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IMPROVED POWER QUALITY MONITORING kWh-METER

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Abstract - **We have developed a method for measuring power quality quantities such as voltage distortion, voltage unbalance and frequency from undersampled measurements. It is based on an adaptive state observer for the voltage phasors. The method, its implementation to an existing kWh-meter and experience is documented in previous papers. In this paper we show how to include also the measurements of individual harmonic voltage components, very short voltage dips and interruptions and the flicker indices. First we describe the adaptive state observer and its extension to measure individual harmonic components. Then we discuss the measurement of voltage flicker and short voltage dips as well as the requirements these set on the sampling rate and how to minimise the errors caused by sparse sampling. Also experience with these new meters is summarised.**

1. INTRODUCTION

The need to monitor and manage power quality in distribution networks is increasing at the point where the customer is connected. There are more and more devices that pollute the power quality. Also the number of devices sensitive to poor power quality is increasing. Mere strengthening the distribution networks does not solve these problems with reasonable costs. Also the rules of the new competitive electricity market force cost effective power distribution. Thus both the distribution tariffs and the condition of the power distribution networks need to be regulated. Power quality is one of the indicators of the condition of the networks and the level of service they provide. It is also important to avoid the overloading of the components connected to the network such as transformers, motors and capacitors. Poor power quality causes heating of such components and thus increases their thermal loading. Power quality problems can also disturb the proper operation of some electronic devices. Power quality analysers are too expensive for permanent installation and many of them are not suitable to be operated remotely. Thus also power quality monitoring kWh-meters are needed.

To reduce the data processing costs in the kWh-meter we use sampling rates below the Nyquist sampling rate. This is called undersampling.

A method for measuring power quality quantities such as voltage distortion and voltage unbalance from undersampled measurements has been developed, see /7/. Also the implementation to a power quality monitoring kWh-meter is described there. The reference /14/ tells about the meter reading system developed for these meters. Experience with these meters is shared in /5 and 10/. The requirements, problems and possibilities of power quality monitoring billing meters are discussed in /6/. The experience and requirements revealed that in a power quality monitoring kWh-meter it would be better to include also the measurements of the most important individual harmonic voltage components, very short voltage dips and interruptions, and the flicker indices.

In this present paper we show how these improvements can be added. We describe the features and methods of a new version of these power quality-monitoring kWh-meters. That is why we first review the adaptive state observer described in /7/ and extend it to the measurement of individual harmonic voltage components. Next we describe the measurement of short voltage dips and interruptions. Then the measurement of flicker indices is considered. After that the measurement errors related to sparse sampling and requirements for the sampling rate are analysed. Also experience with these new meters is summarised. Finally we discuss the requirements, future needs and possibilities of the power quality monitoring kWh-meters.

2. METHODS

2.1. Estimation of frequency and voltage phasors

It is necessary to use narrow band notch filters that follow the fundamental frequency of the voltage when measuring the power quality quantities with sparse sampling. This is because high frequencies including some harmonics are aliased on lower frequencies in sparse sampling. In order to achieve the necessary frequency resolution we developed a method that is based on a model reference adaptive state observer that estimates the voltage phasors and the fundamental frequency. In this subchapter we discuss other relevant methods that we found in the literature.

In these kWh-meters there are two methods for measuring the fundamental frequency of the power supply network. One is based on counting the zero crossings and the other one uses the adaptive observer. The zero crossing counting has a wider operating range while the adaptive observer is more robust to distorted voltage waveforms and responds faster to changes in the frequency. In /1/ more methods for measuring the network frequency are briefly discussed and referenced.

Discrete Fourier Transform (DFT) is often used to measure the harmonics in the voltage and current. Also the network frequency and voltage phasors can be estimated with DFT /12/. However, the requirement for good frequency resolution due to sparse sampling makes this approach too inefficient and slow in our case.

Recursive adaptive filters are more suitable for our purposes. Such an approach is described in /3/, where extended Kalman filtering is applied for the estimation of voltage phasors and frequency. However, we needed a reliable method that requires even less data processing power. According to /1 and 11/, Extended Complex Kalman Filter is more attractive than the real one from the point of modelling and stability considerations. With Extended Complex Kalman Filter they mean that the $\alpha\beta$−transform of power systems analysis is applied to simplify the model that is used in the extended Kalman filter. This approach is good for embedded on-line estimation of the frequency of the power supply network. The reference /1/ shows how this method can be applied for the estimation of harmonic voltages, too. However, the Extended Complex Kalman Filter does not estimate the separate properties of the three phases of the power network and we would need to add estimation of those quantities.

2.2. Adaptive state observer

Voltage distortion, D, unbalance, direct voltage component U_{dc} and frequency f are measured using time discrete state observers of the voltage phasors, figure 1. In addition to this the reactive power of the fundamental frequency is calculated from the measured current and $\hat{x}_2$, the estimated imaginary component of the estimated voltage phasor. The filtering of the voltage distortion D requires at least two filter stages in order to make the frequency response flat in the middle of the stop band. In the implementation both these stages are state observers. The output error ${}_Ae$ of stage A is the input to stage B, from whose output error ${}_Be$ the effective value is taken in order to get the total distortion D. Only the observer gains ${}_A\underline{k}$ and ${}_B\underline{k}$ are slightly different, because this improves the overall frequency response.

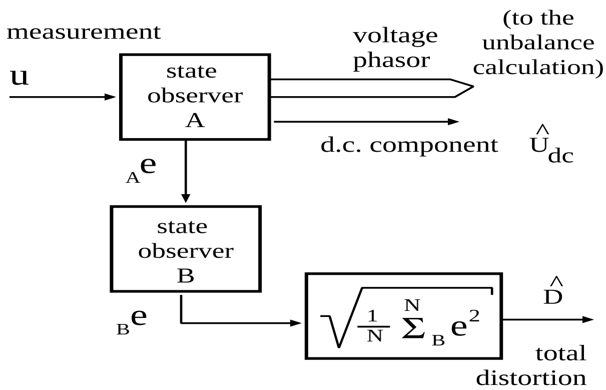

Figure 1. Main structure of the method for power quality monitoring with sparse sampling kWh-meters.

The model of the network voltage u(t) as a function of time t is

$$u(t) = a\cos(\omega t + \phi) + u_{dc} + d(t) \qquad (1)$$

Here we want to estimate a the amplitude, $\omega = 2\pi f$ the angular frequency, ϕ the initial phase shift angle, u_{dc} the direct voltage component and d(t) the zero mean noise or distortion with E[d(t)]=0. We present the equation (1) in state space and discretised with time step T as

$$\begin{aligned} \underline{x}(t+T) &= \Phi(T)\,\underline{x}(t) = \Phi_n(\omega T)\,\underline{x}(t) \\ u(t) &= C\,\underline{x}(t) + d(t) \\ &= [1\;1\;0]\,\underline{x}(t) + d(t) \\ \underline{x} &= [x_0\; x_1\; x_2]^T = [u_{dc}\; u_{\mathrm{Re}}\; u_{\mathrm{Im}}]^T \end{aligned} \qquad (2)$$

x_1 and x_2 are the real and imaginary components, u_{Re} and u_{Im}, of the rotating voltage phasor. $(.)^T$ denotes transpose. Following for example the book of Åström and Wittenmark /16/ and taking into account that ω is not exactly known we get the state observer with feedback gains $\underline{k} = [k_0\; k_1\; k_2]^T$

$$\begin{aligned} \hat{\underline{x}}(t+T) &= \Phi_n(\hat{\omega}T)[\hat{\underline{x}}(t) + \underline{k}\,e(t)] \\ e(t) &= u(t) - \hat{u}(t) = u(t) - C\,\hat{\underline{x}}(t) \end{aligned} \qquad (3)$$

where e(t) is the output error of the observer and the state transfer matrix Φ_n depends only on ^ωT.

$$\Phi_n(\hat{\omega}T) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\hat{\omega}T) & -\sin(\hat{\omega}T) \\ 0 & \sin(\hat{\omega}T) & \cos(\hat{\omega}T) \end{bmatrix} \qquad (4)$$

The relatively low sampling rate, f_s=1/T, of the meter adds some problems. Frequency components higher than $f_s/2$ are included in the total distortion via aliasing except those special frequencies that alias on the fundamental frequency. The stop band is narrow and the sampling rate carefully chosen so that all interesting harmonic components are included in the result. Because of the narrow stop band the state observers are made adaptive, figure 2. They adjust to the fundamental frequency of the network. Thus the fundamental frequency component is excluded from the measured total distortion D, which includes almost all other frequency components under the limit frequency defined by an analogue prefilter before the sampling.

We measure power quality from all the three phases of the power network. Thus each phase needs a separate state observer. However, there is only one adaptation mechanism that is common for all the three network phases, because the frequency is common to all the phases, too.

The adaptation mechanism that estimates the angular frequency ω, is kept as simple as possible:

$$\begin{aligned} \hat{\omega}(t) &= \omega_1 + \hat{\alpha}(t) \\ \hat{\alpha}(t+T) &= \hat{\alpha}(t) - k_{\alpha 1}\hat{\alpha}(t) \\ &\quad - [(k_{\alpha 2} + k_{\alpha 3})e(t) - k_{\alpha 3}e(t-T)]\hat{x}_2(t)/\hat{a}^2(t) \end{aligned} \qquad (5)$$

Where $k_{\alpha 1}$, $k_{\alpha 2}$ >0 and $k_{\alpha 3}$ are small nonnegative adaptation gains that determine the dynamics of the adaptation, ω_1 is the nominal angular frequency. The squared amplitude estimate

$$\hat{a}^2 = \hat{x}_1^2 + \hat{x}_2^2 \qquad (6)$$

is added to the denominator in (5) in order to make the system dynamics independent of the amplitude of the input voltage. It can usually be replaced with a constant.

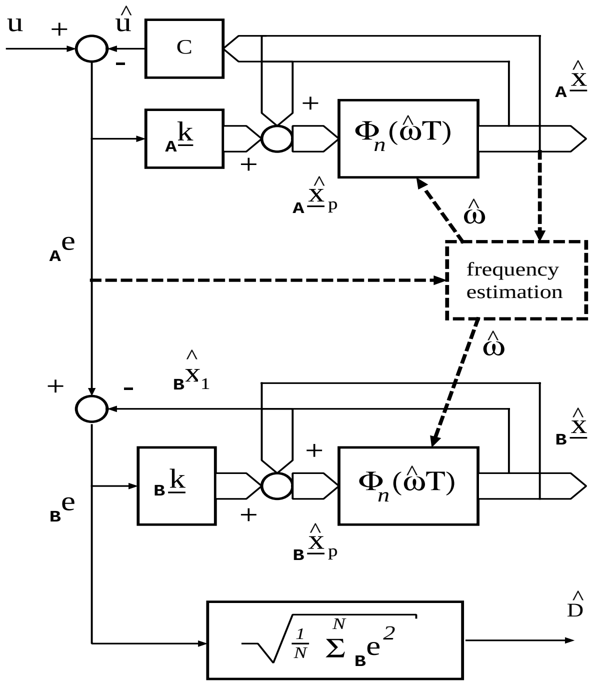

Figure 2. Adaptive state observers for power quality monitoring with sparse sampling.

Using the methods described by Landau /9/ we have derived a globally asymptotically stable adaptive state observer for the time continuous model (1). It does not include any time derivation of e(t) nor even state variable filters for avoiding the time derivation. This time continuous adaptive observer is the same as (3)-(5) with an infinitesimally small time step, k_1>0, k_2<ω, $k_{\alpha 1}$ = 0 and linearised around the nominal network frequency. Thus it can be assumed based on /4/ that for small adaptation gains the system (3)-(5) is asymptotically stable within the needed operating regime. Simulations have confirmed the stability.

In the implementation of the equations (3)-(5) in the described meter version, the limits of the data processing power have caused additional delay in the adaptation mechanism. In simulations this implementation was found to work well in the required region.

Although the sampling is sparse and the state observer is based on the time discretisation, the adaptation mechanism is derived using the time continuous approach. The reasons for this are the following. Only one adaptation parameter is needed and it corresponds directly to the physical quantity (fundamental frequency), that we want to follow. Thus we can keep the data processing load in the meter as small as possible. Unnecessary degrees of freedom in the adaptation would only cause some loss of performance. Thus we can expect faster and more stable convergence and less sensitivity to noise, when we do not have too many adaptation parameters. According to /4/ it is rather easy to map continuous designs into the discrete domain using the Delta operator. In this way stability boundaries for very fast adaptation can be defined, if needed. However, in this case the suitable adaptation speed is rather slow compared to the sampling rate, because we do not want to mix frequency and phase shift together. Using continuous time adaptive system design in discrete-time estimation and control is discussed and recommended in /2/ and /4/.

2.3. Harmonics

Individual voltage harmonics are measured using state observers (7). These are similar to the observer of the fundamental frequency component (3) with the following two exceptions. The notch frequency is an integer multiple of the frequency estimated by the adaptive state observer of the fundamental frequency component described above. Only the state of the fundamental frequency observer includes the estimate for the direct voltage component.

$$\begin{aligned} {}_m\underline{\hat{x}}(t+T) &= \Phi_n(m\hat{\omega}T)\,[{}_m\underline{\hat{x}}(t) + \underline{k}\;{}_m e(t)] \\ &= \Phi_n^m(\hat{\omega}T)\,[{}_m\underline{\hat{x}}(t) + \underline{k}\;{}_m e(t)] \quad (7) \\ {}_m e(t) &= e(t) - {}_m\hat{u}(t) = e(t) - C\,{}_m\underline{\hat{x}}(t) \\ {}_m\underline{\hat{x}} &= [{}_m\hat{x}_1 \;\; {}_m\hat{x}_2]^T = [{}_m u_{\mathrm{Re}} \;\; {}_m u_{\mathrm{Im}}]^T \end{aligned}$$

where m is the order number of the harmonic component.

If only a few harmonic components are calculated, this approach requires less data processing than the usually applied fast Fourier transform FFT especially when good frequency resolution is needed. In some power quality analysers the frequency resolution requirements are compromised in order to reduce the processing power needed for FFT. If tens of individual frequency components need to be measured, it is probably better to use the FFT.

2.4. Voltage unbalance

Each of the three phase voltages U_r, U_s and U_t has an own state observer (3)-(4) for voltage phasors. From them we calculate the voltage unbalance as proportions of zero sequence U_0 and negative sequence U_- components to the positive sequence component U_+ using their definition (8):

$$\begin{aligned} 3\overline{U}_0 &= \overline{U}_r + \overline{U}_s + \overline{U}_t \\ 3\overline{U}_+ &= \overline{U}_r + \angle 120^o\,\overline{U}_s + \angle -120^o\,\overline{U}_t \\ 3\overline{U}_- &= \overline{U}_r + \angle -120^o\,\overline{U}_s + \angle 120^o\,\overline{U}_t \\ U_0/U_+ &= |\overline{U}_0| / |\overline{U}_+| \\ U_-/U_+ &= |\overline{U}_-| / |\overline{U}_+| \end{aligned} \quad (8)$$

2.5 Short voltage dips, swells and interruptions

The first versions of our power quality monitoring kWh-meters could not meter very short dips and interruptions, such as those due to auto-reclosures. Auto-reclosures are common in rural distribution networks where the medium voltage network consists mainly of overhead lines. Thus we need to indicate at least all dips and interruptions that are longer than 100 ms. The sampling rate of our first kWh-meters was too sparse for this and had to be increased. The new version with a higher sampling rate can measure 100 ms long and longer dips accurately enough for our power quality indicator purposes. Even 10 ms long dips are measured although with less accuracy. This limitation can be removed by increasing the sampling rate.

The draft standard IEC 61000-4-30 CD (2001-01-26) says about the measurement of voltage dips and swells that the instrumentation shall measure the r.m.s. voltage cycle by cycle and that the measurement will be updated every half-cycle. It also tells how the depth and height as well as the duration of the dip shall be measured.

In the meter the dip measurements are classified into categories according to the dip depth and duration. In this way less memory is needed for the storage of the dip data.

The present version of the meter meters the dips of phase to neutral or phase to ground voltages. It does not measure the dips in phase to phase voltages. The former are usually more important in the low voltage network and the latter normally in the medium voltage network.

2.6 Voltage flicker indices

Even small variations of voltage at a certain frequency range can cause irritating flicker of lighting. Standards EN 50160 (1999), IEC/EN

61000-3-3 (1994) and IEC/EN 61000-3-5 (1994) define limits that are not allowed to be exceeded for long term and short term flicker indices P_{lt} and P_{st} respectively. Standard IEC 61000-4-15 Ed. 1 (1997) defines functional and design specifications for the measurement of these flicker indices. We have tested by simulation, that this method can be implemented to a kWh-meter, provided that the sampling rate is high enough. The sampling period does not need to be much shorter than 1 ms, if the sampling rate is chosen very carefully. The basic requirement for sampling rate is that it should be possible to measure the r.m.s. voltage of half the period of the fundamental frequency. Another constraint for the choice of the sampling rate is the possible aliasing of harmonics to the flicker measurement band, which must be avoided. Data processing load can be reduced by using multirate algorithms such as described in /15/.

3. ERRORS DUE TO SPARSE SAMPLING

Only the errors related to sampling are discussed here. There are other measurement errors that are not discussed here. The effects of transducers, such as voltage and current transformers, on power quality monitoring are considered in the Annex A5 of the draft standard IEC 61000-4-30 CD (2001-01-26). In low voltage systems the power quality monitoring kWh-meters connect directly to voltage, but transducers are usually needed for current measurements of these meters.

3.1 Sparse sampling (undersampling)

The methods described above have been developed for a power quality monitoring kWh-meter that is based on sparse sampling. With sparse sampling we mean that the sampling rate is low compared to the highest frequency components measured. Then the highest frequency components are included in the measurement via aliasing, which means that high frequency components are transformed to lower frequencies in the sampling process. Components that transform to a frequency f are $n f_s \pm f$, where n is a positive integer and f_s is the sampling frequency.

3.2 Aliasing of harmonic components

In the measured signal certain frequencies that are synchronous with the sampling frequency cause measurement errors by aliasing over the direct voltage or direct current component. This error can be anything between the positive and negative peak values of the problematic signal component depending on its phase angle with sampling. In power distribution networks these errors can be avoided by choosing the sampling rate so that these problematic frequencies are not very close to harmonic components of the fundamental frequency of the power network. If needed, it is possible to remove these errors completely by using two sampling intervals that have an irrational ratio, see /8/.

3.3 Broadband noise and its aliasing

Also broadband noise is aliased by sparse sampling. Thus it affects the individual measurement samples more than usually. Sources of broadband amplitude noise in the sampling are instability of the voltage reference, thermal noise of the A/D-converters, and finite word length of the A/D-converters. Also timing jitter of the sampling may increase the noise seen in the samples.

Broadband noise in the sampling is seen in the measurements as a constant additional distortion that does not significantly depend on the measured signal nor time. This additional distortion reading can be estimated and reduced from the result using the correction function (9).

3.4 Rounding errors

The distortion can be calculated using rather short word length, if the variables are carefully scaled. Then rounding errors cause a significant increase in the raw distortion readings. Simulations were used to determine a suitable word length for an implementation with integer calculation. In the present meter the distortion reading caused by rounding errors is about 0.15 % of U_1, the fundamental frequency voltage. Amplitude noise of the sampling causes similar increases in the results as rounding errors do. For the correction of the readings it is not necessary to separate their contributions. Because these two extra noise sources vary very little over time, much of their contribution can be removed together from the distortion reading using formula (9). However, it is useful to know the rounding errors when analysing other measurement errors. Rounding errors in estimation and control are discussed in /4/.

3.5 Timing errors in sampling

Timing jitter means the uncertainty of the timing of the sampling. When the measured signal changes with time the uncertainty of timing is seen as an additional amplitude uncertainty of the sampled measurement value. There are too types of timing jitter: 1) integrating timing jitter and 2) independent timing jitter.

Independent timing jitter causes in the samples amplitude errors that are proportional to the rate of change of the signal while the rate of change is proportional to both amplitude and frequency. Typically the drift of the sampling clock causes integrating timing jitter. The effect of integrating timing jitter is proportional to the amplitude of the measured signal but depends less on the frequency.

Simulations were made to check how sensitive the distortion measurement is to integrating and independent timing jitters. It was found that timing jitter increases the distortion reading very little compared to other error sources, when such timing jitter levels are applied that can normally exist in the meters.

3.6 End and start effects of measurement periods

When rectangular measurement windows are used the measurement period should be an integer multiple of the period of the fundamental frequency. Otherwise the difference of the sample value of the end point and previous end point will cause error. In principle this error is inversely proportional to the length of the measurement period. Thus these errors are only significant for short measurement periods. When using an exponential measurement window only the end error exists. Exponential window is typical for recursive methods that give a result value for each sample point. When the window is sliding over each sample like that the end and start errors soon cancel each other. In the meter the errors caused by end and start effects can be seen in the immediate values that represent 100 ms periods as a small oscillation, in voltage under $\pm$0.3% of U_1.

If the measurement windows are rectangular with little or no overlap, synchronising the measurement period with the fundamental frequency is needed to make the measurement period start always at the same phase of the fundamental component and thus eliminate the errors associated with the end and start. With the recursive adaptive observer there is less need to synchronise the measurement period than when DFT is used.

3.7 Errors with non-repeating events

The lower the sampling rate is, the more we must assume of the stationarity of the measured signal. Low sampling rate increases the uncertainty of the measurement results caused by transients and individual voltage dips and swells. When a distorted voltage waveform is repeated, the uncertainty disappears rapidly, because the sampling rate is chosen to give a good coverage of the repeating voltage waveform over a certain period such as 100 ms or 1 s. Longer response time is needed only for those events that do not repeat on every network period. The possible effect of non-repeating very short events on 10-minute values is very small. However, sparse sampling causes rather big measurement errors in the measurement of very short dips, interruptions and swells.

3.8 Correction of the distortion measurement

The effect of broadband amplitude noise and rounding errors on the distortion reading can be reduced with a correction function (9). The parameters of the correction function are calibrated using power quality analysers as reference. The fitted relation between the raw distortion estimate $\hat{D}_{raw}$ and the reference measurement D_{ref} is

$$D_{ref}^2 = 0.97\,\hat{D}_{raw}^2 - D_0^2 \qquad (9)$$

where $D_0^2 = 1.45 \times 10^{-4}$ represents the broadband noise of the new meters. See figure 3.

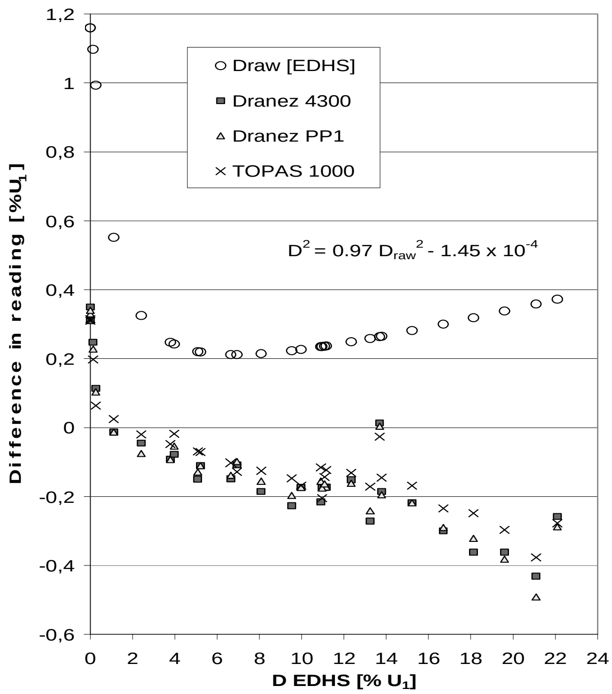

Figure 3. Distortion measurement compared with three reference meters. Zero on the vertical axis means perfect agreement with the reading of the new meter shown on the horizontal axis.

4 MEASUREMENT EXPERIENCE

The analysis of extensive measurement and test results with the older meter version shows that the methods have worked very well, see /5 and 7/. The performance is adequate for the planned task of detecting the quality problems, but the older meter version is not suitable for accurate measuring of small distortions (less than 1 % of U_1). The laboratory tests with the newer version have shown that the performance is in every respect better than with the older version. Frequency, harmonic components, distortion and unbalance of the voltage have always been close enough to the readings of reference meters. A comparison in the figure 3 shows how close the distortion measurement and the r.ms. sum of the measured harmonic voltage components were, when compared to several power quality analysers. Note, that some systematic difference remains that is not compensated by the function (9). The tests included also voltage distortions about 30%, 50% and 70% of the fundamental component. In these the difference in readings was between –0,39 % and + 0,00 % of U_1.

In figure 4 the same meters are compared in the measurement of individual voltage harmonics and DC-voltage.

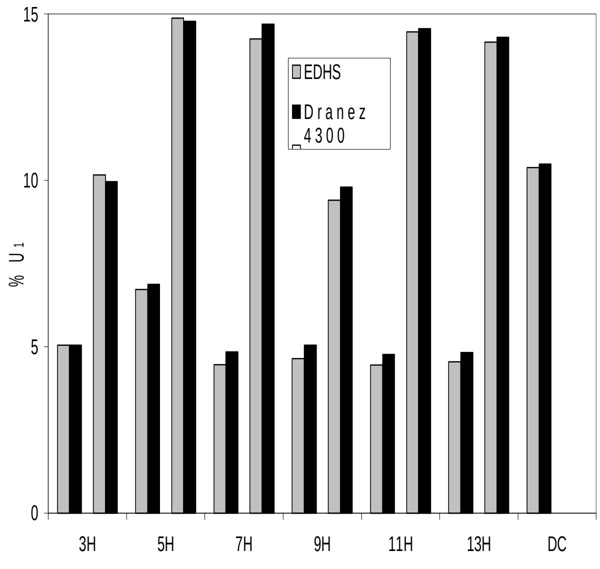

Figure 4. The new undersampling kWh-meter versus a power quality analyser in the measurement of individual voltage harmonics.

5. REQUIREMENTS, FUTURE NEEDS AND POSSIBILITIES

Several power utilities participated in the specification of requirements for power quality monitoring. They saw the following quantities important:

- voltage levels (variations)
- voltage excursions, voltage sags (dips) and swells (peaks), rapid voltage changes
- voltage fluctuations, flicker
- transient and temporary over-voltages
- voltage interruptions
- voltage harmonics and interharmonics
- voltage unbalance
- direct current or voltage component.

It turned out to be possible to meet almost all the above requirements. The relatively slow sampling and limited remaining data processing capacity of the meter prevented the measurement of flicker or transient voltages. We are ready to include flicker in the meter as soon as hardware with some more processing power is made. For the measurement of transient voltages it is better to have a separate device that can give its results via the remotely readable kWh-meter.

The intention is that power quality monitoring kWh-meters are indicators of power quality problems. The kWh-meters are not meant to be reference performance measurement equipment as defined in the IEC 61000-4-30 draft standard for power quality measurement methods. Thus the new quality monitoring kWh-meter is not a substitute for special power quality analysers. It does not need to give a very detailed view of the power quality, but it makes it possible at low cost to continuously monitor and automatically process power quality measurements from the network. The reason for this is that it is integrated into the remote reading system of the power consumption metering /14/ and with distribution automation /10/. At least as long as special power quality analysers are expensive and poorly integrated to other systems, there is a need for remotely readable power quality monitoring kWh-meters.

Power quality monitoring and Non Intrusive (Appliance) Load Monitoring, see /13/, can together become more valuable than separately, because they complement each other. Power quality monitoring kWh-meters are used in the research of this subject at VTT Energy.

The integration of several functions in the same meter decreases investment, installation, data communication and maintenance costs for the overall functionality remarkably. The kWh-meter can read temperature and network state indicators, and remote control for example capacitors in the network. It can be used for monitoring the loading and voltages of transformers. The power quality measurements increase the usefulness of this combination. Both the loads and the power quality of important customers are known and reliably recorded using the same meter.

6. CONCLUSION

Many important power quality problems can be detected with the smart energy meter even with a relatively low sampling rate. The power quality measurements can be processed and transferred by the remote reading system. We think that in the near future even more complete view of the network state and power quality can be measured using low cost remotely readable multi-purpose meters.

References

1. Dash P. K., Pradhan A. K., Panda G.: *Frequency Estimation of Distorted Power System Signals Using Extended Complex Kalman Filter*. IEEE Transactions on Power Delivery, July 1999, vol. 14, No. 3, pp. 761-766.
2. Gawthrop P.J.: *A continuous-time approach to discrete-time self tuning control*. Opt. Contr. App. Methods, vol. 3, no. 4, 1982, pp 399-414.
3. Girgis A.A., Hwang T.L.D.: *Optimal Estimation of Voltage Phasors and Frequency Deviation Using Linear and Non-linear Kalman Filtering*. IEEE Trans. On Power Apparatus and Systems, vol.103, No 10, October 1984, pp. 2943-2951.
4. Goodwin G.C.: *Some observations on robust estimation and control*. in Proc. of the 7th IFAC Sym. on Identification and System Parameter Estimation, York, UK, 1985, pp. 851-859.
5. Koponen P., Farin J., Lemström B.: *Experience with power quality monitoring kWh-meters*. DistribuTECH DA/DSM Europe 98 Conference, 27-29, October 1998, London UK. (CD-Rom).
6. Koponen P. ,Farin J., Lemström B., Vanhala P.: *Problems and Possibilities with billing meters and power quality*. Proc. of the DA/DSM Europe 96 Conference, October 8-10 1996, Vienna, Austria, vol. II, pp. 433 - 452.
7. Koponen P., Seesvuori R., Böstman R.: *Adding power quality monitoring to a smart kWh-meter*. Power Engineering Journal, 1996, 10, (4), pp. 159-163.
8. Kreisselmeier G.: *On sampling without loss of observability/controllability*. IEEE Transactions on Automatic Control, vol. 44, no. 5, May 1999, pp 1021-1025.
9. Landau Y.: *Adaptive control, the model reference approach*, Marcel Dekker, 1979, 406 p.
10. Mäkinen A., Parkki M., Järventausta P., Kortesluoma M., Verho P., Vehviläinen S., Seesvuori R., Rinta-Opas A.: *Power quality monitoring as integrated with distribution automation.* Accepted to be published in 16th International Conference and Exhibition on Electricity Distribution, CIRED 2001, Amsterdam, The Netherlands, 18 –21 June 2001.
11. Nishiyama K.: *Nonlinear Filter for Estimating a Sinusoidal Signal and Parameters in White Noise*: *On the case of a Single Sinusoid*. IEEE Transactions on Signal Processing, Vol. 45, No. 4, 1997, pp. 970-981.
12. Phadke A. G., Thorp J., Adamiak M.: *A New Measurement Technique for Tracking Voltage Phasors, Local System Frequency and Rate of Change of Frequency*. IEEE Transactions on Power Apparatus and Systems, vol. 102, No5, 1983, pp. 1025–1038.
13. Pihala H.: *Non-intrusive appliance load monitoring system based on a modern kWh-meter*. VTT Publications: 356. VTT, Espoo 1998, 63 p. + app. 3 p.
14. Saari H., Koponen P., Tahvanainen E., Lindholm T.: *Remote reading and data management system for kWh-meters with power quality monitoring*. Power Engineering Journal, 1996, 10, (4), pp. 164-168.
15. Toivonen L., Mörsky J.: *Digital multirate algorithms for measurement of voltage, current, power and flicker*, IEEE Transactions on Power delivery, vol. 10. January 1995, pp. 116-126.
16. Åström K.J., Wittenmark B.: *Computer controlled systems*, Prentice Hall, 1984, pp. 34-38 and 207-211.

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