

## PLL AND NUMBER OF SAMPLE SYNCHRONISATION TECHNIQUES FOR ELECTRICAL POWER QUALITY MEASUREMENTS

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**Abstract:** Today and in the future the measuring and analysing of electrical energy is a significant topic because its quality and consumption has more and more importance in scientific means and also practical. Since power frequency is fluctuating measurements must be synchronised to the network frequency to avoid spectral leakage error. In this paper two synchronisation methods are shown and compared.

**Keywords:** electrical power measuring, power quality, synchronisation techniques, Phase-Locked Loop

### 1. INTRODUCTION

Today electrical energy is a significant energy source for industrial and commercial applications, and it will continue to be so in the future. Providing a standard quality of electrical energy at the utilisation site is not an easy task, because non-standard energy cannot be removed from the network and consumers can also disturb each other's usage. The power supplier would like to know who contaminates its power network, while the consumers want to know whether they receive the appropriate quality. Examination of the quality and study of the efficiency of the energy consumption of companies is of economic significance.

One of the most significant problems in power quality analyses is the power frequency fluctuation. The correctly executed Fourier transform demands analysis of integral cycles of the time signal. The duration of cycles will be different if network frequency changes. There is a widely used solution to eliminate this problem, when Phase-Locked Loop (PLL) is applied [1-3] but there are some less frequently used methods involving synchronisation as well [4, 5], which are mainly classified in software solutions based on signal spectral analysis techniques. In this paper yet another method is used: a synchronisation method ensuring analysis of integral cycles is proposed. This new method was also built in a power quality measuring instrument. Details of PLL and a new synchronisation method called synchronisation with number of samples are also discussed and compared.

### 2. SPECTRAL LEAKAGE ERROR AND FREQUENCY FLUCTUATION

The network's frequency fluctuation makes it more difficult to analyse the power quality. When using a rectangular window to analyse power quality, it is important

to synchronise the measurement window with the power system frequency to avoid spectral leakage error (Fig. 1) [6].

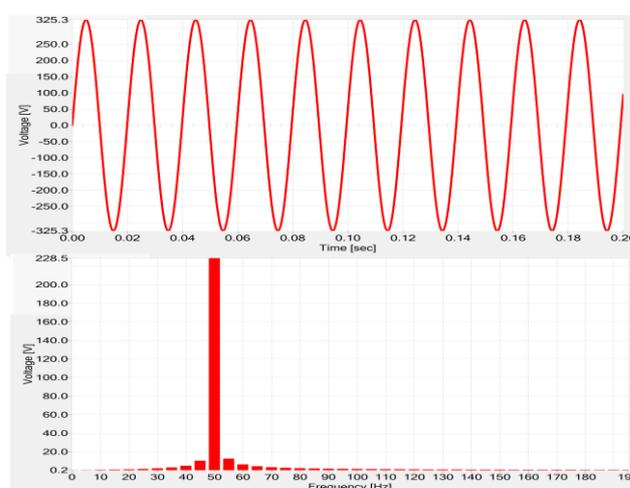


Fig. 1. Spectral leakage error ( $f_{\text{signal}}=50.25\text{Hz}$   $T_{\text{reg}} \approx 10.05$  cycles)

According to the standard EN 61000-4-30:2008 [7], exactly 10 cycles (for a 50 Hz power system) must be used for analysis as a rectangular window. When the power frequency changes, the width of this window changes as well. The measurement window  $T_{\text{reg}}$  can be calculated from the number of samples for 10 cycles  $N_{10\text{cycles}}$  and the sample rate  $f_{\text{sr}}$ :

$$T_{\text{reg}} = \frac{N_{10\text{cycles}}}{f_{\text{sr}}} \quad (1)$$

The measurement window is also equal to the time of 10 power network periods:

$$T_{\text{reg}} = \frac{10}{f_{pn}} \quad (2)$$

Since power network frequency fluctuates (figure 2 and figure 3) the measurement window is not constant.

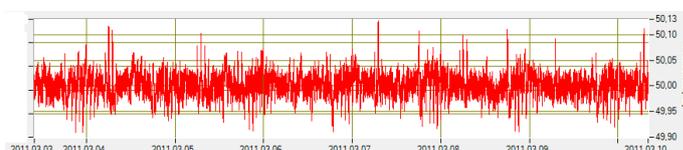


Fig. 2. Fluctuation of power frequency

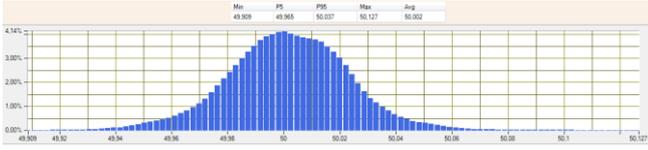


Fig. 3. Statistic of power frequency fluctuation

From the formulae 1 and 2 the power frequency can be expressed as:

$$f_{pn} = \frac{10f_{sr}}{N_{10cycles}} \quad (3)$$

Thus during the measurement sample rate or number of samples must be changed to ensure synchronisation and avoid spectral leakage error.

### 3. PHASE-LOCKED LOOP (PLL)

Synchronisation is solved by a PLL circuit. PLL generates a frequency on its output that is a multiple of the input frequency. Instead of the onboard clock of the acquisition card the output of the PLL is used as a clock. In this case it is sure that 10 cycles will be analysed while the network frequency is changing. A slight disadvantage of PLL is that an additional time measurement is required because time intervals between samples are not known. A more significant disadvantage of PLL is the predefined sample rate. The system can measure only with constant frequency, which is a feature of PLL. If the multiplier of PLL is 100 then the sample rate  $f_{sr}$  is about 5 kHz (it is not exactly 5 kHz because the power frequency is not a constant 50 Hz either).

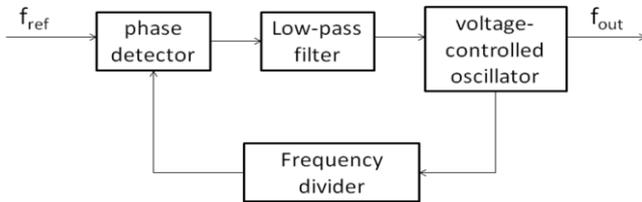


Fig 4. Simple structure of PLL circuit

Source of sample rate is the voltage-controlled oscillator (VCO) which gives the clock rate for the acquisition card (Fig. 4.). The most important part of the PLL is the phase detector which compares phases of the input signals (signal of reference-oscillator and output signal of VCO) and provides the error signal, which is filtered by the low-pass filter. Filtered voltage signal controls VCO to reduce phase difference therefore the output signal of VCO will be the same as the network frequency [2].

So phase-locked loop tracks an input frequency, or if there is a frequency divider in the loopback PLL generates a frequency that is a multiple of the input frequency, therefore it solves the synchronization problem in power analysing systems.

A similar method to PLL which modifies sample rate as well during the measuring is another method. If we know exactly the power frequency and the number of samples is constant, the sample rate can be acquired:

$$f_{sr} = \frac{f_{pn} N_{10cycles}}{10} \quad (4)$$

This synchronisation method is not a good choice because acquisition cards do not support a change in changing sampling rate without stopping the measuring, and data loss is not allowed, either. Consequently this method requires special data acquisition hardware that can modify the sample rate during the measurement without any data loss.

### 4. SYNCHRONISATION WITH NUMBER OF SAMPLES

Synchronisation with number of samples is a software solution which doesn't need any special hardware. Using this method the sample rate is always constant and the synchronisation can be solved with the number of sample changing only. The number of samples is computed continuously while the sample rate is constant. The value of the actual power frequency is required (5).

$$N_{10cycles} = \frac{10f_{sr}}{f_{pn}} \quad (5)$$

Using this solution at low sample rates, calculation errors are high because the number of samples must be an integer, but at higher sample rate errors are much lower. Since the number of samples must be an integer, Eq. (5) is altered to:

$$N_{10cycles} = \left\lceil \frac{10f_{sr}}{f_{pn}} + 0.5 \right\rceil \quad (6)$$

According to the standard [7], the maximum deviation ( $H_{Treg}$ ) from 10 cycles of the 50 Hz power system is  $\pm 0.03\%$ , which is 60  $\mu s$  at 50 Hz and 52  $\mu s$  at 57.5 Hz. The worst situation is at 57.5 Hz because the permissible error is the smallest.

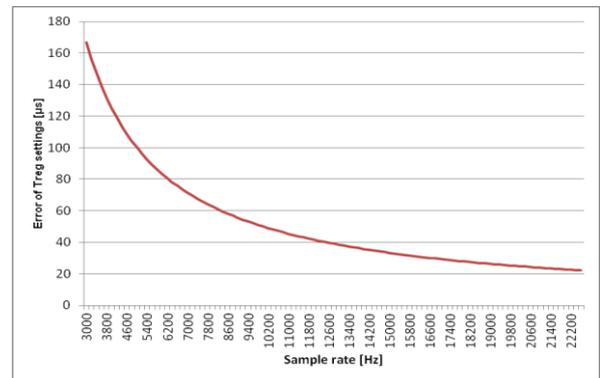


Fig. 4. Maximum deviation [ $\mu s$ ] at 10 cycles using number of samples synchronisation

In Fig. 4 synchronisation with number of samples meets the standard requirements if the sample rate is higher than 10 kHz, because the maximal possible error decreases as the sample rate increases (7).

$$H_{T_{reg}} = \frac{1}{2f_{sr}} \quad (7)$$

Synchronisation with the number of samples is a so-far unutilised method to effectively solve synchronisation to the power frequency. The advantage of synchronisation with number of samples over PPL is that there is no need for additional time measurement because time intervals between samples are well defined by the constant sample rate. The disadvantage of the method is the changing numbers of samples in the different 10-cycle, which has to be solved from the software side. An advantage of the method is avoiding special hardware use. Since the FFT (Fast Fourier Transform) algorithm requires a constant number of samples and the number must be two to the power of  $n$  where  $n$  is an integer, DFT (Discrete Fourier Transform) must be used instead.

### 5. EFFECTS OF VOLTAGE DISTORTION ON SYNCHRONISATION

Voltage distortions can weaken the efficiency and accuracy of both synchronisation methods. Let's see them in details.

Comparators of PLL circuit are triggering the square wave signals to the zero-crossings of the power network's sine wave. In ideal case the power frequency changes only so zero-crossings are synchronised with power frequency. Unfortunately distortions of power network, e.g. THD or voltage sag and dip can cause incorrect zero-crossings at unchanged frequency which disturb the correct operation of PLL. Output frequency will be fluctuating and spectral leakage error will appear.

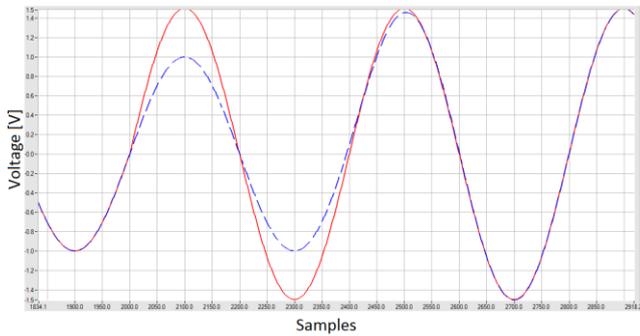


Fig. 5. Shifting of zero-crossing if filter is in used because the voltage increased (dashed line is the filtered signal)

Harmonics can be eliminated with a low-pass filter so PLL gets only the fundamental component. Applying filter brings new problem. Voltage dips and swells shift the place of zero-crossing if filter is applied (Fig. 5.) This phenomenon causes again false synchronisation but only caused by sudden voltage increase or decrease.

When synchronisation with number of samples is applied the same problem arises at voltage dip or swell. A new algorithm was developed to solve this phenomenon which is introduced in the next chapter.

## 6. FREQUENCY ESTIMATION

Accurate power frequency value is needed during measuring when synchronisation with number of samples is used. Power frequency is changing continuously therefore frequency has to be estimated continuously as well. In literature there are several methods to measure frequency of the electrical network [8], e.g. zero-crossing detection, interpolated discrete Fourier transform, chirp-Z transform, Kalman filtering, Gauss-Newton method and advanced signal processing methods are used to frequency estimation.

Nevertheless the most commonly used method is the simple counting of zero crossing. This algorithm is also used by the IEC power quality measurement standard [7]. According to the standard the fundamental frequency output is the ratio of the number of integral cycles counted during the 10 s time interval, divided by the cumulative duration of the integer cycles. This standard also says before each assessment, harmonics and interharmonics shall be attenuated to minimise the effect of multiple zero crossing. In order to fulfil this requirement 3<sup>rd</sup> order low-pass Butterworth digital filter was used. Unfortunately the time varying amplitude of the signal would have adverse impact on the estimation result since filter was applied. Shifting of zero-crossing is the problem again as in case of PLL (Fig. 5). At first let's see the frequency estimation with zero crossing detection then the developed algorithm to avoid false zero-crossing detection.

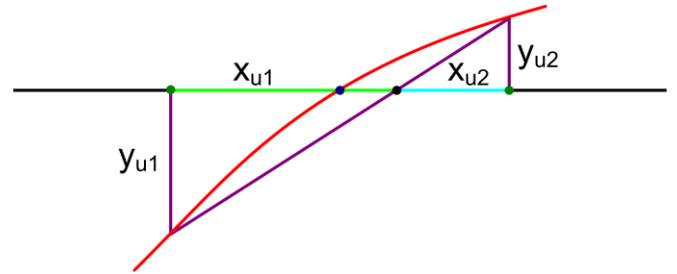


Fig. 6. Linearisation method at zero-crossing

$$X_{u1} + X_{u2} = \frac{1}{f_{sr}} \quad (8)$$

$$X_{u1} = \frac{\frac{1}{f_{sr}} |Y_{u1}|}{|Y_{u1}| + |Y_{u2}|} \quad (9)$$

$$f_c = \frac{\text{Number\_of\_Cycles}}{(\text{LastREdge} - \text{FirstREdge}) \frac{1}{f_{sr}} - X_{u1} + X_{u2}} \quad (10)$$

Linearisation method was used which increases the accuracy of this calculation. The sampled data usually do not exactly a value of zero. In most cases the signal jumps across the zero value and doesn't hit that therefore the location of the zero crossing should be estimated or interpolated. If we could find the exact location where the signal would have the zero value, the estimated frequency would be more accurate. Figure 6 shows how works a more

accurate method for frequency estimation.  $Y_{u1}$  and  $Y_{u2}$  are the samples next to the zero-crossing.  $X_{u1}$  and  $X_{u2}$  can be calculated using Eqs. (8) and (9). Sum of  $X_{u1}$  and  $X_{u2}$  is the reciprocal of the sample rate so these values can be easily calculated by following equation. The actual calculated power network frequency ( $f_c$ ) is obtained with Eq. (10).

Digital filter must follow the varying voltage amplitude. If the order number of digital filter is higher, filter needs more time to catch amplitude change. Figure 5 shows filter needed one and half cycle to catch the input voltage signal. Samples in this interval are unusable for zero-crossing detection. At the beginning of the measuring these samples can be dropped but samples after amplitude change are part of the continuous measurement. Higher voltage amplitude changes affect only the next one or two zero-crossing if the order of digital filter is not higher than 5. Whereas accurate place of the first and last zero-crossings are necessary only it is enough to know the number of zero-crossings during the interval. So the problem can be caused only either by the first or the last zero-crossing.

In power networks significant voltage amplitude changes are not occurring so often. It means during one second there are no more than 2-3 amplitude changes. One second voltage signal contains 100 zero-crossings. In this case there are a lot of zero-crossing which is not shifted by amplitude changes. If false zero-crossings can be determined right frequency estimation will be provided. To find false zero-crossings is not an easy task therefore other way was chosen to solve this problem. Let's choose an interval, e.g. one second and estimate frequency value for this interval. This interval will be shifted with half cycle then new frequency estimation will be executed for the new interval. This shifting and frequency calculation is executed repeatedly  $n$  times. Result of the algorithm is  $n$  frequency values. Some of them will significantly deviate from the real frequency in consequence of amplitude changes. Most of value will be correct because there are not amplitude changes in the power network at every cycle. Frequency values are sorted and correct power frequency ( $f$ ) is obtained using formula 11.

$$f = \frac{\sum_{i=n/3}^{i=2n/3} f_{pn_i}}{n/3} \quad (11)$$

Simulations were performed where amplitude changes were generated every half second. If the chosen interval for frequency estimation was not shorter than 0.4 s than frequency estimation was accurate with this algorithm. Below 0.4 s dropping of highest and lowest frequency values was not enough to eliminate the wrong frequency value which results wrong estimation.

This extended zero-crossing detection algorithm can estimate frequency about at every 0.4 s but it is sufficient when synchronisation with number of samples is applied.

## 7. MEASURING FLUCTUATION OF POWER NETWORK FREQUENCY

Synchronisation with number of samples works properly if the estimation of power frequency is accurate. Accurate

estimation can be provided by the method introduced in latest chapter. Unfortunately power frequency is fluctuating continually because load of the power network is changing. Therefore frequency can change significantly during the measuring interval for frequency estimation which causes inaccurate synchronisation. 10 s time interval which suggested by the standard [7] is too wide to estimate frequency for synchronisation with number of samples. If the power frequency fluctuation is more than 10 mHz in the time interval then the synchronisation will not be accurate and suit standard requirements [9].

Power frequency fluctuation has to be measured to get how wide time interval is necessary to ensure less than 10 mHz frequency fluctuation within the interval. Frequency was calculated at every 0.5 s for 1 week with the estimation method introduces in this paper. During 10 s 20 frequency values were estimated and different ( $\Delta f_{10s}$ ) of maximum ( $f_{max}$ ) and minimum ( $f_{min}$ ) value is calculated for this interval (12) so frequency fluctuation is estimated for 10 s.

$$\Delta f_{10s} = f_{max} - f_{min} \quad (12)$$

Figure 7 shows probability of frequency changes during 10 s. In several cases the frequency fluctuation was more than 10 mHz, therefore estimation of frequency at ever 10 s is not acceptable when synchronisation with number of samples are used.

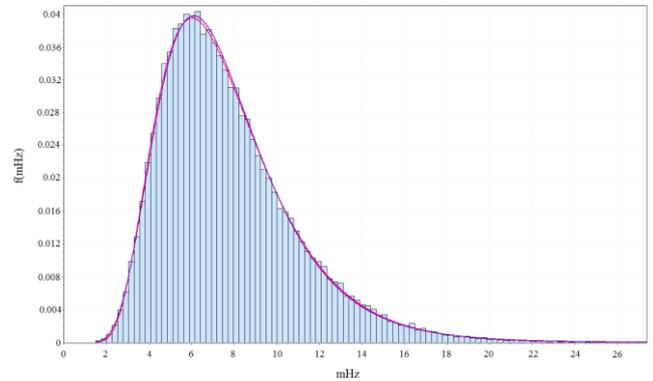


Fig. 7. Probability of frequency changes during 10 s

If the frequency values are obtained from 5 s time interval than the frequency fluctuation is much lower (Fig. 8.). 98% of the frequency deviations during the 5 s time intervals were lower than 10 mHz but it is also not adequate for synchronisation with samples.

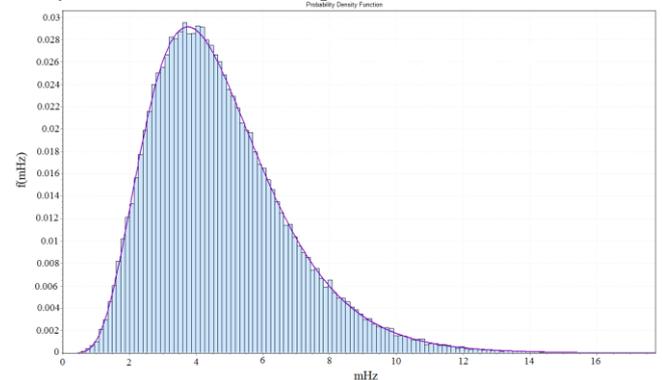


Fig. 8. Probability of frequency changes during 5 s

Using 2 s time interval 99.993% of the deviations were lower than 10 mHz which means there are only few 2 s time intervals where the deviation is higher than 10 mHz which can cause wrong synchronisation (Fig. 9.).

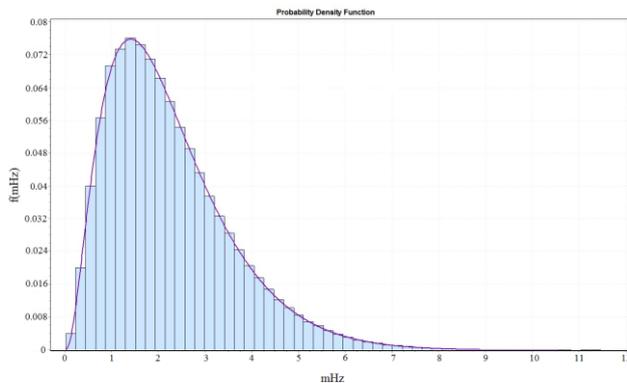


Fig. 9. Probability of frequency changes during 2 s

Consequently power frequency has to be estimation at least every 2 s from the 2 s time interval to ensure right synchronisation when synchronisation with number of samples is used. According to additional measurements it is worth using 1 s time interval for estimation because synchronisation will be more accurate but lower interval is not recommended because frequency estimation is increasingly unreliable when interval decreases using algorithm introduced in chapter 5.

### 8. USING SYNCHRONISATION WITH THE NUMBER OF SAMPLES IN MEASUREMENTS

Our department are continuously developing a complex measurement system which can measure four three-phase systems and solve real time measuring [10].



Fig. 10. Complex measuring instrument

Actual device (Fig. 10.) provides synchronized power network measurement without PLL circuit because in its software realisation synchronisation with number of samples is applied. During measurements waveforms of voltage and current are displayed in real-time. Commonly 20 kHz sample rate is used by the device to measure power network therefore in case of 50 Hz power frequency 4000 samples will be acquired from 10 cycles. Figure 11 shows three-phase voltage signals where the actual power frequency is 49.9715 Hz. In this case cycles are longer therefore more

than 4000 samples are required in order to avoid spectral leakage error. Application instead of 4000 acquires 4002 samples to provide the required synchronisation which suits standard requirements. Hence spectral leakage phenomenon doesn't appear in figure 12. Fundamental harmonic is 4.9975 Hz in this example.

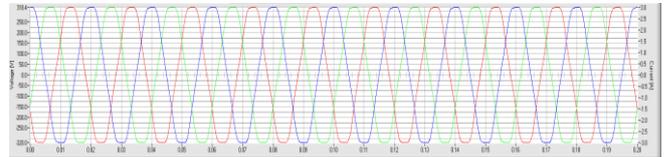


Fig. 11. Ten integrals cycles from three-phase voltage signal

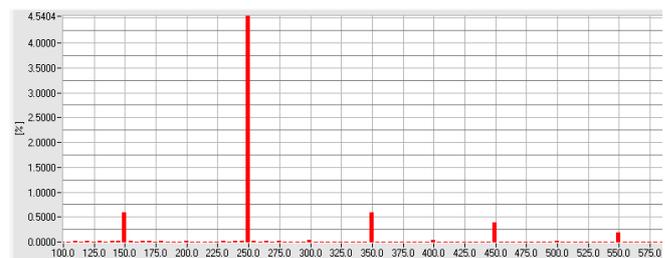


Fig. 12. Amplitude-frequency spectrum of one phase voltage signal in figure 11.

Our network analyser system has already used to analyse several industrial network. During the more weeks long measurement all power parameters (RMS, THD, power factor, active power, reactive power, distortion power, etc.) are being calculated in real-time and all samples and calculated parameters are being saved in repository of hard disk drive.

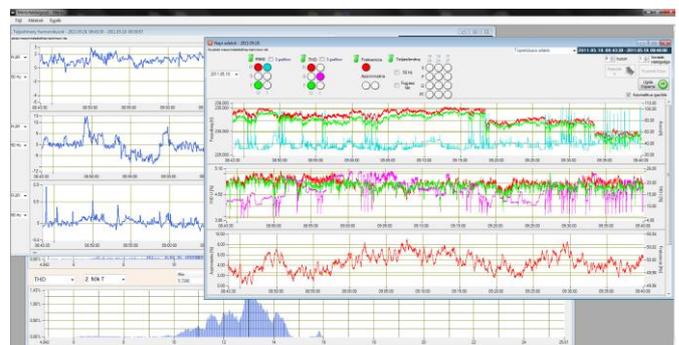


Fig. 13 Evaluation of the measurements

Analyser application was developed [11] where saved values can be displayed and examined (Fig. 13). This software is capable to process those measurements which were measured by the instrument using synchronisation with number of samples.

This application can display the following values and changes of these values in time according to IEC 61000-4-30 and IEC 61000-4-7 where all parameters here except the frequency and flicker are synchronized by samples:

- Frequency of the voltages to be measured
- RMS values for all channels (voltages, currents);
- Flicker values for voltage channels
- Supply voltage unbalance

- Amplitude - frequency spectrum (voltage harmonics and interharmonics) and THD values for all channels;
- Power factor and fundamental power factor ( $\cos\phi$ ) for channel-pairs (voltage - current)
- Apparent, active and reactive power for channel-pairs (voltage - current)
- Fundamental and nonfundamental apparent, active and reactive power for channel-pairs (voltage - current)
- Voltage, current and harmonic distortion power for channel-pairs (voltage - current)

Application also can recognise voltage interruptions, voltage dips and swells and create statistical distribution of any properties for any time interval.

After the tests and laboratory measurements power network analysing system are used in industrial environment. We are continuously performing evaluation of power networks with this product and give advices to companies where they can decrease their electricity bill.

## 9. SUMMARY

Two synchronisation methods were introduced. PLL have been using decades but synchronisation with number of samples is new and works only at high sample rate. At low sample rate only PLL can ensure the synchronisation but at high sample rate synchronisation with number of samples is a better solution because about 10 kHz there is no limitation in sample rate and no need of special hardware. Voltage distortion can disturb synchronisation but a new frequency estimation method was developed which eliminate this problem.

Power frequency has to be estimated between 1 and 2 s time interval to ensure the right synchronisation when synchronisation with number of samples is applied. This synchronisation method was build in an own developed power network analysing instrument which has already analysed several power networks successfully in industrial environments.

## 10. ACKNOWLEDGEMENT

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## 11. REFERENCES

[1] A. Cataliotti, V. Cosentino, S. Nuccio, A new Phase Locked Loop Strategy for Power Quality Instruments Synchronisation, Proc. IMTC 2005 – Instrumentation and Measurement Technology Conference, Ottawa, Canada, 941-946

[2] L. Kazup, G. Z. Marcsák, Application of Phase-Locked-Loop Circuit in Electrical Network Diagnostic Systems, 21<sup>th</sup> International Conference on Computers and Education, Cluj, Romania, pp. 85-90, 2011

[3] F. D. Freijedo, J. Doval-Gandoy, O. Lopez and J. Cabaleiro: Robust Phase Locked Loops Optimized for DSP Implementation in Power Quality Applications, Proc. IECON 2008, 34th Annual Conference of the IEEE Industrial Electronics Society, FL, *Orlando*, 3052-3057

[4] M. Aiello, A. Cataliotti, V. Cosentino, S. Nuccio, Synchronization Techniques for Power Quality Instruments, IEEE T. Instrum. Meas., vol. 56, no. 5, pp. 1511-1519, October 2007

[5] A. Nagliero, R. A. Mastromauro, M. Liserre, A. Dell'Aquila, Monitoring and Synchronization Techniques for Single-Phase PV Systems, Proc. SPEEDAM 2010, International Symposium on Power Electronics, Electrical Drives, Automation and Motion, Pisa, 1404-1409

[6] Math H.J. Bollen, Irene Y.H. Gu, Signal Processing of Power Quality Disturbances, Processing of Stationary Signals, IEEE Press Series on Power Engineering, New York, pp. 163-276, 2006

[7] Standards IEC 61000-4-30:2008: Testing and measurement techniques – Power quality measurement methods

[8] Pedro M. Ramos, A. Cruz Serra: Comparison of frequency estimation algorithm for power quality assessment, Measurement 42, pp. 1312-1317, 2009

[9] A. V. Szarka, Measuring harmonic distortion in electrical power networks – New approach, Measurement 43 pp. 1628-1635, 2010

[10] R. Bátorfi, Electrical Power Quality and Efficiency Diagnostic System, XIX IMEKO, 2009, Lisbon

[11] R. Bencs, R. Bátorfi, Development of a measurement data processing application in Measurement Studio to analyse electrical networks, XII. ENELKO, Cluj-Napoca, Romania, pp. 15-21, 2011