generate the events mentioned in Section II.B, and measure the corresponding generated signals for analysis. In fact, this test is similar to a real calibration of a power quality analyzer under test (see Fig. 1), but without any power quality analyzer connected. This way, apart from validating the setup for being capable of calibrating a power quality analyzer under test for specific parameters at values used in practice, or at values given in the different standards, we can also test it to correctly detect certain power quality events. As set out in the 61000-4-30, for the detection of events, the values of the parameter under test are updated every half power line cycle, even though the value itself reflects the value of the parameter during a whole cycle. In practice that means that the value is updated after each zero-crossing.

As an example of testing the generation, measurement, detection and analysis of events, a series of swells of 100 % overvoltage above the nominal value of 92 V is generated with durations of one power line cycle (0.02 s), two cycles, four cycles, 0.19 s (equivalent to 9.5 power line cycles), 0.89 s, and 2.99 s, followed by a series of dips leaving only 20 % of the voltage with the same durations as for the swells. This series of swells and series of dips is based on a test described in the upcoming IEC 62586-2. The nominal value of the voltage in this functionality test was 92 V because we did not include a transformer to scale the voltage up.

Fig. 8 shows the results of the measurement of this sequence of voltage fluctuations. Note that because the

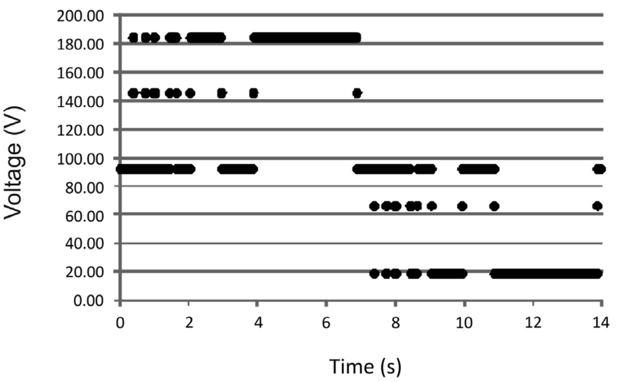

Fig. 8. Measurement of simulated dips and swells as generated and measured using the configuration of Fig. 1 (without power quality analyzer under test connected).

measurement values are updated every half power line cycle and reflect the rms value during a whole cycle, we observe extra values neighboring the dips and swells at values in between the nominal value and the dip or swell value, at which half of the cycle has the nominal amplitude and the other half has the adjusted amplitude. Hence, as a consequence of the procedure of half cycle updates, for these specific fluctuations we observed that indeed the event log shows durations of the detected dips and swells that are two times half a cycle or 0.02 s too long as compared to the generated signals.

4. SUMMARY, CONCLUSIONS AND FUTURE WORK

The introduction of the standard IEC 61000-4-30 has led to comparable test methods and, therefore, more comparable results in the evaluation of power quality analysers. However, apart from being carried out according to specified methods, the measurement values themselves should also be comparable in order to have undisputable measurement results. This can only be achieved by traceability to the International System of Units (SI) and to international measurement standards by means of calibrations. The upcoming standard IEC 62586, in which uncertainty tests and calculations are described in detail, makes the availability of traceable calibrations of power quality analyzers even more important. Therefore, at VSL, the Dutch national metrology institute, we developed a reference setup for calibration of power quality equipment, fully traceable to SI units.

In this paper we showed the results of realizing the SI traceability of our new reference setup by calibrating the components comprising the setup. Furthermore, initial tests on the low-voltage distribution grid show that the analysis of the sampled data is in accordance with the IEC 61000-4-30 for the power quality parameters that were investigated. As an example, correct event detection was demonstrated for a generated series of simulated dips and swells. The analysis shows that the setup is suitable for performing traceable calibrations and for type testing of commercial power quality analyzers.

Apart from further fine-tuning and validation measurements of the reference setup, future work will focus on real on-site measurements of power quality in transmission and distribution grids using a calibrated commercial power quality analyzer. In order to use our reference setup for the calibration, we also need to upgrade the setup to a three-phase system. The results of the on-site grid measurements will be used to improve our setup and make it suitable for more specific electricity grid applications. Furthermore, this way we can disseminate the importance of power quality analyzers to be traceable to international measurement standards for all power quality parameters.

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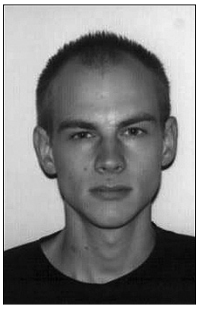

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