COMPARATIVE STUDY ON CHOSEN METHODS OF VOLTAGE DIP TRACKING BASED ON REAL EXAMPLE

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Abstract − The paper presents results of experimental study of two methods of voltage dip tracking. First is based on half cycle absolute peak value monitoring, whereas second is based on low-pass filtration of squares of voltage samples. Both methods are devised for application in low-cost integrated circuits, dedicated to power quality monitoring. The real voltage dip has been considered for the aim. The results have been compared with reference method recommended in IEC Std. 61000-4-30.

Keywords: voltage dip, low-cost measurement, power quality

1. INTRODUCTION

The problem of power quality in electric power networks has became arguably one of the hottest topics at electrical power engineering over recent years. Proliferation of non-linear loads completed by introduction of renewable energy resources has led to notorious supply voltage disturbances, like voltage and current waveform distortions, voltage dips and so on. In order to ensure the proper operation of future power systems, particularly smart grids and/or their predicted building blocks, namely microgrids [1], the intelligent metering and monitoring systems are necessary [2]. This smart metering infrastructure are to monitor power flow and various voltage and current parameters in numerous locations thorough the whole grid. However, the actual purposes of the monitoring are to be carefully analysed and proper solutions has to be implemented, in order not to increase the cost of the whole infrastructure. In author's opinion, apart from high grade power quality analysers, a number of low-cost devices will be necessary, like instruments based on dedicated integrated circuits (IC). Fortunately, such a solutions are already available on "the shelf", e.g. Analog Devices *Single Phase, Multifunction Metering IC with Neutral Current Measurement ADE7953* [3] or Cirrus Logic *Single phase bi-directional Power/Energy IC CS5461A* [4]. These are low-cost IC that enable measurement of voltage and current r.m.s. values, power and energy as well as monitoring of dips or swells. Although they are based on various processing principles, the common feature of the devices is signal processing executed by fixed function digital signal processor (DSP) [3]. Among other signal processing functions, the input signals filtrations are used for different aims like: elimination of input channels offset, zero-crossing detection as well as r.m.s. values of voltages and currents and active power measurements [3].

This paper is focused solely on the singular feature of these ICs, namely capacity of voltage dip or swell detection. For the aim, the method based on the absolute value of instantaneous voltage was used [3], [4]. Simply put, if magnitude of instantaneous voltage (its absolute value) is below the pre-defined threshold value, the dip is detected. Similarly, the swell is to be identified if absolute value of magnitude of instantaneous voltage is above pre-defined threshold value. Obvious disadvantage of this solutions is clear impact of distortions of input voltage on the outcome of dip or swell identification. This can be avoided by superseding this method by equally simple one based on low-pass filtration of squares of input voltage samples. In fact, the method has been used for r.m.s. value of voltage and current measurements by some manufacturers [3] but not for dip and swell identification. Therefore, the paper aim is to explore the possibility of using this solution easily applicable in IC with fixed DSP functions for dip and swell identification. It is compared with above mentioned method based on absolute value of instantaneous voltage monitoring. Both solutions are related to reference method laid in IEC Standard 61000-4-30 for Class A measurements, namely method based on measurement of r.m.s. voltage over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle $U_{rms(1/2)}$ [5]. The latter solution is recommended for voltage dip, voltage swell and interruption detection and evaluation [5]. All analyses are based on real voltage dip registered in exemplary microgrid. For the aim the dip of supply voltage in network of sensitive data centre has been chosen during its island operation mode. It has to be added that some documents use the term sag as synonym to the term dip [3-4], [6]. But since the term dip is used by IEC, it will be used consequently thorough this paper.

Finally the paper is organized as follow. Section II describes the standard framework and both solutions under investigation. Section III describes the results of experimental research. Section IV contains final remarks and conclusions.

2. STANDARD FRAMEWORK AND THE METHODS UNDER INVESTIGATION

The voltage dip is defined as sudden decrease in r.m.s. value of supply voltage to a value between 10% and 90% of declared voltage for durations from 0.5 cycles to 1 min [6].

In some other standards the values of the r.m.s. value reduction are assumed in between 1% to 90% of declared voltage [7]. A voltage dip is to be described by pair of data: residual voltage (sometimes dip's depth) and duration [5]. The residual voltage is the lowest r.m.s. value of voltage during the considered event, whereas duration is time difference between start time (falling of r.m.s. voltage below the dip threshold) and end time (increase of r.m.s. voltage above dip threshold plus hysteresis typically equal to 2% of declared voltage) [5]. In some cases, the voltage dip is followed by a voltage peak (small swell), e.g. during asynchronous motor start up in microgrid [8]. Typically, a voltage swell is monitored by the very same methods like voltage dip, e.g. voltage instantaneous values [3] or r.m.s. values [5].

It was mentioned above that for Class A measurements the considered r.m.s. voltage should be calculated over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle. It is designated as $U_{rms(1/2)}$ [5]. It includes all components like: harmonics, interharmonics, etc. [5]. It has to be added that Class S has been defined at IEC Standard 61000-4-30 as well. For the class the dip assessment is to be carried out in similar way like above described but the voltage r.m.s. value can be refreshed each cycle. Manufacturer of measuring instrument should specify which method is used [5].

Finally, the evaluation of real dip carried out by the method devised for Class A will be considered as reference for other methods evaluation. In fact, it has been used by author for whole voltage shape assessment during the considered processes, namely bulk load startup in microgrid. Next, it has been compared with the same shape determined by the other methods under investigation.

The application of standard method can be inconvenient in simple low-cost devices, due to some requirements for hardware resources of measuring instrument. In shorthand, it requires storing of voltage samples for at least one cycle, conditional operation, some data address generators, etc. Obviously, it can be easily implemented in digital signal processors (DSP) but not necessary in low-cost dedicated IC. Therefore, manufactures of low-cost measuring devices implement other principles of dip detection and evaluation [3], [4]. It is permissible for Class B measurements, if the manufacturer specify the method used for the aim [5].

Arguably, the simplest solution is detection of time instants when the absolute value of the voltage falls below the programmable threshold [3], [4]. This feature is easy to implement in IC. Simply, the dedicated peak register is updated every time that the absolute value of the waveform exceeds the current value stored in the register. The register can be cleared after reading [3], which can be synchronized with voltage fundamanetal component zero-crossing in order to determine the end of each half-cycle. Apart of its simplicity, the obvious disadvantage of the solution is the above mentioned possible impact of voltage distortions. It will be proved below that even in the case of low-level distortions, the results of dip analysis by the method can differ significantly from assumed reference method.

The solution of the problem is a method only a little bit more complicated but used for r.m.s. voltage measurement

otherwise [3]. It is based on squaring of input voltage samples and subsequent low-pass filtration of these squares. Next, the square root is calculated of the output of the low-pass filter (LPF). It corresponds to r.m.s. value of input signal [3]. Because of the ripples of LPF output, the reading is synchronised with voltage fundamental component zero-crossing. It is determined after voltage samples low-pass filtration by other LPF. The block diagram of the algorithm is shown in Fig. 1. It is based on ref. [3] after some modifications. It should be added that the solution is applied in *ADE7953* [3] for r.m.s. measurement but not dip detection and evaluation.
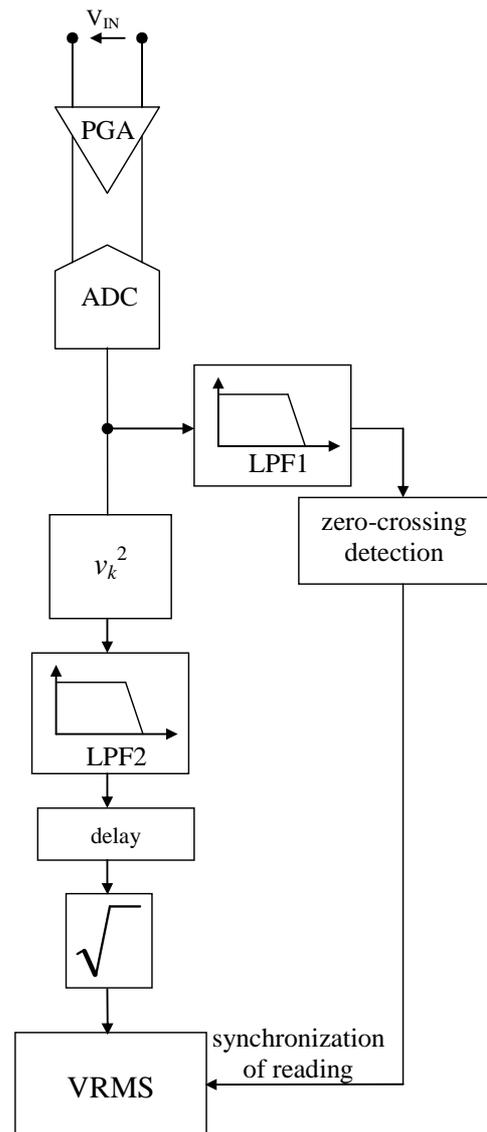

Fig.1. Block diagram of signal processing path for measurement of r.m.s. voltage, including dip detection and evaluation.

The above depicted (Fig. 1) signal processing path can be used for both: measurement r.m.s. value of voltage during steady-state as well as dip monitoring. The reading is to be carried out after each zero-crossing of voltage fundamental component, similarly like in the case of $U_{rms(1/2)}$ measurement. This r.m.s. value is used directly to dip or

swell detection and evaluation. Namely, it is to be compared with assumed threshold level, once again similarly like in the case of the standard method. In order to obtain 10-cycles rms voltage some accumulation and averaging would be necessary. The block "delay" shown in Fig. 1 is to account for LPF1 and LPF2 characteristics (group delays of both filters).

3. RESULTS OF EXPERIMENTAL RESEARCH

Author decided to use the real example of voltage dip for this paper's purpose. So, the research consisted in voltage samples registration in real network and subsequent processing by various signal processing methods. For the voltage samples recording, National Instruments controller PXIe-8106 equipped with two data acquisition cards PXIe-6124 has been used. The analog input channel consisted of the CV3-1500 LEM voltage transducers and LTC 1564 anti-aliasing filters. The sampling frequency bas been equal to 25 kHz and the cut-off frequency of anti-aliasing filters has been equal to 10 kHz.

The voltage recording took place in network of office building that contained very important and sensitive for power quality disturbances data centre, particularly interruptions. Therefore it was equipped with two UPSs and two generators driven by diesel engines for power backup. The whole research has been carried out during the object island operation mode, due to suspicion of power quality problems during the mode. Various parameters of voltage and currents have been analysed in various points of the system. During the investigation the process of switching bulk load on and following voltage dip and some ripples have been noted. The waveform of recorded voltage is presented in Fig. 2.
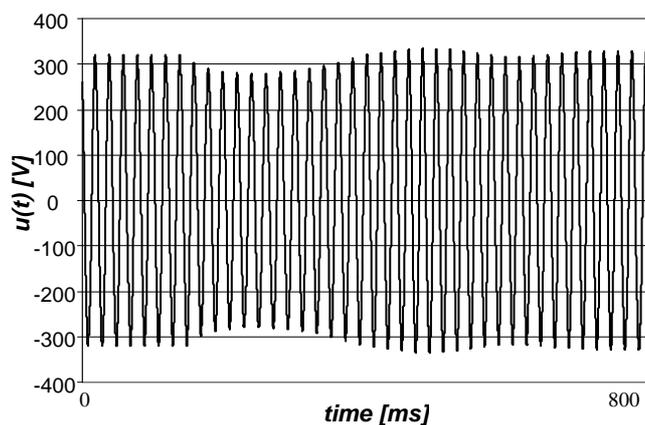

Fig. 2. Voltage waveform during switching bulk load on in power network of data centre during island operation.

It is easily discernible that the process of switching bulk load on in power network of data centre causes voltage dip up to 85% of rated voltage followed by small voltage swell. It is only 101.6% of rated voltage but approximately above 5% of registered mean steady-state voltage, which was approximately equal to 96.8% of rated voltage (230 V).

Nevertheless, this phenomenon has been considered as well, in order to properly asses the methods under investigation. The details of $U_{rms(1/2)}$ voltage calculated according to IEC 61000-4-30 standard and the resulted voltage shape are shown in Fig. 3.
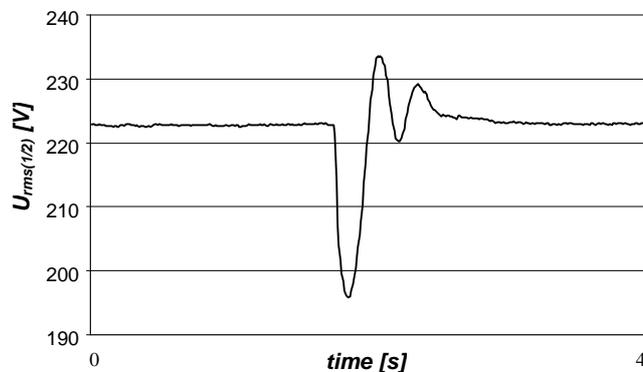

Fig 3. Variations of $U_{rms(1/2)}$ value (reference method) during switching bulk load on in power network of data centre during island operation.

Obviously, the processes of switching bulk load on in microgrids cause voltage changes and concurrent momentary frequency changes. For the considered example the lowest momentary frequency understood as reciprocal of fundamental cycle has been equal to 48.61 Hz followed by the frequency increase up 51.51 Hz. Typically, standards related to marine microgrids, e.g. [9], [10] deal with the phenomenon, but it has not been analysed for the paper's aim. However, the both investigated methods, which depend to some respect on fundamental component zero-crossing, enable concurrent assessment of momentary frequency changes, both value and duration.

Finally, the parameters for dip description has been calculated by both investigated methods. The results obtained by analysis of voltage local peak values have been designated as U_{ABS}. It is recorded absolute value of voltage magnitude divided by square root of 2 in order to obtain voltage r.m.s. value and subsequently compared with reference method. The results calculated by voltage samples squaring and low pas filtration of the result have been designated as U_{LPF}. It represents r.m.s. voltage momentary values. In this case, third order Butterworth filter has been used with various cut-off frequencies. It has been mentioned (see Fig. 1) that in order to diminish the effect of ripples of the filter output, its reading is to be synchronised with fundamental component zero-crossing. Zero-crossing of the fundamental component of the voltage has been determined after low-pass filtration by third order Butterworth filter, but with higher cut-off frequency equal to 80 Hz. Such a solution is recommended in IEC 61000-4-30 standard for diminishing impact of higher frequency components. The cut-off frequency has been chosen after ref. [3]. Finally, the results of calculation of pair of parameters (residue voltage U_{min} and duration) for the dip assessment are laid in Table 1. The dip duration is expressed in half cycles of the considered voltage. It is completed by results of calculation

of r.m.s. value of voltage of the mini-swell U_{max} that followed the considered dip.

Table 1. Results of calculation of dip (duration and U_{min}) and swell (U_{max}) parameters.

	f_{cutoff}	duration (half cycles)	U_{min}		U_{max}
			[V]	[%]	[V]
$U_{rms(1/2)}$		18	195.86	85.16	233.58
U_{ABS}		17	197.6	85.91	236.47
U_{LPF}	1 Hz	---	212.83	92.53	226.95
	2 Hz	16	203.57	88.51	228.13
	3 Hz	17	198.26	86.20	232.5
	4 Hz	17	196.19	85.30	233.39
	5 Hz	17	195.2	84.87	233.62
	6 Hz	17	194.92	84.75	233.66
	7 Hz	17	194.94	84.76	233.68
	8 Hz	18	195.13	84.84	233.63
	9 Hz	17	195.39	84.95	233.65
	10 Hz	18	195.65	85.07	233.62
	11 Hz	18	195.84	85.15	233.63
	12 Hz	17	195.93	85.19	233.63
	13 Hz	17	195.92	85.18	233.61
	14 Hz	18	195.89	85.17	233.57
	15 Hz	18	195.86	85.16	233.58
	16 Hz	18	195.85	85.15	233.57
	17 Hz	18	195.86	85.16	233.56
	18 Hz	19	195.85	85.15	233.55
	19 Hz	18	195.86	85.16	233.53
	20 Hz	18	195.88	85.17	233.52

Analysis of the results laid in Table 1 leads to conclusion that application of U_{LPF} method leads to better results than U_{ABS} method for quite a range of cut-off frequencies of used LPF2. Nevertheless, the cut-off frequency has to be carefully chosen. If it is too low or too high, the results of calculation worsens. In the former, it is due to increase in response time and in the latter it is due to increase of ripples of the filter output (reading exactly at the moments of zero-crossing is hardly possible). It should be noted that for cut-off frequency of LPF2 equal to 15 Hz the obtained results are exactly the same like in the case of reference method. However, it does not mean that the method is fully comparable with reference method. The comparison of voltage shape, in fact the differences between the U_{LPF} (cut-

off=15 Hz) and $U_{rms(1/2)}$ for the whole dip (and subsequent swell) envelope is shown in Fig. 4.
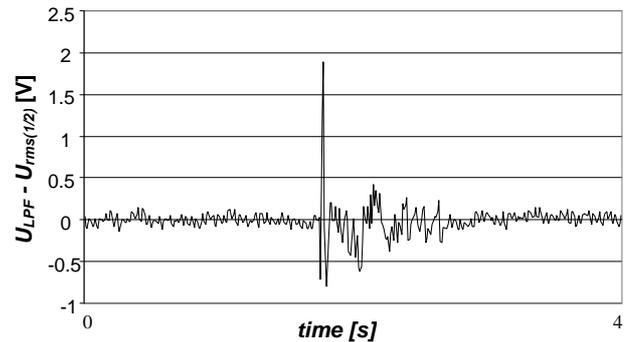

Fig.4. Differences between r.m.s. value of voltage calculated by filtration of square samples U_{LPF} and reference method $U_{rms(1/2)}$.

Similar differences between obtained shapes of voltage changes for the method applied by manufactures of two considered ICs, namely U_{ABS} and reference method are depicted in Fig. 5.
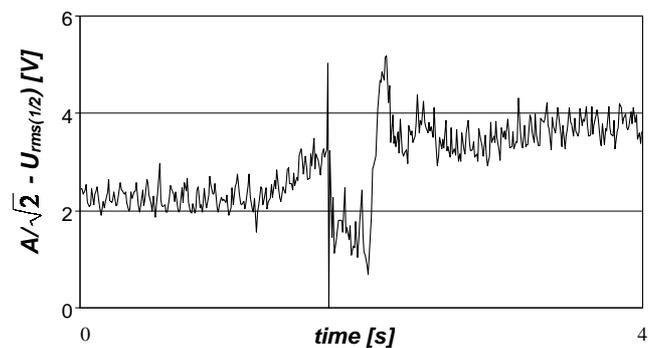

Fig.5. Differences between rms value of voltage calculated on basis of absolute peak value of voltage U_{ABS} and reference method $U_{rms(1/2)}$.

Comparison of Fig. 4 and Fig. 5 once again reveals clear superiority of the first solution, i.e. U_{LPF}. Only for very short time (two consecutive readings) the difference between considered method and reference method is above 1 V. It is for the dip beginning, four cycles before the lowest voltage r.m.s. value. Similar differences for U_{ABS} method reach values above 5 V. The reason is distortion of investigated voltage, although of relatively low level. The value of voltage *THD* factor has been equal to 3.13% prior to dip and 3.26% after the phenomenon occurrence. It can be noted that even this small increase leads to significant increase in differences between U_{ABS} and $U_{rms(1/2)}$ (see Fig. 5). It increases nearly two times under steady-state conditions: before and after dip. The chief reason is increase of 5th harmonic content by 0.19% of fundamental component completed by phase shift of some harmonics in relation to fundamental one after the dip.

In order to exemplify the capability of tracking of $U_{rms(1/2)}$ small variations by U_{LPF} method, the two algorithms

have been graphically compared in Fig. 6. Assumed cut-off frequency of LPF filter has been equal to 15 Hz.
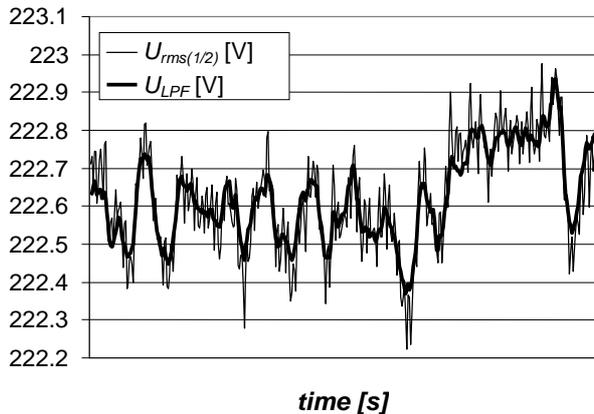

time [s]

Fig. 6. Comparison of tracking capabilities of short-term small voltage variations by U_{LPF} method with $U_{rms(1/2)}$ method.

The analysis of Fig. 6 once again indirectly proves that U_{LPF} method would be appropriate for considered aim, namely voltage dip or swell detection and evaluation.

4. CONCLUSIONS

The paper aim has been to investigate some simple algorithms for dip or swell detection and evaluation applicable in low-cost ICs, dedicated to multifunction electricity parameters measurement. It has been proved that method of signal processing based on low-pass filtration of input voltage samples is more suitable for the aim than commonly used method based on absolute values of momentary voltage peak. It is true in the case of input signal

distortions, even seemingly insignificant, which are rather norm than exception in nowadays power systems. Since it is already used for r.m.s. value estimation by the same ICs, it requires only some modification of their design, but special attention has to be paid to cut-off frequency and group delay of implemented LPFs.

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