A New Approach to Power Grid Measurements - Measuring in Frequency Domain

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Abstract

Measurements in power grids showed that the frequency stability is normally higher than 0,1 %. This reveals that the frequency is one of the most stable variables in power systems and that the standard assumptions of time domain measurements - the unknown frequency and the need for frequency extraction from time samples - are unjustified. In this paper we present a new approach in which the frequency is considered to be exactly 50 Hz, while its small excursions normally present in power grids are treated as small perturbations upsetting the standard harmonic composition of the signals in the grid. In this approach the frequency is measured independently of other variables as a frequency of a voltage signal in the grid and it is used in a perturbation calculus, while other variables such as phase voltages, phase currents, active power etc. are measured and represented through their harmonics. This paper also describes an instrument based on this approach which measures sine and cosine components of 50 harmonics of voltage and current signals in frequency domain, without the use of any form of Fourier transform and with the accuracy higher than 0.04 % from range, regardless to the order of the harmonic or time shape of the voltage and current signals. The measured sine and cosine components of voltages and currents together with the frequency represent fundamental set of measurement information and all other variables, due to the equivalency of time and frequency domains, are calculated from the obtained harmonics. The availability of harmonics also enables an easy integration and derivation of signals, as well as their shifting in time. The latest is of special importance in measuring some ambiguous variables in power grids such as reactive power in non-sinusoidal regime.

1. INTRODUCTION

According to the Theorem of Weierstrass given and proved in Фихтенгољц (1) any given signal can be approximated with a trigonometric polynomial of order m with an arbitrary small error, while the coefficients of the approximation are given with the Fourier's transform of the original signal. In theory, finding the order m of the polynomial that will satisfy the given accuracy criterion is not an easy task, but in praxis measurements can give a fair hint. In the power grid of Serbia and Montenegro nominal frequency is set to f = 50 Hz. Taking into account that the power grid acts as a low pass filter, one can easily assume that the harmonics of order higher than 50th are highly unlikely. Therefore according to the Weierstrass' theorem both voltage and current signals in

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power gird can be approximated with a trigonometric polynomial of 50th order (or less) with a negligibly small error. This is in compliance with the latest standards on power quality such as EN-50160 (2) and the common approach in comparison of different frequency-time transform algorithms with the Fourier's transform as given by Yung et al. (3) or by Yoon and Devaney (4).

Hence any given period of a non-sinusoidal signal can be presented with a set of $2m+1$ time samples or a set of $2m+1$ coefficients of a trigonometric polynomial without any degradation of the measurement information on the observed signal. Although in both cases the information entropies appear to be equal, characterization of a signal with time samples is actually excessive with a redundant number of float numbers used, especially in cases of measurements with oversampling required in many AD converters. In that sense, the representation of a signal via harmonics is optimal. Since the coefficients of the trigonometric polynomial can be unambiguously transformed to DFT coefficients defined in frequency domain, it follows that for all non-sinusoidal periodic signals both representations in time and frequency domains are equivalent, assuming that the criteria of the Sampling Theorem are satisfied.

1.1. Frequency stability

One of the most important factors of the power systems stability is short and long term stability of the voltage fundamental frequency. Definitions and examples of frequency stability and the impact of its short time excursions on performances of power systems have been provided by the IEEE/CIGRE Joint Task Force on Stability Terms and Definitions (5) and by Horne et al. in (6). Here we present the results of similar measurements in Serbian power grid prior to and upon the interconnection with the European power system. The measurements have been conducted with an instrument VMP20 described in (7). VMP20 has a very stable oscillator, a high quality zero crossing detector and it is not affected by the presence of a DC component in the signal. In January 2001 a 30 day measurement has been performed with time resolution of 0.1 s or 5 periods. The results are shown in figure 1. The calculated mean value and standard deviation of the frequency in an unbalanced power grid were 49.98 Hz and 0.084 Hz. The results of another measurement conducted in 2005 by Djukanovic (8), after the connection to the European power system, are shown in figure 2. The mean value of the frequency has improved to 50.00 Hz, while the standard deviation has decreased approximately four times to a value of 0.02 Hz or 0.04%. This is in compliance with our research performed in 2004, where it has been shown that the average variation of fundamental frequency within 2 s is less then 0,007 %.

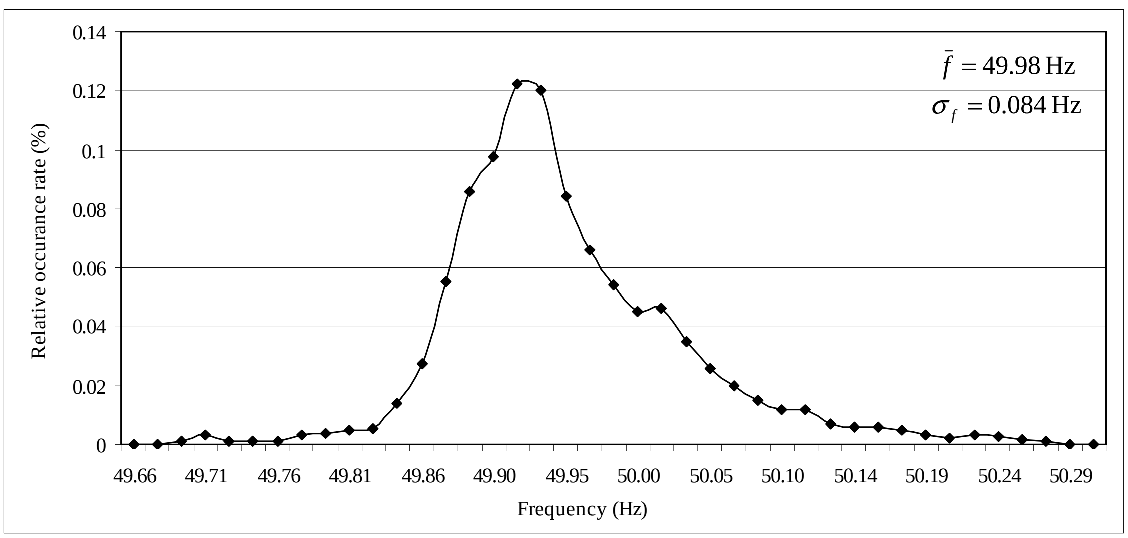

FIGURE 1 - HISTOGRAM OF THE SERBIAN POWER GRID FREQUENCY IN JANUARY 2001

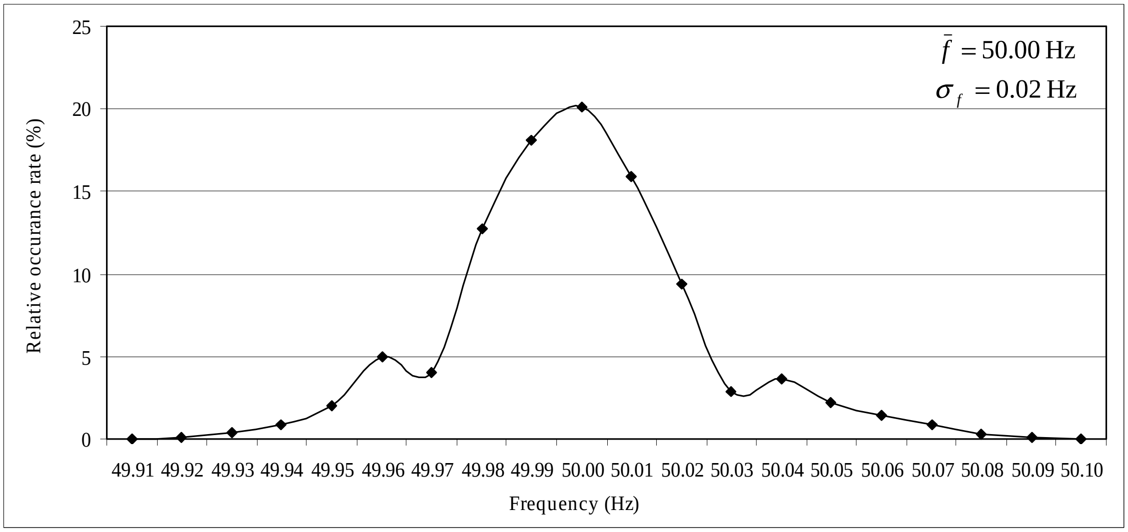

FIGURE 2 - HISTOGRAM OF THE SERBIAN POWER GRID FREQUENCY IN JANUARY 2005

The presented results and analysis explain why the frequency is stable enough to be considered a known parameter in most power measurements, where averaging over significant period of time is performed. However frequency instability occurs and is commonly caused with abrupt changes in power consumptions (up to 10 MW). Both in (5) and (6) a significant frequency excursion has been described as a very short occurrence in stabilized power grids. Prolonged frequency excursions commonly lead to power failures and therefore they will not be an object of this article. Short discrepancies of the frequency can be assessed directly as described by Cai and Ni in (10) and can be used in perturbation calculus to estimate the scope of the fundamental frequency excursion and its influence on the accuracy of the harmonics measurements. If the fundamental frequency exposes a deviation of 0.02 Hz, than the 50^{th} harmonic will be slipped on the frequency scale for 1 Hz, leading to 50 times larger measurement error. However a simple frequency extraction circuit such as PLL can be used to scale the results obtained in frequency domain along the frequency axis, enabling relative measurements regardless to the fundamental frequency of analyzed signal. This ability is another unique feature of frequency domain measurements, but the synchronization circuits must be fast enough to answer the needs of a specific application.

2. MEASURING VARIABLES IN POWER GRID USING HARMONICS

RMS value of a voltage or current signal can be expressed and measured either as a continuous integral given with the equation 1 or as a sum of trigonometric polynomial as given with the equation 2.

$$Y = \sqrt{\frac{1}{T}\int_0^T f^2(t)dt} \tag{1}$$

$$Y = \sqrt{\frac{a_0^2}{4} + \sum_{i=1}^{m}\left(\frac{a_i^2 + b_i^2}{2}\right)} \tag{2}$$

Equation 1 can also be expressed through time samples as

$$Y = \sqrt{\frac{1}{2n+1}\sum_{i=1}^{2n+1} \grave{y}_i^2}\ , \tag{3}$$

where $n \geq m$ is the number of time samples taken in each period of the signal and $\grave{y}_i$ is i^{th} time sample. Since both voltage and current are physical variables, from the point of classic physics they must have finite derivates. Therefore both voltage and current in power grid systems are continuous and derivable variables and according to the Theorem of Weierstrass they can be represented with an arbitrary small error using a trigonometric polynomial. In praxis the polynomials are commonly limited to the 50^{th} order.

With an access to harmonics, one can easily calculate total harmonic distortion factor or TDH as given by the equation (4).

$$TDH = \frac{\sqrt{\sum_{i=2}^{m} Y_i^2}}{Y_1} \tag{4}$$

where Y_i, (i = 1,2,3,…,m) presents the amplitude of harmonic of order i. Ideal situation in power grids is stated to be in case $TDH = 0$ for both current and voltage signals. However, presence of harmonics in modern power grids is unavoidable due to the widespread use of power electronic devices. Commonly a value of TDH less than 8 % is considered to be tolerable.

Active power defined with equation 5 can also be expressed as in equation 6. This yields that the active power can be measured as sum of active powers of individual harmonics as proposed by Yoon and Devaney in (6).

$$P = \frac{1}{T}\int_0^T uidt \tag{5}$$

$$\begin{aligned} P &= \frac{1}{T}\int_0^T \left[U_0 + \sum_{i=1}^{m} U_i \sin(i\omega t + \phi_i)\right] \cdot \left[I_0 + \sum_{i=1}^{m} I_i \sin(i\omega t + \psi_i)\right] dt = \\ &= U_0 I_0 + \frac{1}{2}\sum_{i=1}^{m} U_i I_i \cos(\phi_i - \psi_i) \end{aligned} \tag{6}$$

Using equation 2, active power can be written as

$$P = \frac{a_0 c_0}{4} + \frac{1}{2}\sum_{i=1}^{m}(a_i c_i + b_i d_i) \tag{7}$$

where a_i, b_i (i = 0,1,2,…,m) are coefficients of the trigonometric expansion of the voltage signal while c_i, d_i (i = 0,1,2,…,m) are coefficients of the trigonometric expansion of the current signal

Reactive power is defined with equation 8

$$Q = \frac{1}{T}\int_0^T u(t - \frac{T}{4}) i(t) dt\ , \tag{8}$$

and can be equivalently expressed via voltage and current harmonics as given with expression 9.

$$Q = \frac{1}{T}\int_0^T \left[\sum_{i=1}^{m} U_i \sin(i\omega(t - \frac{1}{T}) + \phi_i)\right] \cdot \left[\sum_{i=1}^{m} I_i \sin(i\omega t + \psi_i)\right] dt \tag{9}$$

To perform measurements of reactive power using harmonics we can modify the expression 9 and obtain equation 10.

$$Q = \frac{1}{2}\sum_{i=1}^{m} U_i I_i \cos(\phi_i - \psi_i - i\frac{\pi}{2}) \tag{10}$$

This can also be expressed using coefficients of trigonometric expansion of voltage and current signals as given in equation 11.

$$\begin{aligned} Q &= \frac{1}{T}\int_0^T \left[\sum_{i=1}^{m}(a_i \cos i\omega(t - \frac{T}{4}) + b_i \sin i\omega(t - \frac{T}{4}))\right] \cdot \left[\sum_{i=1}^{m}(c_i \cos i\omega t + d_i \sin i\omega t)\right] dt = \\ &= \frac{1}{2}\sum_{i=1}^{m}((a_i c_i + b_i d_i)\cos(-i\frac{\pi}{2}) + (b_i c_i - a_i d_i)\sin(-i\frac{\pi}{2})) \end{aligned} \tag{11}$$

Acquiring phase shifted voltage signal is relatively easy using adequate digital all pass filters.

The apparent power is defined with equation 12.

$$S = \sqrt{\frac{1}{T}\int_0^T u^2 dt} \cdot \sqrt{\frac{1}{T}\int_0^T i^2 dt} \tag{12}$$

It can be measured using harmonics' amplitudes as illustrated with equation 13 or using coefficients of the polynomial expansion of voltage and current signals as in equation 14.

$$S = \sqrt{U_0^2 + \frac{1}{2}\sum_{i=1}^{m} U_i^2} \cdot \sqrt{I_0^2 + \frac{1}{2}\sum_{i=1}^{m} I_i^2} \tag{13}$$

$$S = \sqrt{\frac{a_0^2}{4} + \sum_{i=1}^{m}\left(\frac{a_i^2 + b_i^2}{2}\right)} \cdot \sqrt{\frac{c_0^2}{4} + \sum_{i=1}^{m}\left(\frac{c_i^2 + d_i^2}{2}\right)} \tag{14}$$

3. MULTICHANNEL HARMONIC INSTRUMENT IN FREQUENCY DOMAIN USING DITHERING

The first instrument constructed for harmonics measurements in power grids directly in frequency domain was a generalization of a low frequency true RMS instrument described by Pjevalica V. and Vujicic in (11). It is based on dithering of input signal prior to quantization and averaging the added Dithering signal to obtain more accurate measurements. This instrument had only one channel for measuring cosine or sine component of the input signal. The scheme of the instrument is given in figure 3.

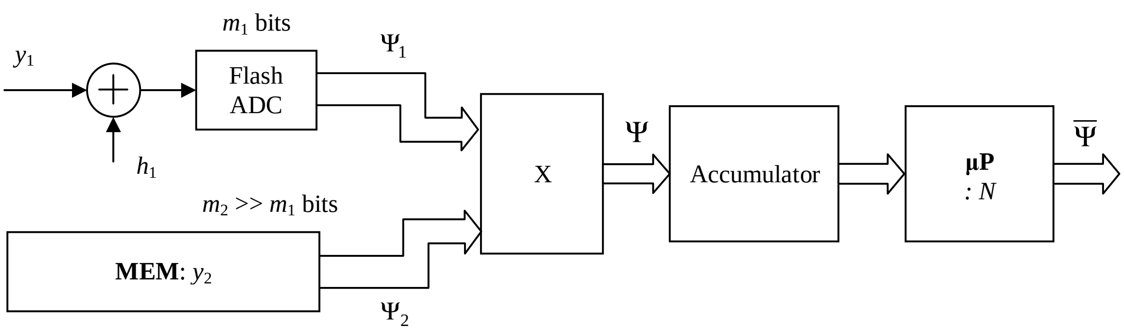

FIGURE 3 - HARDVARE FOR MEASURING SINE OR COSINE COMPONENT OF THE k^{th} HARMONIC OF THE INPUT SIGNAL

$h_1(t)$ is dithering signal for the input function, while in memory block MEM, with y_2 is represented a digital sequence of the dithered basis function $R\cdot\sin(k\omega t) + h_2(t)$ or $R\cdot\cos(k\omega t) + h_2(t)$, where R is the known constant usually equal to the range of the used flash ADC. If dither signals are mutually statistically independent, they are averaged out and the output of the scheme in figure 3 is given with expression 15.

$$\overline{\Psi} = \frac{1}{N}\sum_{n=1}^{N} y_1(i)y_2(i) \overset{N\to\infty}{=} \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} y_1(t)y_2(t)dt \overset{e.g.}{=} \frac{R}{t_2 - t_1}\int_{t_1}^{t_2} y_1(t)\cos(k\omega t)dt \tag{15}$$

If the measurement interval is a multiple of fundamental period of the input signal and the number of samples per period is an integer number, than the output of the instrument is given with expression 16

$$\overline{\Psi} = \frac{R}{mT}\int_0^{mT} y_1(t)\cos(k\omega t)dt = \frac{R}{T}\int_0^{T} y_1(t)\cos(k\omega t)dt = \frac{R}{2}\cdot a_k, \tag{16}$$

where a_k is the coefficient of the trigonometric expansion of the input function representing cosine component of the k^{th} harmonic in the input signal as given with equation 17.

$$a_k = \frac{2}{T}\int_0^T y_1(t)\cos(k\omega t)dt, \tag{17}$$

Should a resolution of the memory block exceed the resolution of the flash ADC, the upper error limit of measuring coefficient a_k is given in (11) as

$$\sigma_{a_k} = \frac{2}{R}\sigma_{\overline{\Psi}} \le \frac{2}{R}\cdot\frac{\sqrt{\frac{\Delta_1^2}{4}\cdot\frac{1}{t_2-t_1}\int_{t_1}^{t_2} f_2^2(t)dt + \frac{\Delta_2^2}{4}\cdot\frac{1}{t_2-t_1}\int_{t_1}^{t_2} f_1^2(t)dt + \frac{\Delta_1^2\cdot\Delta_2^2}{16}}}{\sqrt{N}} \approx \frac{\Delta_1}{\sqrt{2N}} \qquad (18)$$

where Δ_1 and Δ_2 are the quanta of the flash ADC and the memory block respectively. It is clear that in this case the instrument has an upper error limit independent of the waveform of the input signal and the order k of the measured harmonic. Acquiring coefficient b_k of the k^{th} harmonic's sine component is simply performed through the reprogramming of the memory block and setting its content to digitized values of the dithered signal $R\cdot\sin(k\omega t) + h_2(t)$. Another approach is to use two hardware blocks from figure 3 in parallel - one for sine and one for cosine component. The second approach has many advantages, but two major ones are that both components are available simultaneously and that the duration of measurement with same accuracy is halved.

This idea has been further generalized in the first integrated instrument for harmonics measurement based on direct measurement in frequency domain with the use of signal dithering. The instrument is described by Tomic in (12). This instrument has a single channel multiplexed to 16 different configurations for measurement of 16 trigonometric coefficients (8 harmonics) and assumes a known and stable fundamental frequency of measured signals. The scheme of the instrument is given in figure 4.

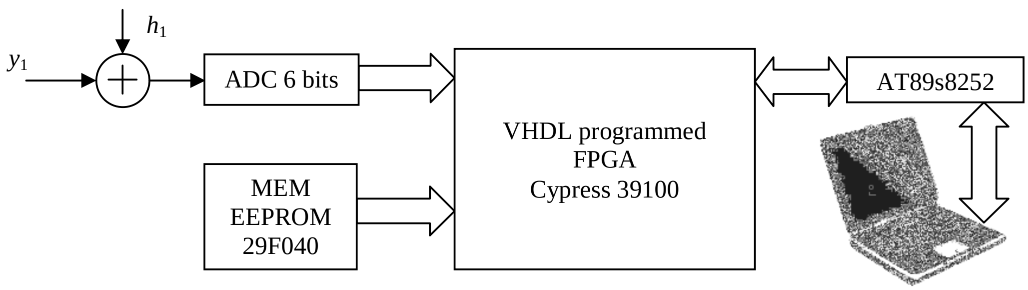

FIGURE 4 - BLOCK SCHEME OF THE INTEGRATED INSTRUMENT FOR HARMONIC MEASUREMENT

FPGA CY39100 was used to implement independent mulitplication and averaging of digital samples in 16 parallel channels, each represeing one hadware block from figure 3. Memory block was a fast EEPROM M29F040 capacity of 512 Kb. Processor Atmel AT89s8252 was used for communication with a PC. The bottle neck of the realized harware is the ability of the processor to perform great number of aritmetic calculations in a limited interval between two samples. It may appear tht another disadvantage of the above instrument is the assumption of a stable and known fundamental frequency in the input signal. But when applied in power grids, this instrument can utilise the fact that the frequency stability is high enough, so no significant measurement errors will be caused if an internal sinchonisation of 50.00 Hz is used. This can easily be taken into accout if freqency is not sinthetiyed within the instrument but estimated from the samples taken as done by Cai and Ni in (10) or by any other complementary method. A sight modification of the instrument form figure 4 and insertion of circutis for fundamental freqeuncy extraction could take into account any frequency drifts. An idea for the measurements of harmonics of time-varying frequencies has been recently proposed by Karimi-Gharteman and Iravani in (13). It is based on the use of PLL for frequency extraction and also, exludes the use of FFT obtaining harmonics directly in frequency domain. The achieved ralative measurement error was lower than 0,05 %.

After a successful deployment of the integrated harmonic instrument with 16 channels and number of laboratory tests and analyses, the next step was to perfect the concept and increase the number of input channels to correspond the present power quality standards and to enable measurements of up to 50 harmonics. As FPGA has proven to be an optimal solution for the realization of the described hardware, the idea was to pack the entire instrument within a single FPGA leaving only ADC and DAC as external components. Benefits of the FPGA approach compared to alternative solutions with μP or ASIC are: high level of parallelism, hardware pipelining of arbitrary depth, widespread and accepted cook-book solutions (both as open source or IP cores), possibility of pre-implementing verification through simulation, fast prototyping and significantly lower implementation costs. Some drawbacks of FPGA implementation are smaller overall speed performance compared to ASIC solutions and more complex debugging than with μP. However, with a rising technology development we are witnessing an explosion of variety of FPGA chips with lower and lower costs. Such market growth makes the FPGA approach very attractive, especially for application in systems with high computational complexity.

The scheme of the proposed instrument is given in figure 5.

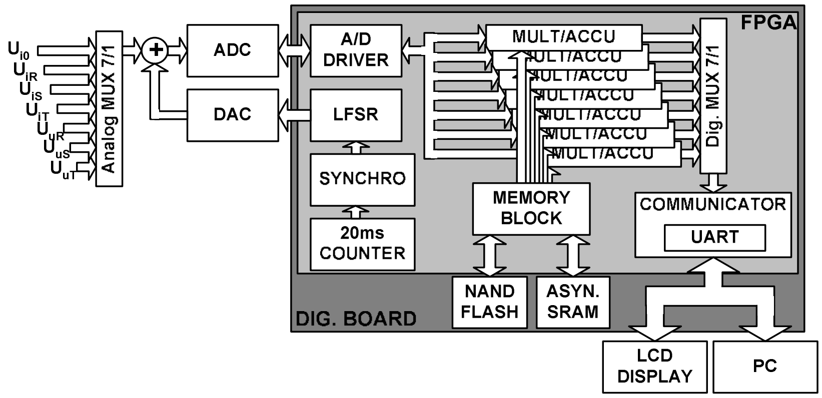

FIGURE 5 - HIGH-ACCURACY MULTI-CHANNEL HARMONIC INSTRUMENT

The instrument has been realized at the begging of 2006. It is currently undergoing a series of tests. Compared to the previous version it has an increased number of channels (7) with the preserved measurement accuracy and measures 50 harmonics of each channel in parallel. These seven channels can be used for measurement of 3 phase voltages, 3 phase currents and current through the neutral lead. From harmonics of these seven variables any parameter of the power quality in grid can be calculated. Due to high speed signal processing the measurement interval is reduced to a single period of the fundamental harmonic. This means that the instrument is fast enough to be implemented in any power measurement requiring information and reaction to that information within 20 ms. By reconfiguring the input module for single channel measurements and reorganizing the memory block, the instrument could measure up to 350 harmonics of a single input signal. Calibrations have confirmed that the relative measurement error of individual harmonics is less than 0.05 %, but further improvement in measurement accuracy is an object of the ongoing tests and research.

4. CONCLUSION

Measuring sine and cosine components of harmonics of current and voltage signals directly in frequency domain enables straightforward acquisition of their spectra, as well as the information on active, reactive, apparent and distortion power and their spectral densities. This is of special importance in power quality measurements where fast, reliable and accurate measurements are required for power quality monitoring. Frequency stability in power grids is high enough to be considered a known parameter. This fact can be used for simple and efficient harmonics measurements directly in frequency domain. In cases of smaller frequency excursions within the measurement interval, additional circuits and computational methods can be applied to minimize measurement error of the highest harmonics. Frequency domain measurements are also optimal since the measurement information can be presented with a minimal set of harmonic coefficients. We have proposed this new concept of power grid measurements in a fast and highly accurate multi-channel harmonic instrument. The instrument has 7 parallel channels and can measure up to 50 harmonics within a single period of the basic harmonic, achieving measurement uncertainties lower than 0.05 %. Using only one channel it can be adapted to measure up to 350 harmonics of a single input signal. This is superior to any measurements performed in time domain based on the usage of DFT or other types of time-frequency transforms and current research promises further advancing in performances.

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Keywords: power quality, harmonics, frequency domain measurements, Fourier transform